Modelling, simulation and experimental investigation for generating ‘I’ shaped contour using electro chemical machining

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CERTIFICATE

This is to certify that the work in the thesis entitled "Modelling, simulation and experimental investigation for generating 'I' shaped contour on using electro chemical machining" by Anshul Abhijit Nayak, has been conducted under my supervision required for partial fulfilment of the requirements for the degree of Bachelor of Technology in Mechanical Engineering during session 2014-2015 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.

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Abstract

Performance in Electrochemical Machining (ECM) is primarily governed by flow characteristics of electrolyte. Although, some analytical work has been reported on mechanism of material removal and distribution of current density, information on flow characteristics of ECM, pressure and temperature profile is relatively scarce. In the present work, analytical simulation of various phenomena occurring in the IEG such as velocity variation, pressure variation, turbulent kinetic energy and temperature profile to study passivation was performed using a 'I' shaped tool and Inconel 825, a Nickel based super alloy as workpiece material. According to computational fluid dynamics (CFD) simulation results, velocity distribution is minimum while the turbulence is maximum near the bend and sharp corners. Simulation also indicated that formation of negative pressure zone around the periphery of the tool resulting in eddies. Temperature was found to be less around the central region of electrolyte in machining gap as well as near the sharp corners due to high flow velocity and turbulence respectively. Further, experiment was conducted to correlate the finding of simulation with various performance measures in ECM such as material removal rate (MRR), surface roughness and overcut. Effect of parameters like voltage, concentration and feed rate was investigated and finally optimised using grey relation analysis which yielded concentration of 80g/l, feed rate of 0.2 mm/min and voltage of 10 V for best responses.

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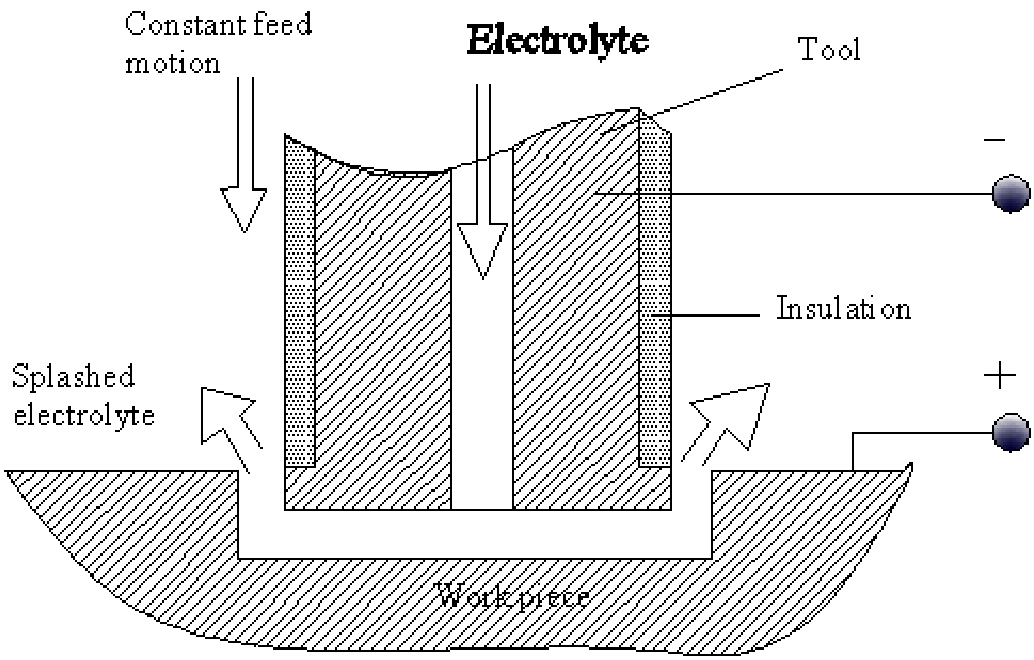
1. Introduction

Electrochemical machining (ECM) is a non-traditional machining process based on the principle of electrolysis and is also a reverse electroplating process in which anodic dissolution of the workpiece at atomic level is carried out by a desired tool due to flow of high current at low potential difference with the help of an electrolyte which can be water based neutral salt solution like sodium chloride or sodium nitrate. Sometimes, difficult to cut materials especially high strength alloys and heat-resistant materials can not be machined into complex and intricate shapes by conventional techniques, but such materials can be accurately machined by electrochemical machining. ECM is an electrochemical process where the negative impression of tool is formed on workpiece by moving the tool towards the workpiece at a rate precisely enough to maintain the rate of dissolution because if the equilibrium gap changes rapidly because of the feed rate of tool, sometimes it might lead to spray machining or else short circuit due to the contact of tool and workpiece and stop machining. ECM has many advantages over other non-conventional process as machining occurs without inducing any residual stress, tool wear and heat affected zone with high material removal rate as compared to Electro Discharge machining which is a thermal process where the surface layer changes by 0.5 -1 mm generating internal stresses and cracks High precession machining with better surface finish also provides an edge to ECM especially in aerospace and automobile industries as it eliminates the need for further cost intensive polishing. Moreover, ECM works at low voltage and high current intensity with an inorganic salt solution as an electrolyte to complete the circuit and act as a heat exchanger.

1.1. Working Principle

ECM is an electrochemical process that works by the anodic dissolution of workpiece surface with tool as cathode and workpiece as anode. Electrodes are immersed in the electrolyte and potential difference is applied to these electrodes. The electrolyte being conductive in nature dissociates to form ions and the movements of ions between the anode and cathode helps in electrochemical reaction. The current generated due to movement of ions will cause the dissolution of anode. This process of electrolysis is working based on Faradays law of electrolysis.



workpiece and at the cathode or the tool along with within the electrolyte.

Let us take an example of machining of low carbon steel which is primarily a ferrous alloy mainly containing iron. For electrochemical machining of steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes ionic dissociation as shown below as potential difference is applied

$NaCl \leftrightarrow Na^{++} Cl^{-}$; $H\text{-}OH \leftrightarrow H^{+} + (OH)^{-}$

As the potential difference is applied between the workpiece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the workpiece.

Thus the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

$2H^{+} + 2e^{-} = H_2\uparrow$ at cathode

Similarly, the iron atoms will come out of the anode (workpiece) as:

$Fe = Fe^{++} + 2e^{-}$

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide

$Na^{+} + OH^{-} = NaOH$

In practice $FeCl_2$ and $Fe(OH)_2$ would form and get precipitated in the form of sludge. In this manner it can be noted that the workpiece gets gradually machined and gets precipitated as the sludge. Moreover there is not coating on the tool, only hydrogen gas evolves at the tool or cathode.

1.2.Literature Review

The influence of intervening variables like feed rate, molar concentration of electrolyte, voltage and inter electrode gap upon material removal and surface roughness was studied [9-11].

Electrolyte flow in the inter electrode gap has significant effect on MRR and surface roughness. Among them, Sodium nitrite presents the best result for surface finish while brine solution gives high MRR [10].

Again, Datta et.al [12] and Rajurkar et.al [13] separately studied the pulse electrochemical machining characteristics and found that the current efficiency was 100% for NaCl while it varied with current density for $NaNO_3$ [9-13].

Hinduja and Kuneida [14] extensively reviewed modelling techniques used for ECM and EDM processes. The critical aspects in modelling of ECM include electrochemical reactions, electrolyte flow, thermal effect and anodic dissolution. Design of tool electrode (cathode) in ECM needs careful consideration particularly for generating complex contours.

Tool design using Cos Ө method is valid mainly for flat end tool since curved tool surfaces involve complex calculations and are difficult to analyse. The distance between workpiece and tool is inversely proportional to Cos Ө where Ө is the angle between tool feed direction and normal of the workpiece [15].

Sun et.al [16] accurately predicted tool shape for electrochemical machining with the help of finite element model (FEM). But, the use of FEM had some drawbacks like discretization of entire space bounded by tool and workpiece and dynamic meshing. To overcome the drawbacks, Narayan et.al [17, 18] proposed boundary element method (BEM) for design of two dimensional tool electrode during drilling and even formulated tool shape by inverse boundary problem of Laplace equation.

