Optimization of Parameters in Electrochemical Machining of Ni-Base Superalloy

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Abstract

Electrochemical machining (ECM) is a non-traditional as well as non-mechanical machining process. This is used mainly to machine hard or difficult to cut or machine materials such as Ni-base super alloys, composites, stainless steels etc. The difficulties in machining of superalloys and other hard and high strength materials by conventional processes are responsible for the development of nontraditional machining processes such as electrochemical, electrodischarge, ultrasonic etc. machining processes. The process characteristics are affected by various parameters such as electrolyte flow rate; tool feed rate; applied voltage; inter-electrode gap; current density; pH of electrolyte; concentration and temperature of electrolyte etc. In this study analysis of parameters affecting surface roughness has been carried out. The parameters considered for experimentation are: tool feed rate, electrolyte flow rate and applied voltage. Taguchi L9 orthogonal array is used for parameter setting during the experimental runs. Aqueous solution of sodium nitrate ($NaNO_3$) is used as an electrolyte of concentration 200 g/l. The results show that good surface finish is obtained at low feed rate (0.5 mm/min), high electrolyte flow rate (350 L/hr) and high voltage (16 V). ANOVA is used to validate the results. The R Square value is above 90 % and F value positive at 95% confidence level.

Keywords: Analysis, Electrochemical machining process, surface roughness, optimization, Taguchi methodology, Ni-base superalloy

1. Introduction

Electrochemical machining (ECM) is a non-traditional as well as non-mechanical machining process used mainly to machine hard and high strength or difficult to cut or machine materials such as Ni-base super alloys, electrically conductive composites, stainless steels etc. The difficulties in machining of superalloys and other hard and high strength materials by conventional processes are responsible for the development of nontraditional machining processes such as electrochemical, electrodischarge, ultrasonic etc. machining processes..The difficult to cut metals or materials requires high energy to deform the material in chips resulting into thermal stresses due to the high temperatures. In traditional processes, the heat generated during the machining is dissipated to the tool, chip, workpiece and environment, affecting the surface integrity or surface characteristics of the workpiece.

ECM is an electrolytic process and its basis is the phenomenon of electrolysis. Electrolysis is the name given to the chemical process which occurs, for example, when an electric current is passed between two conductors dipped into a liquid solution; John (1997,p-233-247). A typical example is that of two metal rods connected to a source of direct current and immersed in a solution (salt, acid or base) in water, as shown in Figure 1. An ammeter is placed in the circuit measure current. A solution which conducts electricity is termed as "Electrolyte". In Electrochemical machining process the cutting tool is not touching the workpiece. Electrochemical reactions (electrolysis) are responsible for the material removal mechanism. Main components of ECM system are voltage, a high current power supply and an electrolyte; Tery L. (1989,p-533-541). The electrolyte is normally solution of inorganic salts, like sodium chloride (NaCl) or sodium nitrate ($NaNO_3$), acids, bases or combinations of salt, acid and base. The objective of this work is to optimize and analyze the process (cutting) parameters in electrochemical machining of Hastelloy C-276 (Ni-Base superalloy) to get good surface finish. Hastelloy C-276 alloy is a nickel-molybdenum–chromium wrought alloy that is generally considered a versatile corrosion-resistant material.

