A Study of Influence of Electrochemical Process Parameters on the Material Removal Rate and Surface Roughness of SS AISI 304

[1,]S. S. Uttarwar, [2,]Dr. I. K. Chopde
[1,]Department of Mechanical Engineering, Priyadarshini College of Engineering, Nagpur, Maharashtra, India
[2,]Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur Maharashtra, India

Abstract
The machining of complex shaped designs was difficult earlier, but with the advent of the new machining processes incorporating in it chemical, electrical & mechanical processes, manufacturing has redefined itself. This paper presents results of the Electrochemical Machining (ECM) process, which was used to machine the SS AISI 304. Specifically, the Material Removal Rate (MRR) and Surface Roughness (SR) as a function of ECM were determined. The experimental work was based on the Taguchi approach of experimentation and table L_{32} was used. Furthermore, a theoretical and computational model is presented to illustrate the influence parameter variations in results. The influence of independent parameters such as time of electrolysis, voltage, current, concentration of electrolyte, feed rate and pressure on output parameters material removal rate and SR is studied in this work. The results indicated that MRR was remarkably affected by variation in current and Surface Roughness decreased with increase in current. Hence, it was apparent that irregular MRR was more likely to occur at high currents. The results showed that MRR increased with increasing electrical voltage, molar concentration of electrolyte, time of electrolysis and feed rate. However, the time of electrolysis was the most influential parameter on the produced surface finish.

Keywords: Electrochemical machining; Material removal rate; Time; Feed rate; electrolyte concentration, Anova, Percentage error.

1. Introduction
Electrochemical machining (ECM), a nontraditional process for machining[1,2] has been recognized now a days for performing numerous machining operations.[4] Earlier the machining of complex shaped designs was difficult, however, with the advent of the new machining processes that incorporate in it chemical, electrical and mechanical processes, manufacturing process has redefined itself.[3] New materials which have high strength to weight ratio, heat resistance, hardness and are also complex shapes needing greater accuracy demand development of newer type of machining process. The new and improved machining processes are often referred to as unconventional machining processes. For e.g. ECM removes material without heat. Almost all types of metals can be machined by this process. In today's high precision and time sensitive scenario, ECM has wide scope for applications.[5] More specifically, ECM is a process based on the controlled anodic dissolution of the work piece anode,[6] with the tool as the cathode, in an electrolytic solution.[11] The electrolyte flows between the electrodes and carries away the dissolved metal.

Since the first introduction of ECM in 1929 by Gusseff, its industrial applications have been extended to electrochemical drilling, electrochemical deburring, electrochemical grinding and electrochemical polishing.[13] More specifically, ECM was found more advantageous for high-strength alloys. Today, ECM has been increasingly recognized for its potential for machining,[7] while the precision of the machined profile is a concern of its application.[9,10] During the ECM process, electrical current passes through an electrolyte solution between a cathode tool and an anode work piece.

The work piece is eroded in accordance with Faraday's law of electrolysis.[12] ECM processes find wide applicability in areas such as aerospace and electronic industries for shaping and finishing operations of a variety of parts that are a few microns in diameter.[13] Furthermore, it has been reported that the accuracy of machining can be improved by the use of pulsed electrical current and controlling various process parameters. Amongst the often considered parameters are electrolyte concentration, voltage, current and inter electrode gap.[14] Though there is a possibility of improving the precision of work, the dependency of accuracy on numerous parameters demand that a thorough investigation should be carried out to ascertain the causality to different parameters. In the backdrop of above information, this study was carried out to assess the best conditions (with respect to different process parameters) for improving the accuracy of ECM process. In this paper the authors propose an analytical model of electrochemical erosion to predict the finishing machined work piece. The study envisaged an empirical data obtained from the experiments carried out to assess effect of operating parameter variations on material removal rate (MRR) and surface roughness (SR) for Stainless steel (AISI 202).

2. ECM Setup

Fig 1and 2 shows the schematic set up of ECM in which two electrodes were placed at a distance of about 0.1 to 1mm and immersed in an electrolyte, which was a solution of sodium chloride.[15] When an electrical potential (of about 20V) is applied between the electrodes, the ions existing in the electrolyte migrate toward the electrodes[15].