ECM involves high precision machining for which the inter electrode gap must be as small as possible but C.de [19] predicted that in conventional ECM if the interelctrode gap (IEG) was too small then it might lead to stiffness of machines, boiling and passivation of electrolyte as well as errors in tool positioning and short circuit finally leading to cessation of machining process. In order to prevent short circuit and stray machining, insulation of tool is essential as insulated tool has higher machining rate than an un-insulated tool electrode as there is no size effect with increasing depth [20-21].

Later, Rajurkar et. al [22] carried out modelling and monitoring of inter electrode gap for pulsed ECM where smaller IEG less than 150 µm was used without the risk of electrolyte boiling or passivation[22-24].

Reduction in machined surface area of cathode tool increases geometrical accuracy of workpiece shape and helps in preventing generation of the heat and H_2 bubble in the IEG. Model for numerical simulation of two-phase electrolyte flow using finite difference method (FDM) [25] and computer simulation to validate the experimental model with mathematical model [26] have been studied respectively. The thermal properties like temperature and void fraction of electrolyte were calculated using FEM [27-28]. Later BEM was utilised for 3-D modelling during electrochemical drilling and sinking [29] and also for electrochemical milling and turning [30]. Purcar et.al [31] then proposed advanced computer aided 3-D model to determine tool shape change and found the current density and potential distribution using isolines and contours. 3-D modelling of thermo-fluid and electrochemical characteristics for planar SOFC in ECM is nonlinear and too complex to compute mathematically, hence ANSYS-CFX was used for simulation [32]. Liu et.al [33] developed a turbulent model for complex and swirl flow patterns with mesh refinement, wall treatment and appropriate definition of boundary conditions and SST k-w model was found to give better result for complex turbulent flows.

Previously, some work has been done in ECM tool design using the L shaped and U shaped tool to determine their effects on MRR, surface roughness and optimisation of tool shape has been done using FEM but no work has been done to show the effect of I shaped tool . So the main objective of the paper is to design and fabricate I shaped tool, determine its effects on experimental outcomes and also the strength of tool compared to other shapes. Moreover, CFD analysis of the electrolyte in tool grove and IEG (inter electrode gap) to determine the flow pattern and pressure distribution has never been studied for the tool although tool designs have been made in the past to avoid passivation. The optimization of process parameters to determine the dominance in removal of material is done using ANNOVA method and effect of I shaped tool on surface roughness has been discussed in the paper.

MODELLING

ECM involves several physical and chemical reactions especially electrochemical reactions, electrolyte flow, thermal effects and anodic dissolution.

Electrochemical reactions occur at anode and cathode which release oxygen and hydrogen ions enabling the current distribution and hence the removal of material by anodic dissolution. More importantly, the flow of electrolyte through the gap between tool and workpiece under high current density form a two phase gaseous mixture of hydrogen and oxygen bubbles alters the conductivity making ECM more complicated. The velocity and pressure of flush of electrolyte determines whether the flow will be turbulent or laminar. The electrochemical reactions can cause the electrolyte reach its boiling temperature due to joule heating changing the electrical conductivity of the electrolyte further. Electrochemical reactions occurring cause the dissolution of workpiece resulting in the negative impression of cathode electrode on it with time.

Table.1. Modelling requirements for ECM

1)AIM OF MODELLING	**TO Predict workpiece shape , optimise the process parameters and CFD modelling of fluid flow in tool and workpiece interface.**
2)PHYSICS OF PROCESS	**Electrochemical modelling (Anodic dissolution of**

	workpiece material) under high current density and low voltage, fluid flow modelling
3)GEOMETRY CONSIDERATIONS	**Modelling and fabrication of tool and its effect on workpiece final shape.**
4)POWER SOURCE AND POLARITY	**Constant Dc voltage** **Tool –negative** **Workpiece –positive**
5)MACHINE CONTROL	**Constant feed rate while maintaining an equilibrium electrode gap of 0.5 mm to avoid short circuit and spray machining.**
6)ADAPTIVE CONTROL MODEL	**Predict workpiece shape, thermal properties of electrolyte,**

ECM is a complex process involving electrochemical reactions at the cathode, flow of electrolyte in the electrode gap and distribution of current density between electrodes. Electrochemical reaction leads to the generation of hydrogen gas bubbles in particular, adversely affecting the flow pattern and conductivity of electrolyte which in turn causes changes in velocity profile, pressure distribution, generation of eddies, temperature of electrolyte the combined effect of which adversely affects MRR, surface finish and dimensional accuracy. At the same time, all these phenomena lead to complexity in modelling ECM process. Systematic approach of

CFD is therefore necessary to accurately predict the phenomena described above in the IEG.

2.1. Modelling of electrolyte flow using CAD for CFD simulation

Electrolyte flow is an essential parameter that not only enables the electrochemical reaction by completing the circuit but also acts as a heat exchanger in removal of heat (Joule heating) from the flow domain. The modelling of electrolyte in the IEG carried out for a single phase flow and one dimensional NAVIER STOKES equation for incompressible fluid is used:

$$\rho.\ \nabla\bar{\vartheta} = 0 \qquad (1)$$

$$\rho\left(\frac{\partial\bar{\vartheta}}{\partial t} + \bar{\vartheta}.\nabla\bar{\vartheta}\right) = \nabla p + \mu\Delta\bar{\vartheta} \qquad (2)$$

where p is the pressure, $\bar{\vartheta}$ is the velocity and μ is the viscosity.

However, the limitations of one dimensional fluid model is its inability to show the negative pressure zones where the recirculation occurs especially near bends and sharp corners. Hence, Hourng et.al. [23] proposed a two dimensional flow model to show eddies and were able to demonstrate better workpiece accuracy. But, the presence of eddies especially near the corners tend to reduce the heat removal efficiency of the electrolyte and reduce surface finish. However, there is hardly any simulation using 3 dimensional model to determine the fluid flow, pressure distribution, turbulence and temperature profile of the electrolyte in the flow domain which is the primary objective of our research.

The velocity and pressure of flush of electrolyte determines whether the flow will be turbulent or laminar. Reynolds's number for the electrolyte flow is more than 4000 due to high inlet velocity and low viscosity of brine solution which signifies a turbulent flow. Therefore, two-equation K- ε model is selected for CFD simulation that uses gradient based hypothesis for making relation between Reynolds stress to the mean velocity gradient and the turbulent viscosity. The transport equations for the model are:

$$\rho(u.\nabla)k = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right).\nabla k\right] + \rho_k - \rho_\varepsilon \quad (3)$$

$$\rho(u.\nabla).\varepsilon = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right).\nabla \varepsilon\right] + c_{c1}\frac{\varepsilon}{k}\rho_k - c_{c2}\frac{\varepsilon^2}{k}\rho \quad (4)$$

K- ε model assumes that the turbulent viscosity depends on turbulent kinetic energy (k) and dissipation rate.

$$\mu_{t=}c_\mu * \rho * \frac{k^2}{\varepsilon} \quad (5)$$

$$\mu_{eff=}\mu + \mu_t \quad (6)$$

where c_μ , c_{c1}, c_{c2} are constants and σ_k, σ_ε are turbulent prandtl numbers for turbulent kinetic energy and turbulent dissipation rate.

Table.2.The values of constants in k e model.

Constants	c_μ	c_{c1}	c_{c2}	σ_k	σ_ε
value	0.09	1.44	1.92	1	1.3

In the present simulation process, the CAD model was done with exact tool dimensions (33 mm X 15 mm) for the ‘I’ shape tool and a 3 mm through hole was made for electrolyte flow as indicated in Fig.1. The IEG was set to 0.5 mm between the tool and the workpiece surface. The model was then imported for meshing in ANSYS.