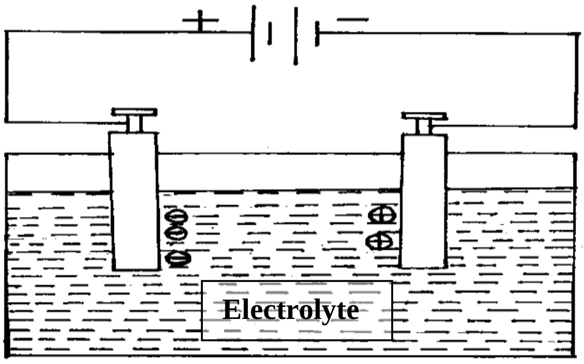

Figure1. Electrolysis

It also has excellent resistance to pitting and stress- corrosion cracking. It is one of the few materials that withstand the corrosive effects of wet chlorine gas, hypochlorite and chlorine dioxide; E. Paul DeGarmo (1997,p-947). Because of its versatility, C-276 alloy can be used where "upset" conditions are likely to occur in multipurpose plants. A prototype specimen developed at the laboratory is used for experimentation. Three parameters are changed during the experiments: tool feed rate, electrolyte flow rate and applied voltage. Aqueous solution of sodium nitrate ($NaNO_3$) is used as an electrolyte of concentration 200 g/l of H_2O to machine Hastelloy C-276. Experimental runs are carried out using the equipment developed, with different parameter combinations. Taguchi methodology is used for optimization of the process parameters; Phillip J. Ross (1996). To combine parameters at different levels L9 orthogonal array is used.

2. Process Control Parameters

The primary variables that affect the material removal rate in ECM are (1) applied voltage; (2) tool feed rate; (3) electrolyte conductivity; (4) electrolyte composition /concentration; (5) electrolyte flow rate and (6) workpiece material.

Among these entire process parameters electrolyte is very important and largely affecting ECM process. Therefore selection of proper electrolyte is important to achieve good machining characteristics. The electrolyte has three main functions in the ECM process. (1) It carries the current between the tool and the workpiece, (2) it removes the product of the reaction from the cutting region, and (3) it removes the heat produced by the current flow in the operation. Electrolytes must have high conductivity, low toxicity and corrosivity, and chemical and electrochemical stability and controllable passivating effect. The properties and types are discussed in the following paragraphs.

2.1 Electrolyte

Chemically, electrolytes are substances that become ions in solution and acquire the capacity to conduct electricity. The electrolytes used in the past for the electrochemical machining usually involve aqueous solutions of inorganic salts such as sodium chloride, potassium chloride, sodium nitrate and sodium chlorate. Other electrolytes such as sulphuric acid and hydrochloric acid solutions have been used in certain instances.

a) Electrolyte Conductivity

Electrolyte conductivity depends upon concentration and temperature. It must be controlled because it directly affects the power requirement and rate of penetration. For higher conductivity penetration rates are faster. The conductivity changes substantially with temperature. Increase in temperature increases electrolyte conductivity. e.g. Solutions of NaCl are 100 % more conductive at 70 ºC than 24ºC; Tery L. (1989,p-533-541 .Any changes in electrolyte conductivity will affect ECM geometry because the dimensions of cutting gap and side gap depend on conductivity. Therefore temperature of electrolyte is controlled.

b) Electrolyte Concentration/Composition

Electrolyte concentration level for ECM is usually a compromise. A concentrated solution has the advantage of lower voltage and power requirement because of better conductivity, faster rate of penetration and greater precision are also possible because the conductivity of concentrated solution varies less with changes in temperature. Over concentrated solution may become saturated and allow the formation of crystals that can damage machine parts such as pumps, valves etc. The very weak solutions cause local and intermittent passivity of the work which makes machining difficult. On the contrary the diluted low concentration solutions cost less dissolve more quickly and give smoother surface on some work.

c) Electrolyte flow rate

Electrolyte flow rate is also important because it removes heat and products of chemical reaction. Electrolyte flow is related to the amount of current is used. If the ratio of flow to current is large then better the removal of heat and reaction products. Excessive flow rates can cause local erosion on the workpiece or tool.

d) Types

Electrolytes are classified as (i) sludging or passivating electrolytes and (ii) non-sludging or non- passivating electrolytes.

i) Sludging Electrolytes

Sludge is a material formed during the ECM process and consists mainly of metal hydroxides and other reaction products. Under some conditions, as much as 100 cubic inches of sludge may be produced for each cubic inch of metal removed by the ECM process.
Smut consists of extremely fine particles of alloy constituents, mainly metallic. Both sludge and smut are undesirable since they interfere with the ECM process and are difficult to remove from the finished part. As a general rule, solutions of inorganic salts such as sodium chloride are sludging electrolytes.

