ELECTROCHEMICAL MACHINING OF SAE-XEV-S AUSTENITIC STAINLESS STEEL

João Cirilo da Silva Neto
School of Mechanical Engineering/Federal University of Uberlândia
e-mail: jcirilos@mecanica.ufu.br

Marcelo Bacci da Silva
School of Mechanical Engineering/Federal University of Uberlândia
e-mail: mbsilva@mecanica.ufu.br

Evaldo Malaquias da Silva
School of Chemical Engineering/Federal University of Uberlândia
e-mail: emalaqui@mecanica.ufu.br

Marcio Bacci da Silva
School of Mechanical Engineering/Federal University of Uberlândia
e-mail: mbacci@mecanica.ufu.br

Abstract. *This work shows the machining of the SAE-XEV-S stainless steel by electrochemical machining process. A prototype developed at the Federal University of Uberlândia was used. The stainless steel was chosen due a difficult machining for conventional processes. As both studies and experience have shown, the most of the stainless steels are viscous and generate too heat during the machining with poor thermal conduction. The electrochemical machining process shown appropriate to machining stainless steel. The* 2^k *factorial design was used. The accuracy, overcut and roughness were studied. The variables that most influence the system response were feed rate and electrolyte flow.*

Keywords*. Electrochemical Machining, Austenitic Stainless Steel, Machining, Factorial Design.*

1. Introduction

Electrochemical Machining (ECM) is the controlled removal of material by anodic dissolution in an electrolytic cell in which the workpiece is the anode and the tool is the cathode**.** The electrolytic is pumped through the cutting gap between the tool and workpiece, while direct current is passed through the low voltage, to dissolve metal from the workpiece, Metal's Handbook (1989). The electrolytes most appropriates are aqueous sodium nitrate ($NaNO_3$) and sodium chloride (NaCl), a small voltage of 10 – 15V is applied between the electrodes, metal dissolved electrochemically from the anode-workpiece, and gas generation occurs at the cathode-tool electrode.

In the electrolytic cell a number of chemical reactions occur at the cathode (tool) and the anode (the workpiece). An example of a typical chemistry is the machining of iron in NaCl (sodium chloride) electrolyte. The iron ions Fe^{++} leave the surface of the anode and are attracted to the negative ions that exist in the electrolyte:

$$Fe^{++} + 2(OH)^- \longrightarrow Fe(OH)_2 \quad (1)$$

The ferrous oxide mixes with air and oxidizes to $Fe(OH)_3$, a red-brown sludge. The complete reaction is

$$2Fe + 4H_2O + O_2 = Fe(OH)_3 + H_2 \quad (2)$$

The hydrogen gas evolves on the cathode. The material removal from the workpiece is flushed by flow of the electrolyte, Tlusty (2000).

The processes at the electrodes require an electric potential, both as the decomposition voltage and polarization voltage that cannot be used for driving the current through the electrolyte. The electrolyte is essential for chemical reactions, and beyond that, it carries heat and reaction products from the machining zone. An effective electrolyte should have good electric conductivity, inexpensive, readily available, nontoxic, and as less corrosive as possible.

The main objective of ECM is to achieve the required shape of workpiece within given determinants of shape and dimensions. The most common operation of ECM, cavity sinking, a required shape of workpiece can be obtained using the cathode-tool electrode with a shape which is geometrically close to the final shape of workpiece, moving towards of the anode, Kozak et all (1998).

The difficulties to cut of super alloys and other hard-to-machine materials by conventional process have been largely responsible for the development of the ECM process. The process has immense applicability in the field of forceless cutting of conventional type of materials, especially for complex geometry or when several pieces have to be finished by a single stage operation, Bhattacharyya (1973).

Other advantage of ECM is that there is no wear on the tool electrode, therefore, the cost and tool replacement is saved. The required workpiece can be obtained using tool electrode with the shape, whit is not congruent with the workpiece shape, Domanowski and Kozak (1998).

The main purpose of this work is the experimental study of electrochemical machining of SAE-XEV-S austenitic stainless steel. Eight experiments were carried out in an equipment developed at the Federal University of Uberlândia. Three parameters were changed during the experiments: feed rate (f), flow rate of the electrolyte (Q) and voltage (U). The parameters values were defined after 2^k factorial design.