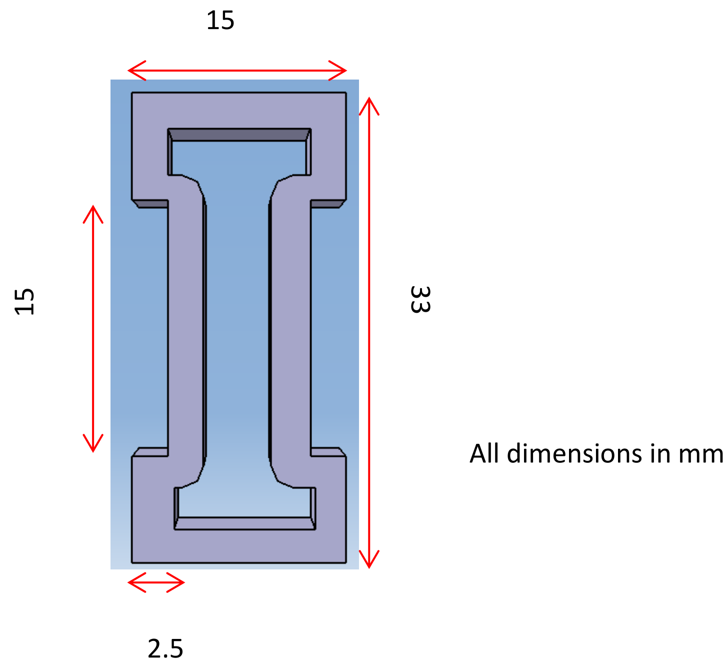


Fig.1. ‘I’ shape tool with dimensions.

Meshing is of utmost importance and is done to define the domain of fluid flow by numerous smaller cells using final volume method (FVM). Meshing has to be efficient to reduce the computational time and get accurate results. Therefore, certain geometrical operations like slicing and extrude were carried out to form three domains: tool, workpiece, electrolyte flow domain in tool holder and IEG. Meshing is done using ANSYS mesh and its relevance center was set to fine meshing with 100% relevance with a high orthogonal quality almost equal to 0.98.

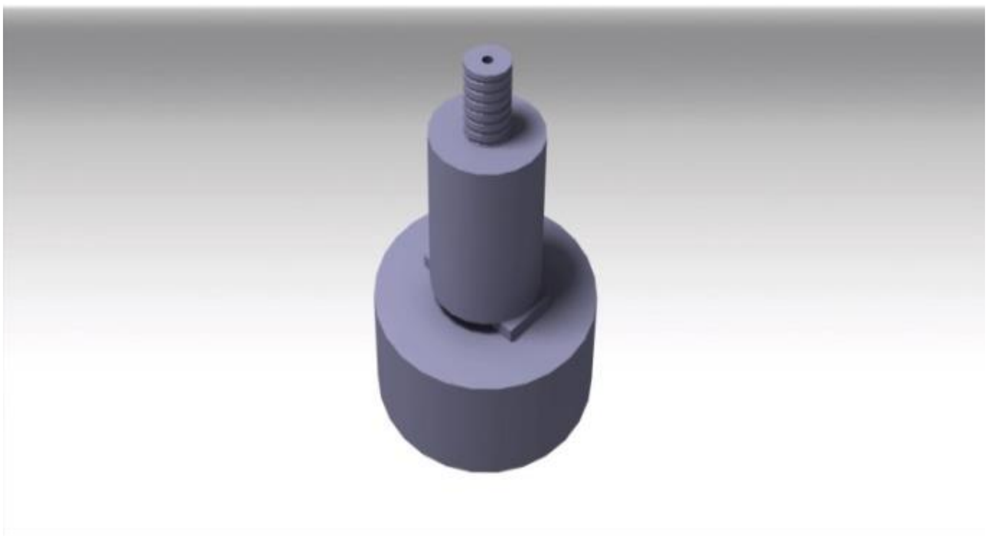


Fig.2. CAD model of ‘I’ shape tool and wok piece

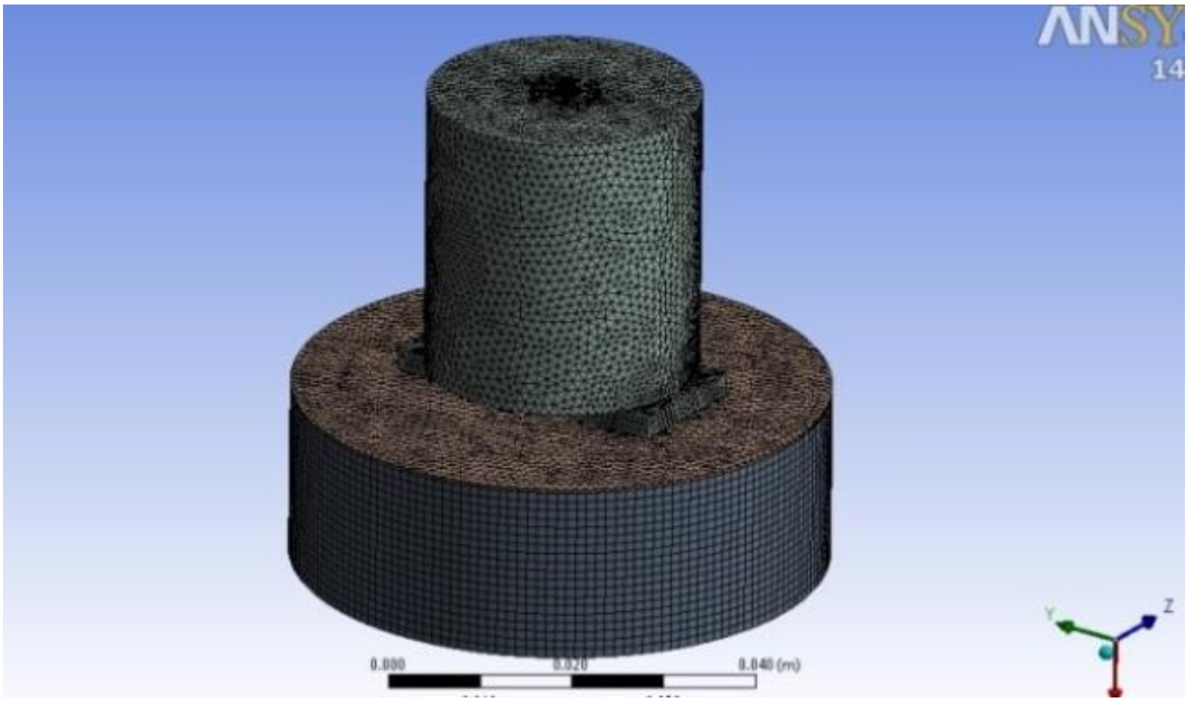


Fig.3. Meshed model

3. Materials and method

3.1. TOOL DESIGN

Tool shape prediction in ECM is done using the inverse problem since using direct problem in determining the tool shapes meant the fabrication of tool without prior calculation and requirements meant a lot of developmental cost. Earlier, to determine the tool shape complex plane and Cosϴ method were used where tool surface distance is proportional to Cosϴ where ϴ being the angle between tool feed direction and workpiece normal [15]. Narayanan et al. [17] using BEM proposed that the conditions on the anode surface are over-specified .Given a Workpiece shape and the feed rate, the required value of the voltage gradient qr is equal to the dissolution rate, i.e. f Cos u= M where M is the dissolution rate. They considered each flux line Independently and suggested three different formulations to calculate the geometrical error at the termination point of the flux line on the cathode surface. The geometrical error in third formulation is most promising and given by:

$$\Delta \text{ Error}= \frac{l^2(q_{r-}q_w)}{(V_w - v_t) + l(q_r - q_w)}$$

Where l is the length of the flux line, q_w the calculated voltage gradient on the workpiece surface, and V_w and v_t the voltages on the tool and workpiece surfaces respectively.

After, certain iterations although the calculated tool geometry can be obtained but it was later found that the workpiece impression is almost similar to exact tool even with the inversely calculated tool. So, I shaped tool was designed using CAD and then fabricated.

Fabrication of tool is done for the ECM experiment with few considerations such as:

Tool material must be stronger and its wear rate must be negligible. So copper is chosen as tool material and mild steel as workpiece.

The electrolyte must flow unhindered through the tool groove and I shaped tool and enable flushing of entire machined surface reducing thermal effects too.

The tool holder being a cylindrical piece turning and facing operations were carried out to give it the required shape along with that threading is done on top to fix the tool with the setup. The fabrication of I-section was done by wire EDM which is an electro thermal process where a thin single strand metal wire was used in conjunction with de-ionized water to cut the metal through electrical spark as per the dimensions mentioned in the table. The tool shape being complex wire cut EDM was used by making a small hole initially in the tool to get the ‘I’ shape.