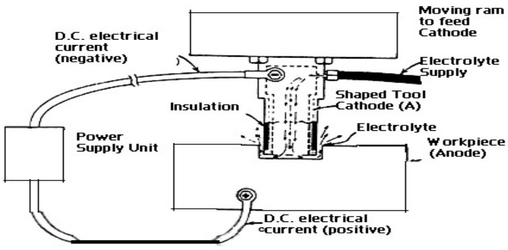

Fig 1. ECM Setup

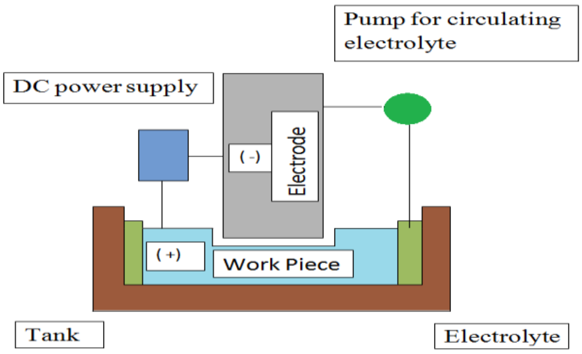

Fig 2. Block diagram of ECM setup

3. ECM Process Characteristics

3.1 Material removal rate:

The MRR primarily depends on the feed rates. The feed rate determines the amount of current that can pass through the work and the tool. As the tool approaches the work piece the length of the conductive current path decreases and the magnitude of current increases. This continues until the current is just sufficient to remove the metal at a rate corresponding to the rate of tool advance. Thereafter a stable cut is made available with a fixed spacing between the work and the tool, which is termed as the equilibrium-machining gap. If the tool feed rate is reduced, the tool advance will momentarily lag behind, increasing the gap and thus resulting in a reduction of current. This happens until a stable gap is once again established. Thus, the feed rate is an important parameter, which was given due consideration in the experiment.

3.2 Accuracy

Under ideal conditions and with properly designed tooling, ECM is capable of holding tolerance of the order of .02 mm & less. Repeatability of the ECM process is also very good. This is largely due to the fact that the tool wear is virtually non-existent on a good machine; tolerance can be maintained on a production basis in the region of .02-.04 mm. As a general rule, the more complex the shape of the work, the more difficult is to hold tight tolerances and the greater is the attention required for developing a proper tooling and electrode shape.

3.3 Surface Finish

ECM under certain conditions can produce surface finishes of the order of 0.4mm. This can be obtained by the frontal cut or the rotation of the tool or the work. Hence care was taken to control the important variables affecting the surface finish are feed rate, voltage, electrolyte composition, pressure, current & flow.

4. Operating Parameters In ECM

The operating parameters which are within the control of the operator and which influence ECM process capabilities are as follows: [14],[15]

4.1 Voltage

The nature of applied power supply is of two types, DC (full wave rectified) and pulse DC. A full wave rectified DC supplies continuous voltage and a pulse generator is used to supply pulses of voltage with specific on-time and off-time. The MRR is proportional to the applied voltage. But, the experimental values were found to be varying non-linearly with voltage. This is mainly because of less dissolution efficiency in the low voltage zone as compared to the high voltage zone.[12] However continuous voltage supply is used for this experimentation work.

4.2 Feed Rate

Feed rate governs the gap between the tool (cathode) and the work piece (anode) it is important for metal removal in ECM.[6] It plays a major role for accuracy in shape generation and hence was constantly monitored.

4.3 Electrolyte and its concentration

ECM electrolyte is generally classified into two categories, passivity electrolyte containing oxidizing anions e.g. sodium nitrate and sodium chlorate, etc. and non-passivity electrolyte containing relatively aggressive anions such as sodium chloride. Passivity electrolytes are known to give better machining precision. This is due to their ability to form oxide films and evolve oxygen in the stray current region. From review of past research, in most of the investigations researchers recommended $NaClO_3$, $NaNO_3$, and NaCl solution with different concentration for ECM and hence, NaCl was used as an electrolyte in this experimentation with concentration of 125gm/lit and 150gm/lt.

4.4 Current

Current plays a vital role in ECM. The MRR is directly proportions to the current (i.e. MRR increases with increase in current). However, this increase can be observed up to a certain limit and exceeding current beyond this level negatively affects accuracy and finishing of work piece. Hence, care was taken to apply current in the desired way.

5. Experimental Setup

Fig 3 shows actual photograph of the experimental set up of ECM on which the experimentation process was carried out.