The roughness of the machined surface, the overcut and dimensional accuracy were measured. The results shows that feed rate and electrolyte flow were the main parameters that affected the process.

2. Surface Machined by Electrochemical Machining

Surface finish electrochemically machined parts is usually 0.30 to 1.9 μm for the frontal cutting-gap area and as roughness as 5 μm or more for the gap area. Important variables that affect surface finish are feed rate, gap dimension, electrolyte composition, viscosity, temperature, flow and workpiece microstructure, Metal's Handbook (1989).

Others process variables also play a significant part in the determination of the surface finish. For example, as the current density is raised, generally, the smoother the finish on the workpiece surface becomes. The use of lower current density results in a further deterioration in surface structure, Strode and Basset (1986).

But sometimes the formation of oxides films 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 more passive. Even when higher voltages are applied, e.g. about 50 V, to break the oxide film its disruption is so no-uniform that deep grain boundary attack of the metal occurs.

The accuracy of the ECM process should be considered from several angles: compliance of the finished part with its drawing in terms of shape and dimensions; transfer of tool shape to the workpiece; and repeatability of dimensions in parts taken from a sufficiently large lot machined with the same electrode tool. In, say, electrochemical die sinking the primary objective is to maintain the form tolerances as closely as practicable. To achieve this, it is essential to use a tool of the right form and size and the right process parameters. This calls for the design of a suitable tool and, in consequence, the computation of the form and dimensions of the finished part that will be produced with a given tool. All of this can be done only from an analysis of ECM accuracy is important to know how machining accuracy is affected by differences in the actual profile of the tool from the design one and the process parameters from those for which the tool has been designed, Rumyantsev and Davydov (1989).

The micro-finish of an ECM surface is governed by the type of electrolyte, the composition of the workpiece material and the machining conditions such as the current density and the electrolyte flow rate. The main factors resulting in poor surface finish in ECM are pitting. Preferential grain boundary attack. surface waviness and results in the formation of oxide layers. Pitting tends to occur in regions of low current density where the passivating layer would slow down dissolution of the majority of the surface. Grain boundary attack is an example of local recession and is very important, Silva and McGeough (1986)**.**

De Barr and Oliver (1968) describe how current density, electrode potential and type of electrolyte can result in differential removal rates in inhomogeneous materials. Bannard (1979) has investigated the surface finish of fine hole drilling using ECM. He has found that electrochemical drilling of multi-phase alloys could present particular prob1ems where, if the correct dissolution controlling anodic film is not generated, differential dissolution of the phases would occur resulting in a rough surface. However, electrochemically machined surfaces are free from residual stress and from any heat-affected zones or recast layers, Benedict (1987).

3. Stainless Steel Machinability

Machinability is a complex concept that embraces several factors, and not just the question of tool wear. In addition to the effect of the material on tool wear, i.e. on tool life, it is also necessary to consider its effect on the magnitude of cutting forces, chip shape and surface quality of the machined surface when considering the overall machinability of a material.

However, Bahadur (2003), has defined the Machinability in two aspects: refers qualitatively to the ease of machining. Thus one might base it on the consideration of factors such as: tool life, power requirement /cutting forces, surface finish, chip disposal, dimensional tolerance. Quantitatively, machinability has been expressed in terms of the machinability rating which means cutting velocity for 60 minute tool life.

Metal cutting of stainless steels is often regarded as difficult. This is due to the fact that certain stainless steels, but far from all of them, are characterized by material properties that result in the cutting edge being exposed to severe conditions when machining. It is primarily the austenitic, ferritic-austenitic and certain of the ferritic-martensitic steels that cause problems during the machining. Ferritic and martensitic steels are seldom particularly difficult to machine, although ferritic steels can give rise to problems of stickiness and the formation of built-up edges. Martensitic steels can, of course, be difficult to machine if they have been hardened to high hardness, although this is nothing unique to stainless steels in particular but applies to all materials with high hardness.

The fact that the austenitic and ferritic-austenitic types of steel give problems is due to the combination of properties of these relatively soft materials, Aveste Polarit (2003). These properties are such that the hardness can no longer be used as an indication of the material's machinability. They can be summarized in five points:

- Stainless steels work-harden considerably
- Stainless steels have low thermal conductivity
- Stainless steels have high toughness
- Stainless steels tend to be sticky
- Stainless steels have poor chip-breaking characteristics.