A crucial part was to form the groove for the flow of electrolyte by drilling a 3mm through hole passing both the tool holder and the ‘I’ shaped tool. Finally, the tool holder and the I shaped tool must be joined permanently so brazing was carried out to join them and the welding zone is cleaned to eliminate any imperfections those may occur during machining .

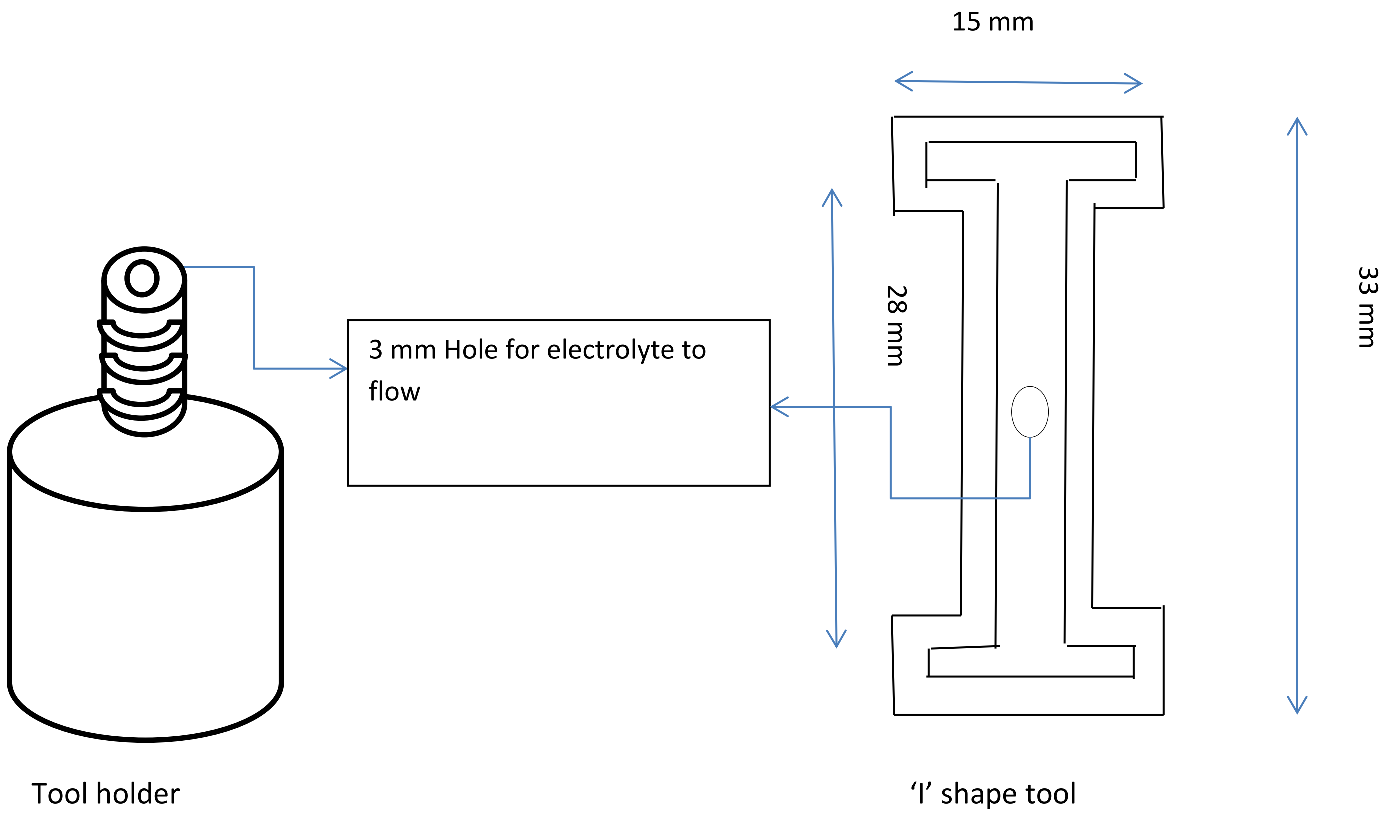


Fig.4.Schematic diagram of tool holder and tool

3.2. Selection of workpiece

The experiment was carried out using Inconel 825 as workpiece specimen on the ECM set up (make: METATECH, INDIA). Keeping in view of the objective of research, the experiment was carried out with three different process parameters and their effects on experimental outcomes like surface roughness, MRR and overcut were studied. The parameters were voltage, concentration of electrolyte and tool feed rate which were applied in an effective combination to determine the dominance of each on the respective outcomes using optimisation techniques like main effect plot and grey scale analysis. The machining of workpiece was carried out by using brine solution as electrolyte which helps in flushing the sludge between tool and workpiece and also acts as a heat exchanger in reducing the thermal effects during machining.

The samples were Inconel 825 specimens prepared with 43 mm diameter and 23 mm thickness and for the experiment Brine solution with density 1050 kgm−3 and viscosity 0.001Pas was used at 3 different concentrations of 80 g/l, 95 g/l and 111.1 g/l were carried out.

Fig below shows the schematic diagram of electrochemical machining process.

FIG.5 (a) shows the tool and workpiece just before machining

(b) shows the machined surface after electrochemical reactions.

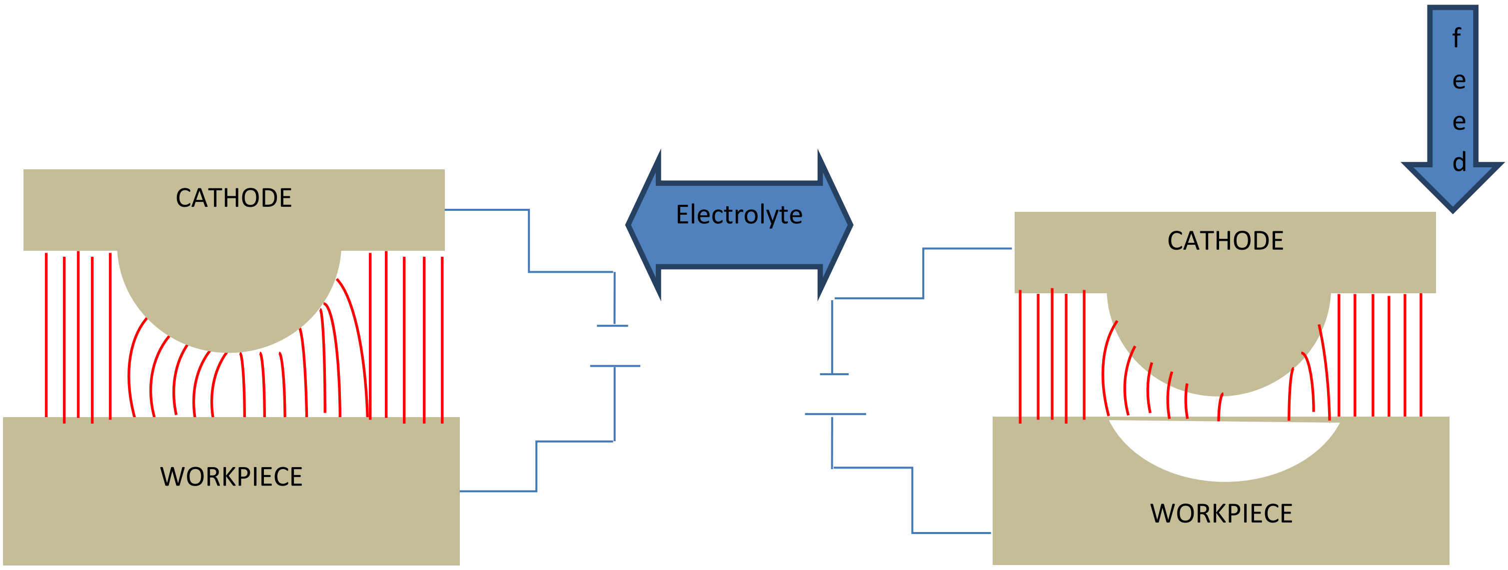


Table.2.Composition of Inconel 825:

Ni	Fe	Cr	Mo	Cu	Ti	Mn	Si	Al	C
38–46	22	19.5–22.5	2.5–3.5	1.5–3	0–1.2	1	0.5	0.2	0.03

3.3. Methodology of experiment

In addition to concentration of electrolyte, influence of voltage and feed on various performance characteristics in ECM such as surface roughness, MRR and overcut was investigated. Further, determination of optimal combination of process parameter was carried out using grey relation analysis (GRA) which is typically used for multi objective optimisation.