Fig 3. Experimental set up of ECM process

5.1 Tool and Work piece Material

The tool used in this study was made up of copper while the work-piece used is this study was made up of Stainless Steel SS 304. This work piece was selected for this study as it has wide applications in various fields. The chemical composition of the used work piece i.e. SS 304 are as follows

Sample	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)	Cu (%)	Fe (%)
SS 202	0.023	0.447	1.16	0.038	0.016	18.31	7.99	1.05	Remaining

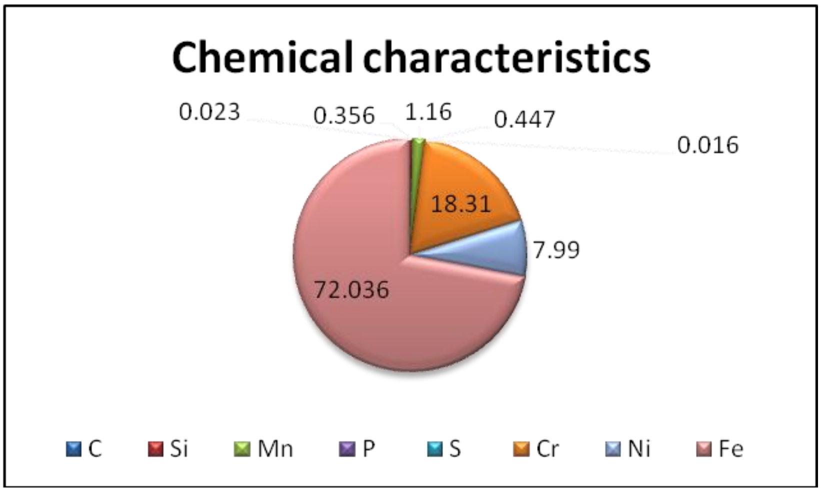

Fig 4. Chemical characteristics of work piece SS 304

5.2 Experimentation Work

An Orthogonal Array $L_{32}(2^1*4^5)$ of Taguchi method was used for conducting the experimentation work. The results of dependent parameters (MRR and SR) with respect to all levels of independent parameters are shown in a following table.

Table 2 Values of Dependent and Independent Parameters (Orthogonal array L 32)

Run No.	Independent parameters						Dependent parameters	
	Electrolyte Conc. (gms/Ltr)	Voltage (V)	Current (Amp)	Feed (MM/min)	Electrolyte Flow (Ltrs/min)	Pressure (Kg/Cm^2)	MRR (mg/min)	SR (µm)
	E	B	A	0.1	C	F	*G*	*H*
1	125	10	100	0.2	4	3.4	5.277	4.074
2	125	10	125	0.3	5	3.6	5.224	3.788
3	125	10	150	0.4	6	3.7	5.259	3.775
4	125	10	175	0.1	7	3.8	6.380	5.591
5	125	14	100	0.2	5	3.6	4.430	3.626
6	125	14	125	0.3	4	3.4	5.586	3.306
7	125	14	150	0.4	7	3.8	5.161	3.491
8	125	14	175	0.2	6	3.7	4.136	3.304
9	125	18	100	0.1	6	3.8	4.705	3.677
10	125	18	125	0.4	7	3.7	5.859	3.603
11	125	18	150	0.3	4	3.6	6.056	5.099
12	125	18	175	0.2	5	3.4	4.811	4.474
13	125	22	100	0.1	7	3.7	4.497	4.013
14	125	22	125	0.4	6	3.8	5.365	3.573
15	125	22	150	0.3	5	3.4	5.086	3.760
16	125	22	175	0.4	4	3.6	4.789	3.458
17	150	10	100	0.3	4	3.8	5.612	4.299

18	150	10	125	0.2	5	3.7	4.922	3.362
19	150	10	150	0.1	6	3.6	5.373	3.510
20	150	10	175	0.4	7	3.4	5.343	3.259
21	150	14	100	0.3	5	3.7	6.703	6.402
22	150	14	125	0.2	4	3,8	4.514	3.268
23	150	14	150	0.1	7	3.4	6.705	5.971
24	150	14	175	0.3	6	3.6	5.468	3.713
25	150	18	100	0.4	6	3.4	5.144	3.149
26	150	18	125	0.1	7	3.6	4.657	3.602
27	150	18	150	0.2	4	3.7	5.439	4.612
28	150	18	175	0.3	5	3.8	6.754	4.474
29	150	22	100	0.4	7	3.6	4.772	3.947
30	150	22	125	0.1	6	3.4	4.540	3.530
31	150	22	150	0.2	5	3.8	5.362	3.589
32	150	22	175	0.3	4	3.7	3.607	3.270
∑	4400	512	4400	0.4	176	112.2	165.044	124.566