The term electrochemical machinability implies the degree of susceptibility of a material to the electrochemically process from the point of view of the ECM properties, such as: the machining accuracy, the surface micro geometry, the dissolution efficiency and the energy consumption. In the ECM the fundamental indicator which determines the proper efficiency of the machining process (that is the amount of the material removed per unit time) and the energy consumption, is the amount of the material removed from the workpiece per unit electric charge, hence further referred as *k (coefficient of the electrochemical machinability).* Additionally, the value of *k* and its dependence on current density, influences the degree of localization of the electrochemical dissolution which, in turn, affects the width distribution of the gap between the cathode-tool and the machined workpiece, and thus affects the machining accuracy. Moreover, consideration the assumption of *k,* as a fundamental machinability indicator is entirely justifiable, Kozak et all (1995).

The knowledge of the electrochemical machinability of a given material is essential to consider electrochemical machining as an alternative process to machine the material. In this paper the problem associated with the methodology to estimate the electrochemical machinability of the stainless steel material was considered in comparative terms with conventional machining process. The *k* will be not considered. Only three process variables were studied. As the metal cutting of stainless steels is often regarded as difficult, the electrochemical machining process can be an alternative to machining stainless steel.

4. Experimental Procedure

4.1. Experimental Set-up

The experimental set-up is very important in the ECM. It consists of, amongst others things, a specially developed tool which allows the formation of gap between the workpiece. There are two aspects of cathode (tool) design for ECM.

The First aspect deals with the determination of cathode-shape together with the optimum machining conditions necessary to produce the required work shape. In general, cathode shape for ECM is designed on the basis of “trial and error” methods which are expensive, time consuming, and inaccurate.

The second aspect of the tool design problem is a practical one. It deals with making a tool of an appropriate material, designing a suitable electrolyte supply system, insulation certain parts of the tool to prevent overcut in the undesired region. Design requirements for some of these aspects may conflicting and may demand modifying the tool geometry, Reddy et all (1988).

Theoretical methods for the tool design have also been developed but they allow only first approximation to the final tool shape. The major problems associated with this variant ECM also is the determination of tool electrode movement in order to obtain the required shape of workpiece i.e. control and programming tool-electrode motion. Computer simulation process is a power tool to solve this problem, Kozak et all (1998).

In this work, the set-up to tool fixation was produced in 304 stainless steel to resist to environment corrosion where occurs machining, as is show in Fig. 1. Two metal sacrifice plates are located between workpiece to minimize the electrolyte jet deviation and prevent the overcut. The operation was realized with the workpiece stopped and the tool moving against the workpiece.

The electrolyte was fed in the interface workpiece-tool. The material used to tool was the electrolytic copper. The tool was produced with external diameter of 9,25mm and internal diameter of 3mm. The external part of this tool has an insulating coating in commercial nylon with 0,20mm of thickness. In the coating of the tool was used fast cure glue. The operation used was electrochemical drilling. The tests were realized in an electrochemical machining prototype developed in the Federal University of Uberlândia, Malaquias (2000).