For that purpose, nine experiments were conducted according to L9 orthogonal array by varying the three levels for each of the three parameters such as voltage, feed rate and concentration as shown in table.4 for which MRR, surface roughness and over cut were measured .

$$MRR = \frac{w_i - w_f}{\rho_{wp} * t} \quad (7)$$

where w_f =weight final,

$w_i =$ weight initial,

$t =$ machining time

Similarly, overcut for the workpiece specimen was also measured both longitudinally and laterally that is along the length and width of the ‘I’ shape tool.

$$\text{overcut} = L_f - L_i \quad (8)$$

L_f = final length of machined surface and $L_i = initial\ length\ of\ machined\ surface$

Surface roughness values for all the specimen were also recorded using talysurf (make: Taylor Hobson, UK; model: Subtronic 3þ) and its surface roughness R_a values and plots were also noted.

Table.4. Machining parameters and their levels.

Parameters	Symbol	Unit	Levels		
			Level 1	Level 2	Level 3
Voltage	V	Volt	5	10	15
Feed Rate	F	mm/min	0.2	0.4	0.6
Concentration	C	g/l	80	95	111.11

Fig.6.Four machined surface with different parameters

Table.5.Experimental results obtained with ‘I’ shape tool.

Concentration(g/l)	Voltage(V)	Feed rate(mm/min)	MRR($\frac{mm^3}{min}$)	Overcut		Surface Roughness
				Longitudinal	Lateral	
80	5	0.2	26.74759	0.09	0.0085	0.923
80	10	0.4	27.30646	0.1105	0.01	0.771
80	15	0.6	20.83473	0.114	0.015	0.536
95	5	0.4	21.23712	0.1005	0.0135	0.842
95	10	0.6	31.7439	0.1215	0	0.643
95	15	0.2	23.39436	0.1055	0	0.92
111.11	5	0.6	25.27217	0.107	0	0.83
111.11	10	0.2	32.93989	0.096	0.029	0.872
111.11	15	0.4	12.00456	0.124	0.025	0.68

b) Physics of CFD simulation

The analysis was done in ANSYS CFD software as simulation of fluid flow models can be easily carried out in Fluent. Analysis requires the categorisation of process into either steady or transient state. Steady state pressure based Navier stoke’s model (pbns) is selected since the inlet velocity can maximum reach up to 40 m/s and flow is incompressible. Later, for the model, initially laminar flow was considered at low inlet velocities and Reynolds’s number less than 2300 but the negative pressure zones were not obtained in the flow domain which cause eddies.

But, on increasing velocity, the Reynolds's number increases beyond 4000 which makes the flow turbulent for which the standard two equation k-e model was selected.

Some assumptions made while carrying out simulations:

1) The inter electrode gap is kept constant at 0.5 mm.

2) Tool and workpiece materials are homogeneous and isotropic.

3) Heating occurs only due to joule heating.

4) A single phase 3 dimensional incompressible electrolyte flow is considered.

3.4. Multi response optimisation

Optimisation of ECM process was carried out using Grey relation analysis method [11, 34]. It provides an efficient solution to determine the dominance of process parameters considering their effects on multiple outcomes like MRR, surface roughness. The known data system is presented by black and the unknown data is presented in white in Grey system theory . GRA very efficiently deals with the incomplete data and follows certain steps to determine the dominant effects:

a) Normalization of data.

In order to avoid the problem of large data sequence,data pre-processing is required in which the experimental data was normalized into a set of dimensionless parameters in the range [0,1].

It enables the data sequence to be converted into a comparable 'grey relation generation'.

"Higher the better "characteristic must be selected for MRR and is given by:

$$x_{i} = \frac{x_i(p) - \min x_i(p)}{max x_{i(p)} - \min x_i(p)} \quad (9)$$

“Lower the better” characteristic must be selected for surface roughness and overcut.

$$x_{i} = \frac{max x_{i(p)} - x_i(p)}{max x_{i(p)} - \min x_i(p)} \quad (10)$$

b) After normalization of data, the correlation between actual and normalized data has to be calculated using grey relation coefficient, $\tau_{i(p)}$

$$\tau_{i(p)} = \frac{\Delta_{min} + \tau_i \Delta_{max}}{\Delta_i(p) + \tau_i \Delta_{max}} \quad (11)$$

Where Δmin and Δmax are the global minimum and maximum value of normalized data, respectively, of the p th response. τ is known as distinguishing factor whose value falls in the range 0–1.In our experiment, the distinguishing factor is taken as 0.5.

C) Calculation of Grey relation grade

The influence of various factors on the output response varies which is assessed by GRG (grey gelation grade). In general, there arises a need to assign a weighting factor to the grey coefficients for calculation of GRG and higher values of GRG indicate better multiple performance characteristics and the corresponding parameter is considered to be close to ideally normalized value or optimal value. GRG is calculated as a sum of the weighted grey relational coefficients and is calculated by the following expression:

$$\gamma = \frac{1}{n} \sum_{i=1}^{n} x_i(p) \quad (12)$$

d) Variance analysis

GRG values obtained during grey relation analysis were further taken as input for ANOVA analysis to determine the process parameter having maximum effect on experimental outcome. ANOVA also provides the percentage contribution for each parameter and is calculated from the expression:

$$\% \text{ contribution} = \frac{sum\ of\ square\ of\ variation}{total\ sum\ of\ square\ of\ variation}$$

4. Results and discussions

4. 1. CFD simulation results for brine flow

A)Velocity profile

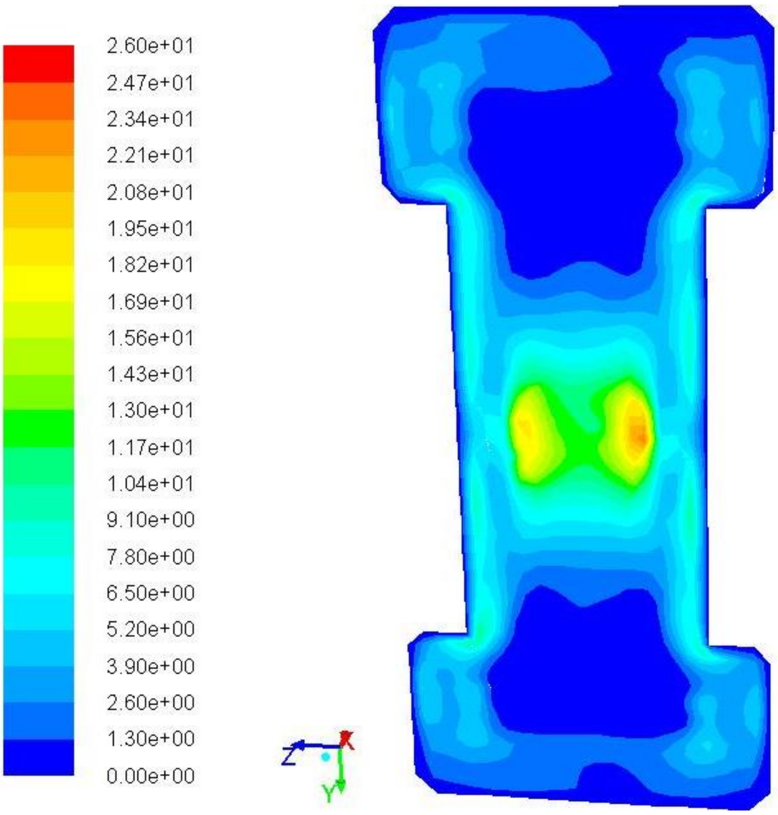


Fig.5. CFD simulation of velocity profile.