5.3 Mathematical Model for MRR and SR

Using Regression Analysis Mathematical models were developed for MRR and SR with their indices. The six decision variables concerned for this model were Current, Voltage, feed rate, Pressure, Electrolyte concentration and flow of electrolyte.

6. Objectives

The various objectives under consideration for the formulation of model were

a) Maximization of MRR and

b) Improving SR (surface finish) and dimensional accuracy

6.1 Derived mathematical Models

Equation 1 and 2 are the mathematical models derived for calculation of MRR and SR.

$MRR = Constant \times A^a \times B^b \times C^c \times D^d \times E^e \times F^f$

Where a,b,c,d,e,f are the indices for current, voltage, electrolyte flow, feed rate, Electrolyte concentration and pressure . The formulated models are as follows

Mathematical Eqn for MRR is

$$MRR= 3.14695\ A^{0.002050} * B^{-0.01061875} * C^{0.001225} * D^{0.10975} * E^{-\ 0.00345} * F^{-0.0104625}$$

--- Eqn 1

Mathematical Eqn for SR is

$$SR= 2.\ 2425000\ A^{0.0024500} * B^{-0.0196875} * C^{0.0212500} * D^{0.0375000} * E^{-\ 0.0022500} * F^{0.0093750}$$

----------- Eqn 2

From the Eqns. 1 and 2, it was evident that the MRR was positively influenced by the independent variables such as current, electrolyte flow and feed rate whereas negatively influenced by voltage, electrolyte concentration and pressure. Moreover, the SR was observed to be positively influenced by current, electrolyte flow, feed rate, and electrolyte concentration whereas it (SR) is negatively influenced by voltage and electrolyte concentration.

7. Comparison Of Practical V/S Theoretical Values Of MRR

A sample set of Comparison of Actual value of MRR calculated by formula and corresponding values derived by mathematical model is shown in Table 3 along with the calculated percentage error.

Table 3: Comparative assessment of the Practical v/s Theoretical values of MRR

Sr. No.	Values of Dependent Parameter (MRR)		Percentage Error
	By Mathematical Model	Actual Experimentation	
1	**5.591386235**	**5.277**	**5.9577**
2	**4.994041391**	**5.224**	**-4.4020**
3	**4.671671187**	**5.259**	**-11.1681**
4	**4.458360504**	**6.380**	**-30.1197**
5	**5.636831741**	**4.430**	**27.2423**
6	**4.987908572**	**5.586**	**-10.7070**

7.1 Comparison of Practical v/s Theoretical values of SR

A sample set of Comparison of Actual value of SR calculated by formula and corresponding values derived by mathematical model is shown in Table 4 with Percentage error.

Table 4: Comparative assessment of the Practical v/s Theoretical values of SR

Sr. No.	Values of Dependent Parameter (SR)		Percentage Error
	By Mathematical Model	Actual Experimentation	
1	**3.367250843**	**4.074**	**-17.3478**
2	**3.374170425**	**3.788**	**8.8501**
3	**3.384412557**	**3.775**	**-10.3467**
4	**5.2312324**	**5.591**	**-6.4348**
5	**3.368413193**	**3.626**	**-7.1039**
6	**3.350383833**	**3.306**	**1.3425**

8. Percentage Error

Percentage error graphs for difference in actual and theoretical values of MRR and SR are plotted with error on Y axis and readings on X axis. Fig 5 and 6 shows percentage error in actual and experimental values of MRR and SR. It was evident from the graphs that the different test runs showed noticeable variation in the percentage error of both the dependent parameters i.e. MRR and SR.