ii) Non-sludging Electrolytes

The other general type of electrolyte is termed non-sludging. For example, solutions of strong acids tend to retain the anodically removed metal in solution and thus do not produce sludge under normal conditions. The use of solutions of mild inorganic acids as electrochemical machining electrolytes does not appear to be common. Most acids used in electrolytes for electrochemical machining are the strong mineral acids such as nitric, sulphuric, and hydrochloric acid.

e) Electrolyte Selection

Type of electrolyte used in the process affects the quality of surface finish obtained in ECM. For example, with nickel-based alloys, the formation of a nickel oxide film seems to be a prerequisite for obtaining a polished surface; a finish of this quality, of 0.2 µm, has been claimed for Nimonic (a nickel alloy) machined in saturated sodium chloride solution. Surface finishes as fine as 0.1 µm have been reported when nickel-chromium steels are machined in sodium chlorate solution. Nickel base superalloys electrochemically machined using the electrolyte such as Nitric Acid, Citric Acid, and Hydrochloric Acid etc. for producing extremely smooth machined surfaces which are free from smut and other undesirable surface problems. Sometimes the formation of oxide film on the metal surface hinders efficient ECM and leads to poor surface finish. For example, the ECM of titanium is rendered difficult in chloride and nitrate electrolytes because the oxide film formed is so passive. Even when higher voltages about 50 V are applied to break the oxide film, its disruption is so non-uniform that deep grain boundary attack of the metal surface can occur. Depending on the material, some electrolytes leave an etched finish. This finish results from the nonspecular reflection of light from crystal faces electrochemically dissolved at different rates. Sodium chloride electrolyte tends to produce an etched, matte finish with steels and nickel alloys. Electrolyte selection plays an important role in ECM. Sodium chloride, for example, yields much less accurate components than sodium nitrate. The latter electrolyte has far better dimensional control owing to its current efficiency - current density characteristics. Using sodium nitrate electrolyte, the current efficiency is greatest at the highest current densities.

3. Design of Experiments

The Design of Experiment process is divided into three main stages as (a) Planning, (b) Experimentation and (c) Analysis stage.

a) Planning

In the planning phase factors and levels are selected and therefore is the most important stage. The parameters selected for the optimization are given in table 3 along with their values. The parameters are (1) Tool Feed Rate; (2) Electrolyte Flow Rate and (3) Voltage. Electrolyte used for the experimentation has concentration as 200 g/L of H_2O. The current is considered constant throughout the experimentation because it depends upon the remaining parameters and never constant. Here the workpiece taken for experimentation purpose is Hastelloy C-276.

b) Experimentation

The experimental setup is fabricated for this investigation to suit the requirements. Experiments are conducted to find optimized combination of parameter and their levels/values to improve performance characteristics to an acceptable or optimum value.

Machining set up used for experimental work is shown in figure 2. The workpiece is held in fixture containing two metal plates; one fixed and other movable. The fixture is kept in a plastic box to avoid loss of current and shock during experimentation. A nut and bolt assembly is used to move the plate for tightening the workpiece. During the process, tool electrode moves according to feed movement while the workpiece is stationary. A threaded shaft is used to provide linear motion to the tool with a gear mounted to rotate shaft through a pinion and a stepper motor. It is welded to steel frame by means of bearing assembly. The shaft is supported in two ball bearings at the ends to ensure free rotation of the shaft. Feed is given manually as well as automatically by means of stepper motor.