Corresponding to inlet velocity of 20 m/s, it can be seen that the central region where the jet of electrolyte strikes has the maximum velocity around it. The area around the central hole has small variation of velocity because of stagnation as the jet strikes the workpiece and loses most of its kinetic energy. Further, the velocity has decreased smoothly and is reduced to approximately 5 m/s near the corners and sharp edges. It shows that because of the sharpness of tool the velocity has become less than 5 m/s and it might prevent the flushing of sludge from workpiece surface leading to passivation. It is when the sludge layer prevents further machining and it is clearly evident in the current experiment that the material removal is more adjacent to the central hole as compared to the periphery because of the velocity distribution as shown in the fig 4.

B)Pressure profile

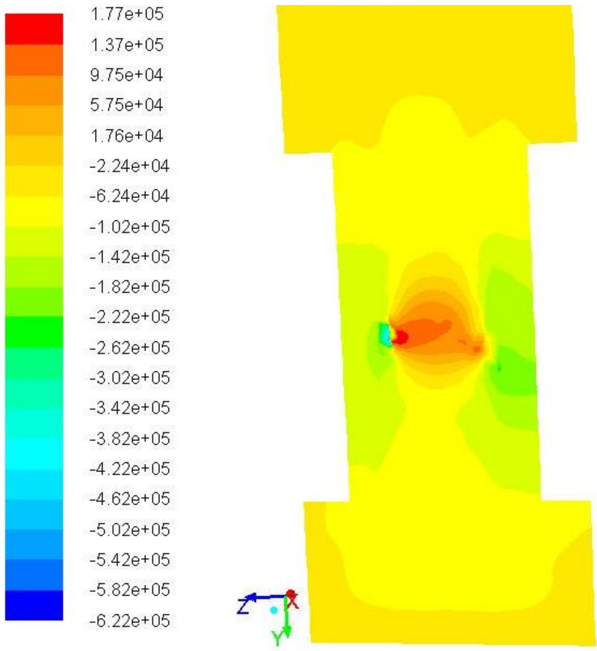


Fig.6. CFD simulation of pressure profile.

Figure 6 shows the pressure distribution of the electrolyte near the outlet. It is evident from the figure that central portion as can be seen has maximum pressure above the atmospheric region and this extra pressure of electrolyte will help in flushing of sludge. Moreover, the region near the edges have slightly low pressure zone which ensures the formation of recirculation structures and eddies. The pressure although low is not sufficient enough in causing cavitation as more negative pressure is required for cavitation by brine solution.

c) Turbulent kinetic energy

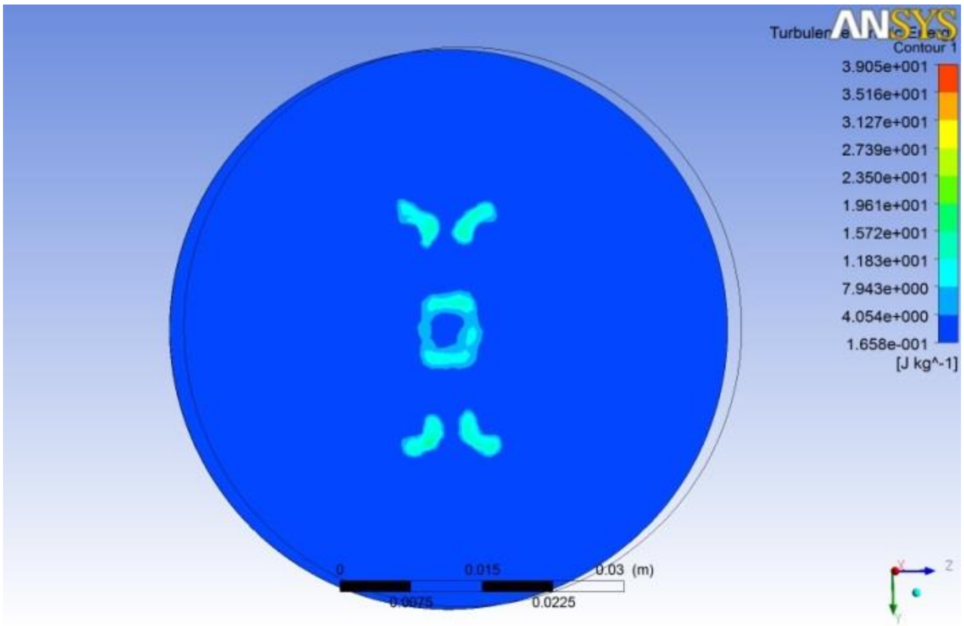


Fig.7. CFD simulation for turbulent kinetic energy.

Turbulent kinetic energy is the energy due to turbulence and eddies in the flow domain and if the turbulence within the inter electrode gap is more ,then the roughness of machined surface is high.This is due to the fact that eddies prevent the smooth and uniform flow of electrolyte over the workpiece surface leading to deposition of sludge and finally passivation.This causes reduction in efficiency of machining and increases surface roughness. Turbulent kinetic energy is produced by fluid shear,rougness of surface and friction.It can be seen that the flow is turbulent around the periphery of the central hole and near the sharp sections of ‘I’ shape .The maximum value of turbulent kinetic energy for the present study is 39.1 J/kg and can be related to the surface roughness value which was more near the sharp edges and periphery of the central hole as compared to central region.

d) Temperature Profile

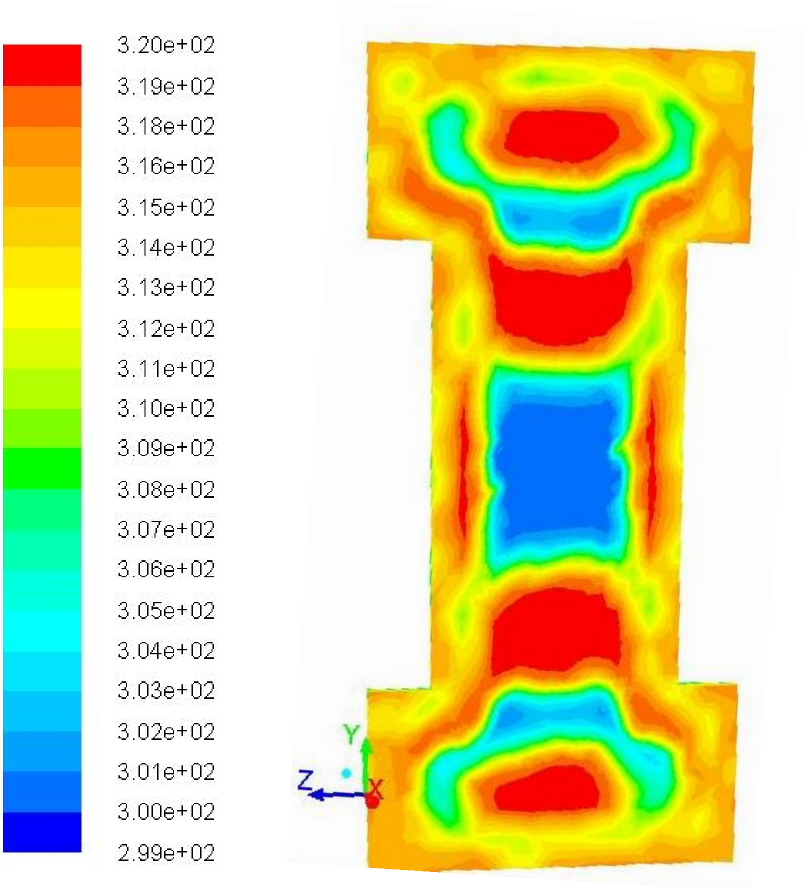


Fig.8. CFD simulation of temeperature profile

It is clearly evident from Fig.11 that temperature is minimum around the central portion of machined surface as the brine acts as a heat exchanger by absorbing the extra heat. Moreover,region around bends and corners has low temperature because of turbulene in the flow which reduces the thermal effects. Maximum temeprature observed was around 320 K which is very much less than 373 K required for electrolyte boiling and passivation of workpiece surface.