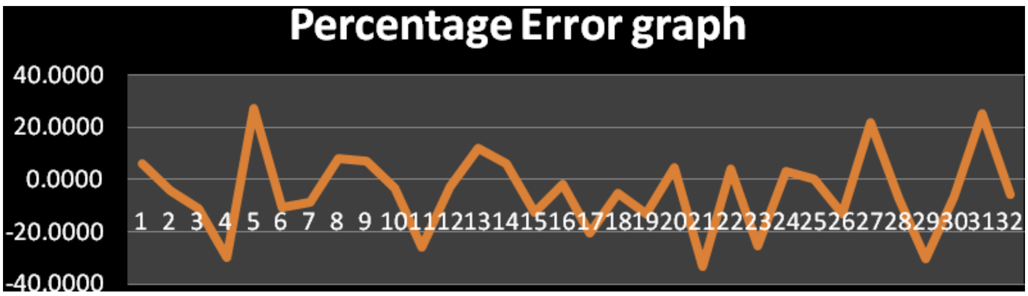

Fig 5. Percentage Error Graph for MRR

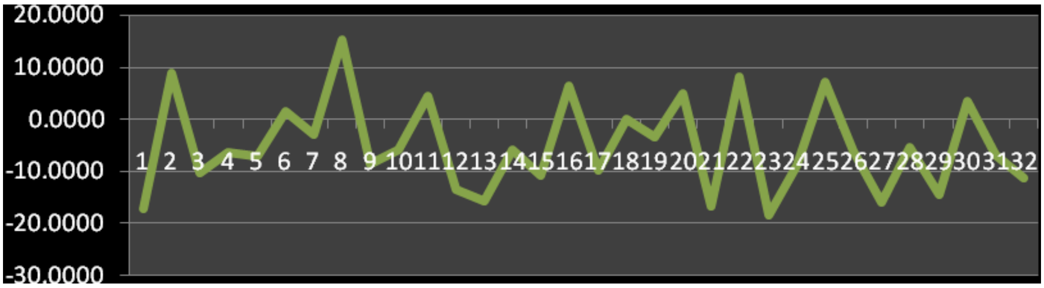

Fig 6. Percentage Error Graph for SR

9. Analysis of Variance or ANOVA

Analysis of Variance or ANOVA is a general technique that can be used to test the hypothesis that the means among two or more groups are equal, under the assumption that the sampled populations are normally distributed. The ANOVA procedure was used to test hypotheses that several means are same. In this study a total of 32 different conditions were selected to study the Material Removal Rate and Surface Roughness. The preliminary comparative assessment was carried out using the ANOVA procedure, followed by Post Hoc Test. The Post Hoc Test was employed to check, which means (obtained from the MRR and SR values as a function of 32 different runs. In addition to this, the Tukey's HSD test was also performed to determine the HSD i.e. Honestly Significant Difference.

Anova and Post Hock Test

SS 304					95% Confidence Interval for Mean			
	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Minimum	Maximum
1	3	3	5.2540	.09115	.05262	5.0276	5.4804	5.16
2	3	3	5.3193	.19453	.11231	4.8361	5.8026	5.12

ANOVA Results for MRR

		Sum of Squares	df	Mean Square	F	Significance.
SS 304	Between Groups	50.491	31	1.629	29.513	.000
	Within Groups	3.532	64	.055		
	Total	54.023	95			

ANOVA Results for SR

		Sum of Squares	df	Mean Square	F	Sig.
SS 304	Between Groups	74.024	31	2.388	18.957	.000
	Within Groups	8.062	64	.126		
	Total	82.086	95			

10. Results

It was observed that MRR was considerably affected by variation in current and SR decreased with increase in current. Hence, it was apparent that irregular removal of material was more likely to occur at high currents. The NaCl electrolyte was responsible for the lower SR and over-cut. Furthermore, MRR increased with flow rate because there was more mobility of the ions from the metal to the solution, thereby increasing the speed of the chemical reactions. Besides, there was a need to constantly remove the sludge formed during machining, which was necessary as the sludge accumulation could have negatively affected the machining efficiency of the ECM process. Results of entire experimentation work are as under:

A) Optimum value of MRR is as follows

	Actual	**By Model**
Optimum Value of MRR	6.754 mg/min	5.654 mg/min
Corresponding value of SR for this MRR	3.5574 µm	3.375 µm

Values of various parameters for above said maximum value of MRR is Current- 175A,Voltage 18 volts, Flow Rate 5Ltr/Min, Feed 0.3mm/min, Electrolyte concentration 150g/lit, Pressure 3.8 kg/cm^2

B) Optimum value of SR is as follows

C)