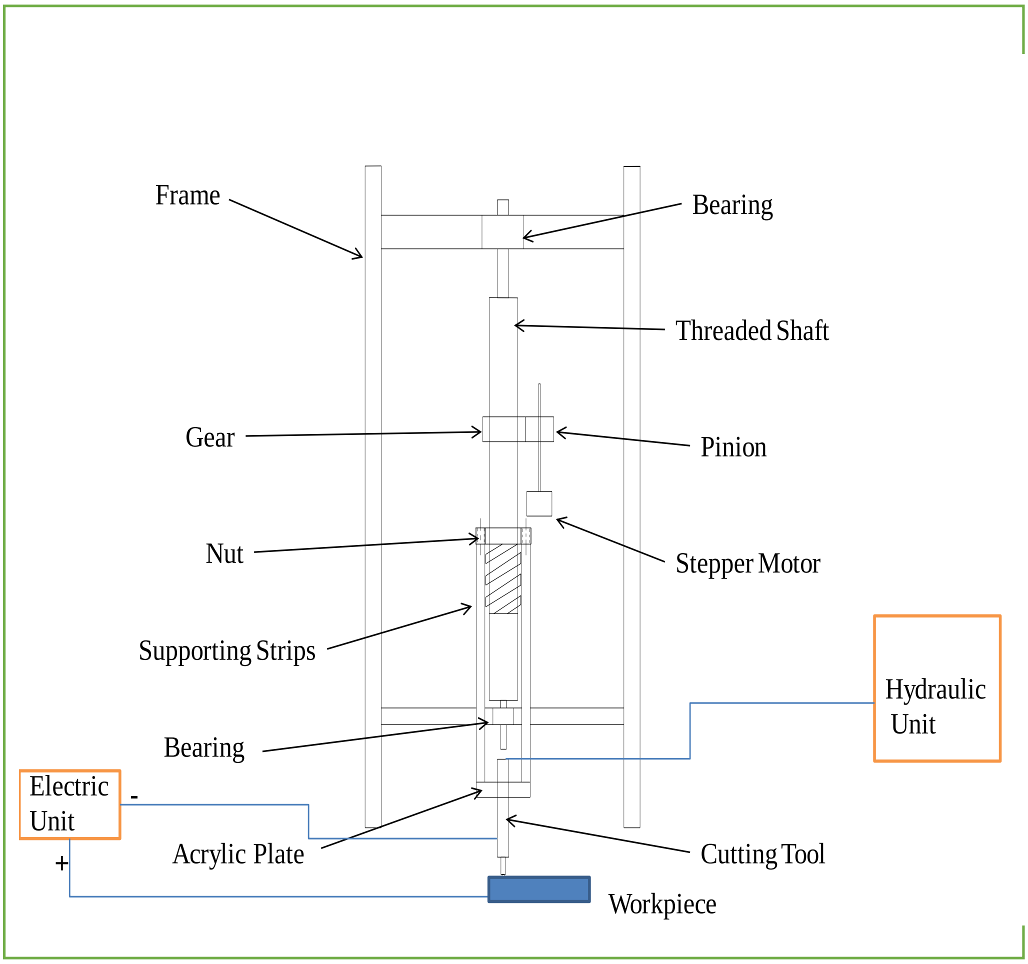

Figure 2. Experimental Set up

The tool is of copper and used to supply current through negative pole of power supply. The electrolyte is supplied for machining through the hole drilled at its centre. Acrylic plate of 10 mm thickness is used to hold the tool and to avoid loss of current and shock during manual feeding.
The electric unit is used to supply voltage and current at desired level during experiments. It supplies current in regulated DC mode and has calibrated voltmeter and ammeter to set values of voltage and current in the range 0-30 V and 0-60 A respectively. The hydraulic unit is used to supply electrolyte at high and desired pressure or

flow rate to facilitate removal the material. It consists of a pump, PVC pipes, fittings and a rotameter. Rotameter is used to measure electrolyte flow rate in liters per hour.

c) Analysis

Analysis/Optimization of parameters to reduce error/noise in the result is important in high cost machining processes. Optimization of parameters is done by means of Taguchi method and the parameter combination for higher material removal rate or result or response is determined. Details of Taguchi method used for analysis are explained further.