2)Effect of parameters on performance measures in ECM

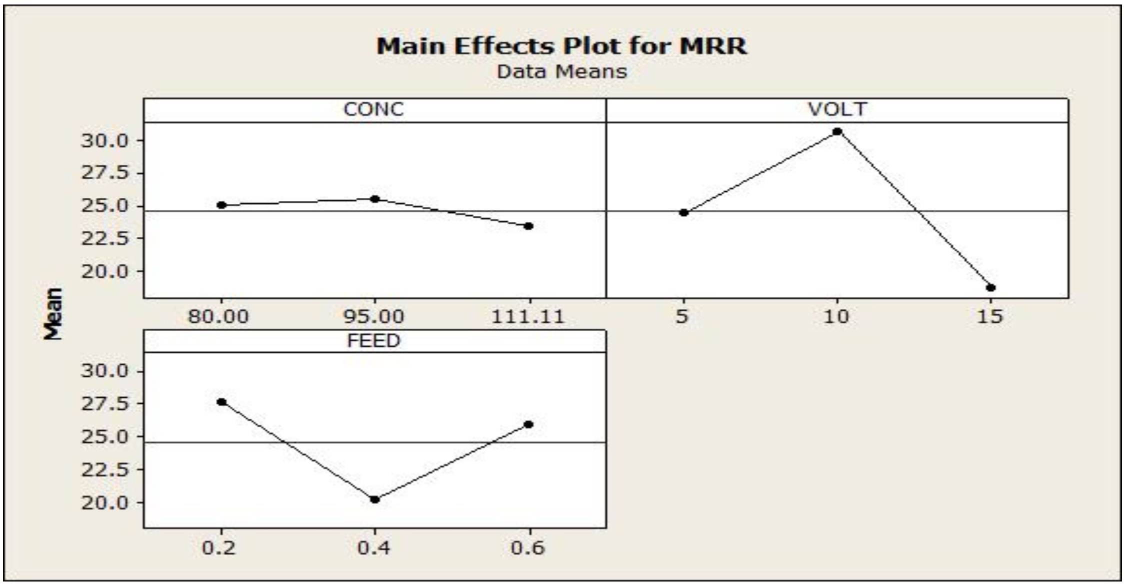


Fig.9.Main effect plot for MRR

Figure 9 shows the effcet of various input parameters on MRR. As the electrolyte concentration increases,more ions are assosiated in machining which increases current density resulting in increased MRR. But,the growth of MRR is not so significant with increase in concentration from 80g/l to 95g/l, because the increment rate of dissolution efficiency is almost constant. Again,with further elevation in concentration up to 111.1g/l,the ions in flow domain significantly increase leading to excess current and thus spray machining occurs causing reduction in MRR.

It is also evident from the figure that MRR increases steadily up to 10 V . Therefore, increase in voltage increases machining current and since MRR is directly proportional to machining current more material is removed.But,as the voltage increases and becomes 15 V,the conductivity of electrolyte in the inter electrode gap varies due to joule heating leading to a non uniform current distribution in the gap which reduces the MRR.The same figure also indicates that there was hardly any clear trend of variation of MRR with feed rate under the operating range.

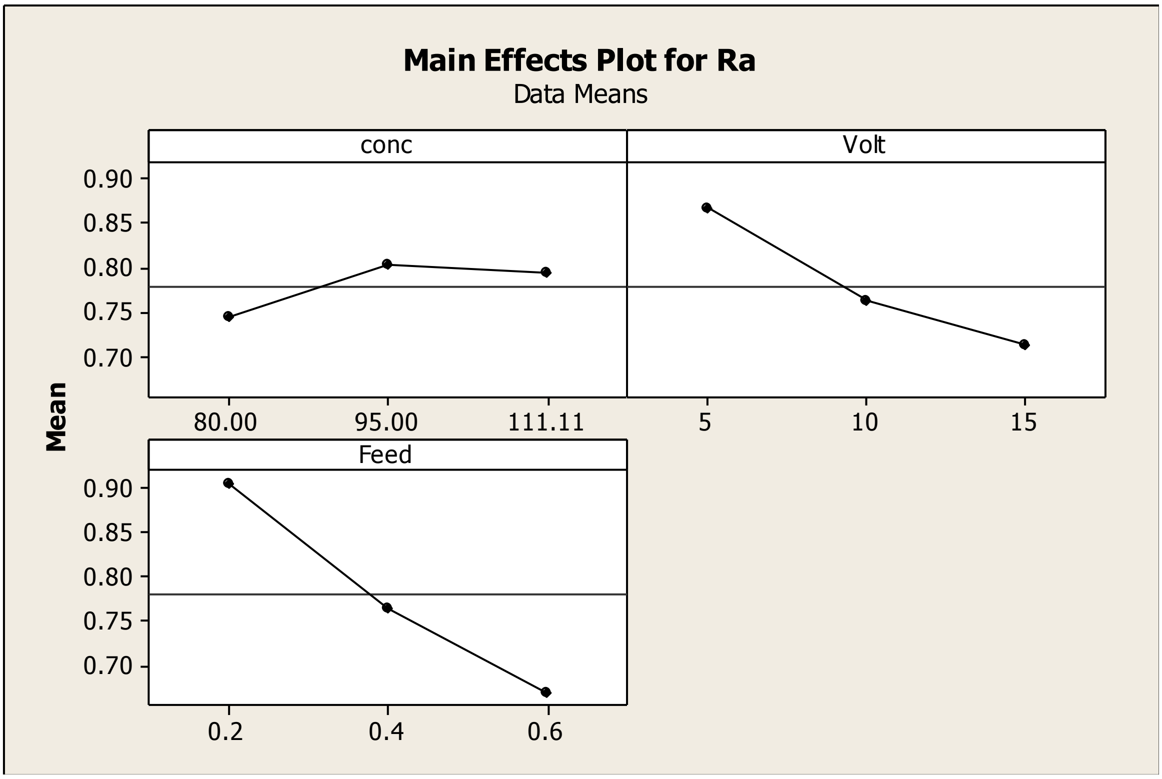


Fig.10. Main effect plot for surface roughness

Variation of surface roughness under various machining conditions is demonstrated in Fig.10 in the form of main effect plot.It shows that surface roughness reduces with increase in voltage because at lower voltage,the current in the inter electrode gap is small for which the anodic dissolution is non uniform and it leads to surface irregularities. Further,with increase in feed rate the surface finish increases as lower feed rate means the tool is not fed to the workpiece properly which reduces the dissolution rate and roughness and workpiece inaccuracy increases.

At Lower electrolyte concentration, surface roughness is small but as the concentration increases the more number of ions present in the IEG increase the current drastically which sometimes lead to spray machining increasing the surface roughness.

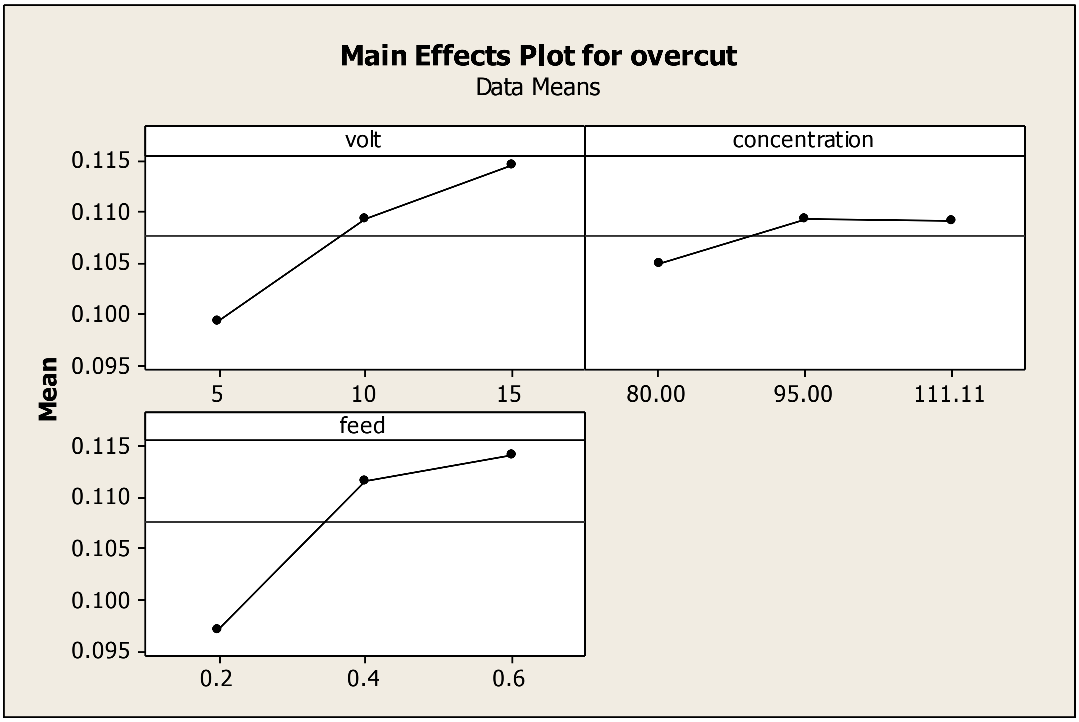


Fig.11.Main effect plot for overcut.