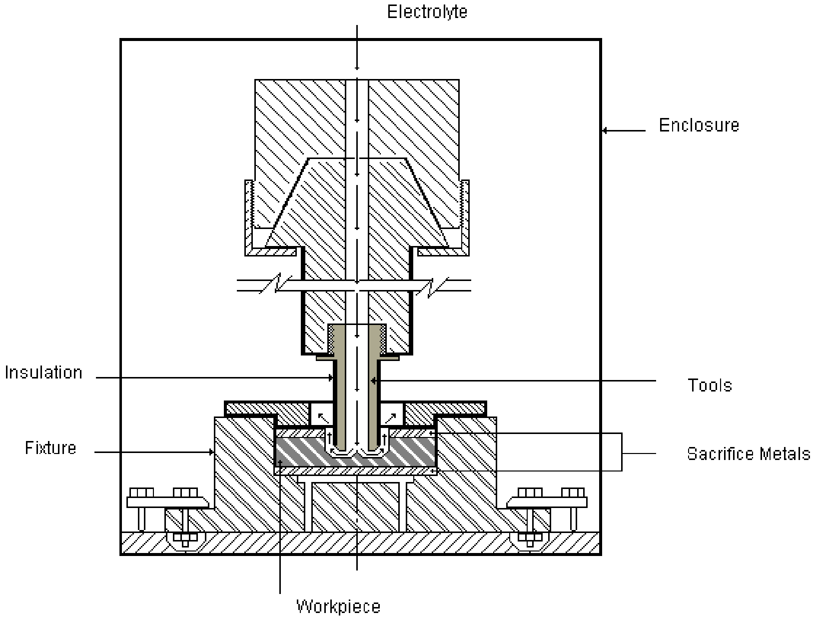

Figure 1. Schematic diagram of the experimental set-up

4.2. Machining Parameters

The material of the workpiece was the SAE-XEV-S austenitic stainless steel. This steel is used in the manufacturing of gas pump of internal motors combustion. The Villares Metals seeks an alternative method for to machining its. The chemical composition of this steel is showed at Table 1. The electrolytic solution used was sodium chloride (NaCl) in a concentration of 100g per litter of water

Table 1. Chemical composition of the SAE-XEV-S austenitic stainless steel

Element	**Chemical Composition**
Carbon (C)	0,50%
Manganese (Mn)	9%
Chromium (Cr)	21%
Nickel (Ni)	2,15%
Nitrogen (N)	0,50%
Tungsten (W)	1,15%
Niobium (Nb)	2,15%

Table 2 shows the variables in two levels, with the maximum value, level (+1) and the minimum value, level (-1).

Table 2. Process variables in two levels to be used in factorial design.

Variables	**Level (+1)**	**Level (-1)**
X_1: f (Feed Rate) [mm/min]	0,7	0,5
X_2: Q (Electrolyte Flow) [l/h]	300	200
X_3: U (Voltage) [V]	10	8

5. Results and Discussion

A common experimental design is one with all input factors set at two levels each. These levels are called high and low or (+1) and (-1), respectively. A design with all possible high/low combinations of all the input factors is called a full factorial design in two levels. If there are k factors, each at 2 levels, a full factorial design has 2^k runs (experimental).

In this paper the factorial design for three factors, namely the 2^3 design in the two-level was considered. This implies eight runs, without replications. Graphically, the 2^3 factorial design can be presented by the cube shown in Fig. (2). The arrows show the direction of increase of the factors. The numbers 1 through 8 at the corners of the design box reference the Standard Order of runs, where this paper X_1 is the feed rate, X_2 is the electrolyte flow and X_{3} is the voltage.

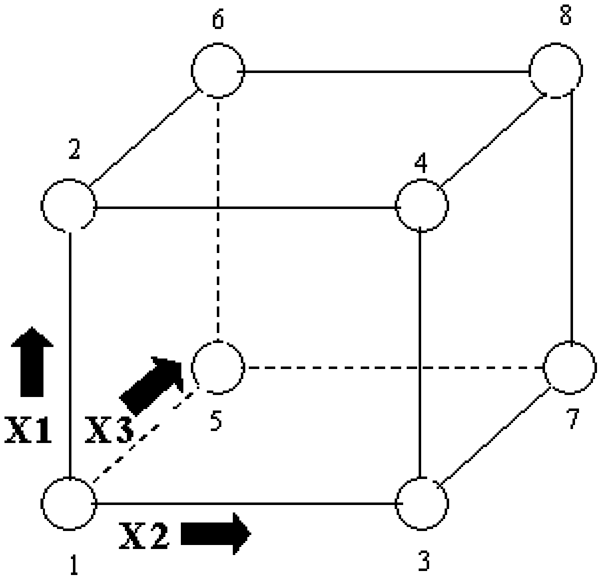

Figure 2. A 2^3 two-level, full factorial design; factors X_1, X_2, X_3, Engineering Statistics Handbook (2003).

Table 3 shows the 2^3 factorial design matrix of experiments, with the responses: R_1 (accuracy in %), R_2 (overcut – top side in mm), R_3 (overcut – end of cut in mm) and R_4 (roughness in μm).

Table 3. 2^3 factorial design matrix.