4. Results and Discussion

Optimization or analysis of parameters is done by means of Taguchi method. The first step in this method is to select the number of parameters and their levels. The methodology for optimization is given below: (i) Selection of number of parameters and their levels (ii) Selection of orthogonal array (iii) Selection of criteria (Higher-The-Better, Lower-The-Better, Nominal-the-Best) (iv) Determination of signal to noise ratio (S/N ratio) (v) Selection of best combination of parameters for maximum material removal rate. In case of the material removal rate the Higher-The-Better criterion is selected. For increasing productivity of the process the material removal rate needs to be high hence this criterion is selected. S/N ratio for Lower-The-Better criterion is calculated by means of equation (1).

$$S/N = -10 \log\left\{\frac{1}{n}\sum_{i=1}^{n} Yi^2\right\} \tag{1}$$

Table 1 shows general results for surface roughness. From the table the optimized combination of parameters for lower surface roughness is low tool feed rate, high electrolyte flow rate and high voltage. S/N ratio is calculated from equation (1). The main effect of parameters on surface roughness is shown in the following figures/graphs. Graphs are plotted from Table 2 to show relation between mean S/N and process parameters.

Table 1 Experimental Results and S/N ratio

Sr. No.	Feed Rate (Mm/min)	Electrolyte Flow Rate (L/hr)	Voltage (V)	SR (µm)	S/N ratio (dB)	
1	0.5	150	12	0.20	13.97	S/N1
2	0.5	250	14	0.25	12.04	S/N2
3	0.5	350	16	0.15	16.47	S/N3
4	0.7	150	14	0.40	7.95	S/N4
5	0.7	250	16	0.35	9.11	S/N5
6	0.7	350	12	0.20	13.97	S/N6
7	1.0	150	16	0.55	5.19	S/N7
8	1.0	250	12	0.45	6.93	S/N8
9	1.0	350	14	0.35	9.11	S/N9

Table 2 Mean S/N values of SR

Level	Feed Rate	Electrolyte flow rate	Voltage
-1	0.2	0.38	0.35
0	0.31	0.35	0.33
1	0.45	0.23	0.25
Δ	0.25	0.15	0.10
	1	2	3

In Figure 3 the effect of feed rate is shown. As feed rate increases surface roughness increases i.e. smoothness decreases because tool is forwarding fast towards the workpiece and removes more material. If the tool is advancing faster than the reaction rate that may cause sparking in the gap resulting in erosion of workpiece material. In Figure 4 effect of electrolyte flow rate is shown. As flow rate increases surface roughness decreases because the electrolyte is flowing at fast rate without contacting surface of workpiece. Contact of the electrolyte is needed to react with the material hence at maximum electrolyte flow surface roughness is minimum. In Figure 5 effect of voltage is given and it has almost linear relation with surface roughness.

The effect of voltage on surface roughness is negligible because it is varied by only two units as compared with feed rate. In Figure 6 combined effect of parameters has been plotted against surface roughness. It clearly indicates that all the process parameters are interrelated as all these three line are crossing each other.

ANOVA for surface roughness has been performed to validate the experimental results and is given in table 3. To validate the results R Square and F values are taken into consideration. If R square value is equal to 1 then more accurate the experimental results. As well as higher the value of F more accurate the results.