Figure 11 shows the influence of process parameters on overcut. It is evident that overcut increases with increase in either voltage or feed because of localization of current intensity which causes spray machining close to the edges and affects larger area of workpiece leading to overcut. Also, electrolyte concentration affects the overcut as increase in concentration leads to more number of ions in the machining zone which increases the current and reduces machining accuracy.

To find the optimum process parameters, the grey relation table was made and the dominant input factors responsible for higher MRR and low surface roughness and overcut were found out using ANOVA table. After, GRG values were calculated, the runs were arranged as per their subsequent grades with the highest grade given to first rank. It was found that the eighth combination that is the experiment carried out with 111.11g/l electrolyte concentration, 10 V and 0.2 feed rate provide the best results for the experiments conducted initially.

Table.6. Grey relation grade and their corresponding rank.

Sl No	GSR	GMRR	GOC	GRG	Rank
1	0.333333	0.628313	1	0.653881959	2
2	0.451575	0.650121	0.453333	0.518343303	5
3	1	0.463729	0.414634	0.626120922	4
4	0.387387	0.472145	0.618182	0.492571477	6
5	0.643927	0.89746	0.350515	0.630634118	3
6	0.335065	0.523038	0.523077	0.460393345	8
7	0.396923	0.577196	0.5	0.491372903	7
8	0.365439	1	0.73913	0.701523176	1
9	0.573333	0.333333	0.333333	0.413333333	9

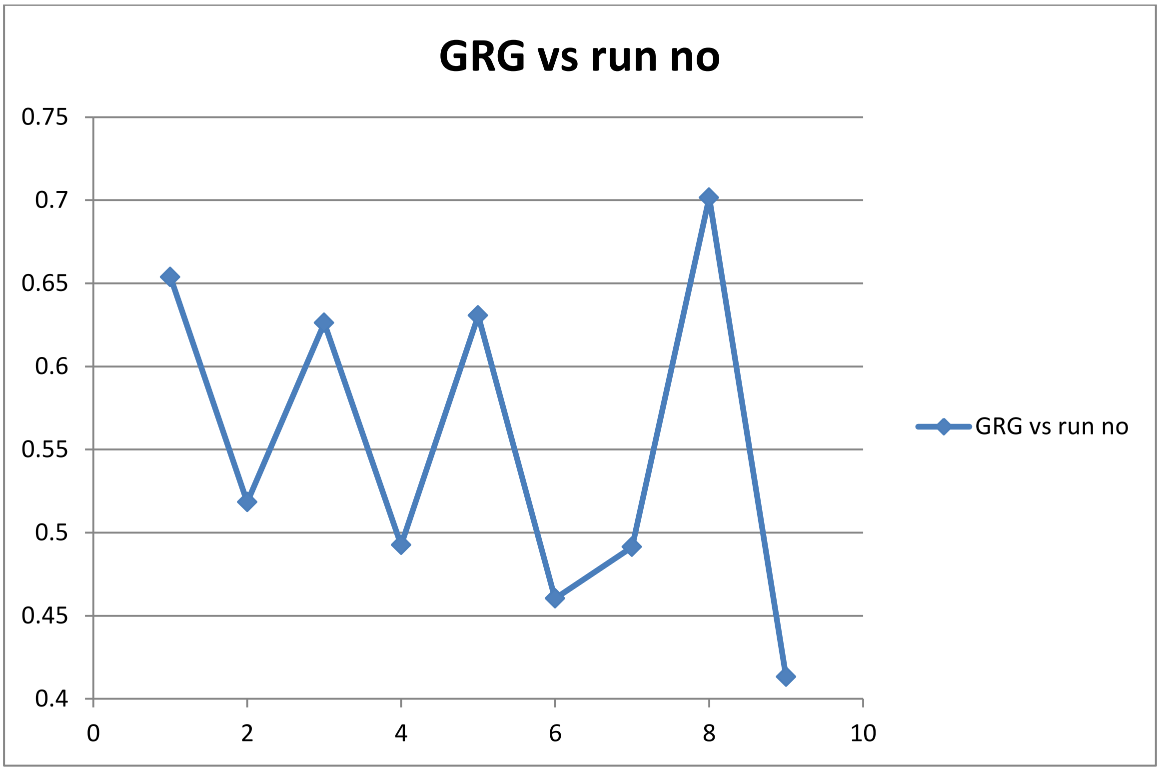


Fig.13. Grey relation grade versus run number

Confirmation test

The optimal condition for a process parameter affecting the outcomes can be found out using average GRG. In order to determine average GRG, the GRG values for a particular level of the parameters were added and their average was taken. Then, for every process parameter the highest value of a particular level will have the maximum effect on experimental outcomes. The optimal condition for machining parameters turns out to be 80g/l concentration,0.2 mm/min feed rate and 10 V. Since, the difference between maximum and minimum value for feed is maximum followed by voltage and then concentration, it can be incurred that feed and voltage have maximum effect on performance characteristics.

Table.7.Response table for Grey relation Grade

	level 1	level2	level3	delta	
C	0.599449	0.527866	0.53541	0.071582	min
F	0.605266	0.474749	0.582709	0.130517	max
V	0.545942	0.616834	0.499949	0.116884	

Confirmatory tests were carried out after determining the optimal condition and experiments was carried out to validate the analysis and the corresponding MRR, surface roughness and over cut were recorded in table 8.

Table.8. Confirmation test results

Optimal condition	MRR(mm^3/min)	SR (μm)	OC (mm)
80g/l concentration, 10 V and 0.2 mm/min Feed rate	33.4817	.84	.091

It was seen that the value of MRR increased with reduction in concentration of electrolyte as can be seen in main effect plot for concentration vs MRR in figure 9 which clearly matches our experimental data. Similarly, surface roughness and over cut decreased

As compared to previous runs.

5. Conclusions

The current study focussed on the CFD simulation of fluid flow in the inter electrode gap and its thermal analysis to explain passivation during electrochemical machining using 'I' shaped tool. Further, the fabrication and experimental analysis using the same tool was carried out on Inconel 825 using copper as tool material and brine solution as electrolyte. Effect of process parameters such as voltage, feed rate and concentration was studied and also optimised in order to achieve best performance characteristics in ECM in the form of MRR, surface roughness and overcut. The following conclusions can be incurred from the current study:

- CFD simulation showed maximum velocity around the central region with velocity uniformly distributed over the periphery of tool. Velocity less than 5 m/s was observed near the sharp edges of tool which might lead to sludge formation.
- Pressure contour near the sharp edges showed negative pressure zone which leads to turbulence and formation of eddies while the pressure is maximum around central portion of 'I' section due to high flushing rate.
- Turbulent kinetic energy is more close to the edges implying low flushing rate for which the machined surface is rough near the tool periphery.
- Temperature profile is minimum near the central zone of workpiece as well as sharp corners because of high flow rate and turbulence respectively.
- MRR increases with increase in voltage and decreases with increase in concentration but concentration has negligible effect.
- Surface roughness decreases with increase in feed and voltage while overcut increases with increase in any of the three parameters.
- The multi-objective optimisation using grey relation analysis showed the optimal condition with voltage 10V, concentration 80 g/l and feed rate at 0.2 mm/min for best output which

can be also validated from the fact that $V_2C_1F_1$ also gives maximum MRR and minimum surface roughness and overcut experimentally.

6. Future Scope

The current study on the simulation of flow field of electrolyte in the machining gap showing the velocity contour, pressure distribution, turbulent kinetic energy and temperature profile shows their variation with the profile of tool which clearly signifies the contour of tool affecting flow parameters. It will help us in determining the tool profile for machining purposes in an efficient manner in future manufacturing methods in electrochemical machining.

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