Experimental	X_1	X_2	X_3	R_1	R_2	R_3	R_4
1	-1	-1	-1	2.9	0.31	0.31	0.14
2	+1	-1	-1	7.7	0.46	0.29	0.50
3	-1	+1	-1	0.5	0.22	0.24	0.83
4	+1	+1	-1	2.4	0.36	0.24	0.28
5	-1	-1	+1	7.2	0.36	0.28	0.75
6	+1	-1	+1	9.0	0.43	0.42	0.41
7	-1	+1	+1	3.2	0.31	0.15	0.20
8	+1	+1	+1	5.2	0.36	0.10	0.29

Table 4 shows a sample two-level three factor design. The design matrix shows the influences of the factors (variables) in the results (response) of the data collected in this experiment. The statistical program was used in the determination of the results.

Table 4: System response by statistical program.

Factors	Significance R_1	Significance R_2	Significance R_3	Significance R_4
X_1	0.182	**0.0155**	0.795	0.798
X_2	0.125	**0.0205**	0.244	0.905
X_3	0.173	0.057	0.647	0.952
X_1X_2	0.544	0.204	0.566	0.781
X_1X_3	0.521	**0.037**	0.692	0.971
X_2X_3	0.979	0.090	0.360	0.551

The results presented in Table 4 shown that the variables investigated in this work do not influenced significantly in the response R_1 (accuracy), at the experimental tests. This behavior can be explained by the thickness of the workpiece to be very small (5mm) in relation to the medium diameter of the holes (9,78mm). Other factor that have been interfering in the response was the toll feed rate to be low (0,50mm/min and 0,70mm/min), however Benedict (1987) suggests 0,50 to 19 mm/min. Larger values of feed rate was not used because of the occurrence of short circuit between the workpiece and tool, that causes poor surface finish. The amount of overcut that occurs at sides of the ECM tool is dependent upon the feed rate. A low feed rate will produce a large overcut, and conversely, a high feed rate will reduce the amount of overcut. At this point, it is interesting to note the relationship between the ECM parameters, namely current density, feed rate and overcut. As the current density is increased, the feed rate increases (to maintain a constant cutting gap), the overcut is reduced and the surface finish is improved.

Figure 3 shows the response surface of the accuracy when the feed rate and electrolyte flow are in two levels, with the maximum value, level (+1) and the minimum value, level (-1), and with the voltage in level (+1). In all experimental tests with the increase of X_1 and X_2 one can note an increase of the accuracy. This result is not according with the literature. Beyond the low tool feed rate and the small thickness of the piece, other variables, as deviation electrolyte jet, for example, should had caused interference in the results.

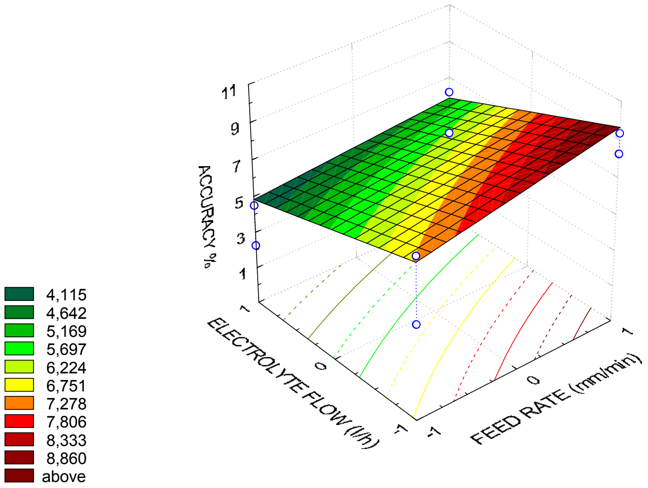

Figure 3: Response surface of the accuracy for $X_3 = +1$

At the response R_2 the experimental tests show that the variables X_1 and X_2 influence the results. However, the variable X_3 has presented smeller influence in the response. The interaction X_1X_3 (a combination of the voltage with the feed rate) also causes changes in R_2.

Only R_2 overcut (top side) suffered influence of the variables X_1 and X_2 with larger intensity and X_3 in smaller intensity. For better visualization of the behavior of the found response, the response surface of the tests made with the overcut (top side) was presented.