	Actual	**By Model**
Optimum Value of SR	3.259 µm	3.46560 µm
Corresponding value of MRR for this SR	5.343mg/min	5.7883mg/min

Values of various parameters for above said optimum value of SR is Current- 125A, Voltage-10 volt, Flow Rate -7Ltr/Min, feed-0.4mm/min, Electrolyte concentration 150g/Lit, Pressure 3.4 kg/cm^2

The mean MRR for SS304 varied between 3.6070 and 6.7540. Lowest MRR was observed for the run no. 32, while the highest value was recorded for the run no. 28. The analysis of data following ANOVA indicated significant difference in the mean values MRR and SR as a function of different conditions (set for different runs).

11. Conclusion

The experimentation work consists of study the influence of process parameters on MRR and SR. Process parameter such as machining voltage, feed, Current, Electrolyte concentration, electrolyte flow were successfully controlled and were allowed to vary according to need. The different combinations of the controlling factors were considered for the experimentation and to determine their (independent parameter's) influence on MRR and SR of SS304 work piece. The experimentation was carried out by varying all parameters in combination as per orthogonal array L_{32}. On the basis of the results obtained in this work, main conclusion can be stated as the selection of appropriate values for the different parameters of ECM process is crucial to achieve the efficiency and high quality of outcome from the process. Furthermore, similar experimental work can be continued to determine optimum process conditions for ECM process for other metals. In addition to this the difference between the theoretical and practical values of MRR and SR are also required (for other metals) to give some thought, so that % error can be reduced.

References

[1] J.A. Mc Geough, *Principle of Electrochemical Machining*. Chapman and Hall, London, 1974.

[2] P. Asokan, R Ravikumar, R Jeyapaul, M Santhi " Development of multi objective optimization models for Electrochemical Machining Process" Springer. Int J Adv. Munaf Technol(2008) 39:55-63 DOI 10.1007/s00170-007-1204-8

[3] M. Haıdopoulos · S. Turgeon · C. Sarra-Bournet · G. Laroche · D. Mantovani "Development of an optimized electrochemical process for subsequent coating of 316 stainless steel for stent applications" Received: 19 January 2004 / Accepted: 24 October 2005 Springer Science+Business Media, LLC 2006

[4] K.L. Senthil Kumar, R. Sivasubramanian, K. Kalaiselvan, "Selection of Optimum Parameters in Non Conventional Machining of Metal Matrix Composite" Portugalia Electrochemica Acta 2009 27(4) 477-486.

[5] R V Rao, P J Pawar, R Shankar "Multi objective optimization of electrochemical machining process parameters using a particle swarm optimization algorithm" DOI:10.1243/09544054JEM1158 Proc. I mech E Vol 222 (2008) Part B

[6] J.A. McGeough and X. K. Chen, Machining methods: electrochemical, in "Kirk-Othmer J. I.

[7] S K Mukherjee, s Kumar, P K shrivastava, Arbind Kumar " Effect of valency on material removal rate in electrochemical machining of aluminium" Elesevier Journal of material processing Technology 202(2008) 398-401

[8] B Bhattacharyya S K Sorkhel " Investigation for controlled electrochemical machining through response surface methodology based approach"Elesevier Journal of Processing Technology 86(1999) 200-207.

[9] Jo˜ao Cirilo da Silva Neto, Evaldo Malaquias da Silva, Marcio Bacci da Silva, 'Intervening variables in electrochemical machining' Journal of Materials Processing Technology 179 (2006) 92–96

[10] J.A. McGeough, Advanced Methods of Machining, Chapman and Hall, London, 1988, pp. 55–88.

[11] J. Tlusty, Manufacturing Process and Equipment, 1st ed., Prentice-Hall, USA, 2000.

[12] M. Datta, Anodic dissolution of metals at high rates, IBM J. Res. Develop.37 (2) (1993) 207–226.

[13] M. Datta, R. V. Shenoy, L. T. Romankiw, "Recent advances in the study of electrochemical micromachining," *ASME J. Eng. Ind.* 118, 29–36, 1996.

[14] P.C. Pandey, H.S. e Shan, Modern Machining Processes, Tata McGraw Hill, New Delhi, 1980.

[15] G.F. Benedict, Nontraditional Manufacturing Processes- Electrochemical Machining, Marcel Dekker, New York and Basel, 1987, pp. 125–172.