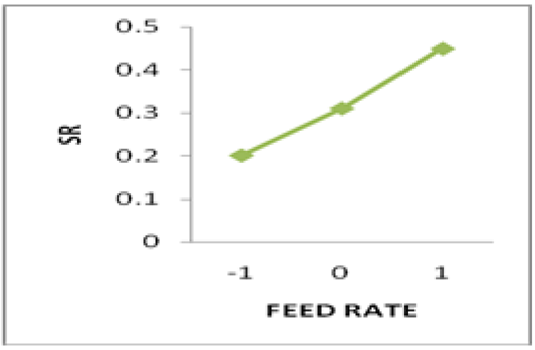

Figure 3. Effect of tool Feed Rate on SR

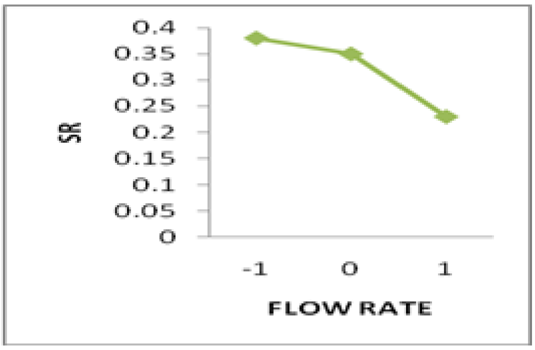

Figure 4. Effect of Flow Rate on SR

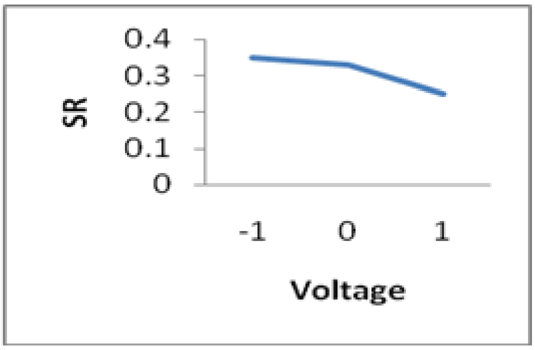

Figure 5. Effect of Voltage on SR

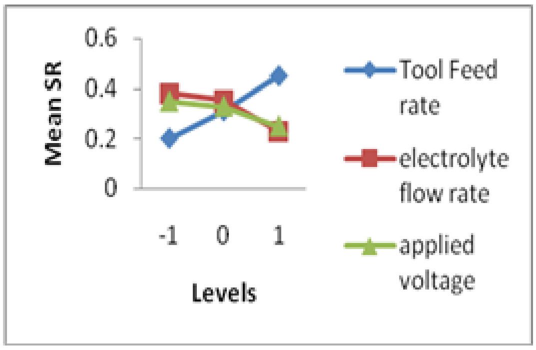

Figure 6. Combined Effect of parameters on SR

Table 3 ANOVA for Surface Roughness

Regression Statistics					
Multiple R	0.975516804				
R Square	0.951633035				
Adjusted R Square	0.922612856				
Standard Error	0.03687342				
Observations	9				
ANOVA					
	df (degree of freedom)	SS (sum of squares)	MS (mean of squares)	F	Significance F
Regression	3	0.133757	0.044586	**32.79211**	0.00102982
Residual	5	0.006798	0.00136		
Total	8	0.140556			

4. Conclusions

In this case the best combination of parameters is low tool feed rare at maximum electrolyte flow rate and minimum applied voltage. The input parameters are termed as Signal (S) and Error in the response/result is termed as Noise (N). As feed rate increases surface roughness increases. The surface roughness is affected by tool feed rate to the greater extent followed by electrolyte flow rate and applied voltage. At low feed rates irregular removal of material is more likely to occur to affect surface characteristics. The effect of voltage on SR is almost linear. At low electrolyte flow rate more material is removed from the workpiece due to longer contact with the workpiece and sometimes causes local erosion resulting into high surface roughness. ANOVA shows the desired results for good surface finish.

In this study only controllable cutting parameters are optimized and analyzed for obtaining good surface finish. Along with these controllable parameters some non controllable parameters are also affecting the surface finish and hence study of those parameters is challenging. In this study only one process characteristic, 'surface finish' is optimized. The process characteristics of the electrochemical machining process are material removal rate, surface finish and overcut in case of drilling. Other characteristics are not considered for optimization.

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A Brief Author Biography

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