In the Fig. (4) an increase in the variable X_1 causes an increase in the overcut (top side). Statically, this result is not according with the literature, because on higher feed rates, the gap is smaller, precision is higher, and the surface finish is also better. But the feed rate is limited by the current available, and by the fact that with smaller gap the pressure in the electrolyte increase which may slow down its. This leads to corresponding increase in temperature, which may produce boiling of the electrolyte and disruption of the process, Tlusty (2000).

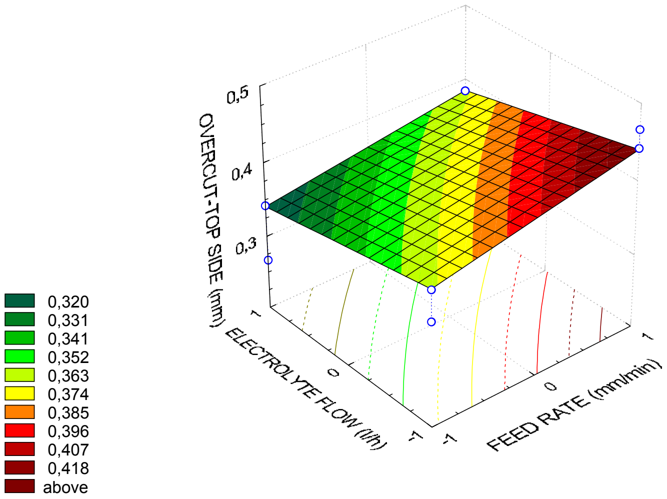

Figure 4: Surface response of the overcut-top side for $X_3 = +1$

In addition, the electrolyte selection is very important in electrochemical machining. Sodium chloride, for example, yields much less accurate components than nitrate, the latter electrolyte having far better dimensional due to its current efficiency and current density characteristics. However, in this paper was used the sodium chloride.

In the Fig. (4), an increase in the variable X_2 causes a decrease in the overcut (top side). This result is according with the literature, because electrolyte flow is also an important factor in electrochemical machining control. The temperature increase of the electrolyte passing through the gap is dependent on the flow rate. In addition, the rate at which hydrogen bubbles are carried away is thought to influence conductivity. The flow rate also affects the level of turbulence of the electrolyte as it passes through the gap, and this influences the surface finish. Therefore, the electrolyte flow must also be great enough to remove machining by-products, for example the sludge, Metal Handbook (1989).

Figure 5 shows the response surface of the overcut-end of cut for $X_3 = +1$.

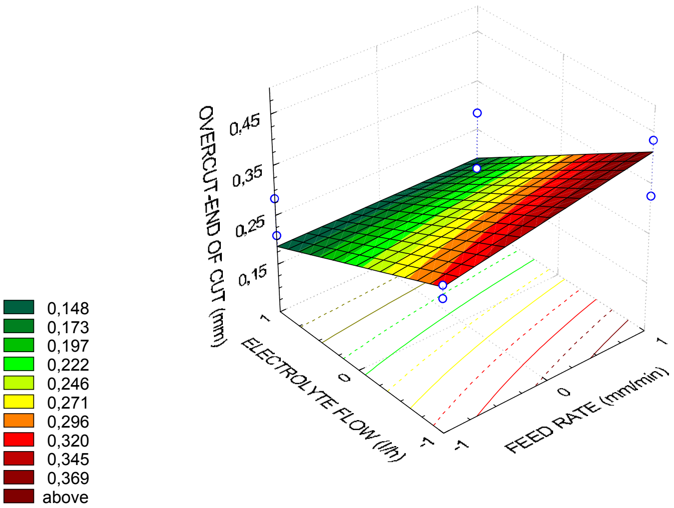

Figure 5: Surface response of the overcut-end of cut for $X_3 = +1$

Statistically, the responses R_3 and R_4 were not influenced by the investigated variables. Also any combination of the variables affected the responses in experimental at the levels studied. This behavior can be explained by absence of analyses of others variables. As well as influencing the metal removal rate, the electrolytes also affect the quality of surface finish obtained in ECM, although others conditions also have an effect.

Depending on the metal been machined, some electrolytes leave an etched finish, caused by the non-specular reflection of light faces electrochemically dissolved at different rates. Sodium chloride electrolyte tends to produce a kind of etched, matt finish with steels and nickel alloys: a typical surface roughness would about 1 μm Ra, McGeough (1989). However in this work the roughness has varied from 0,551 to 0.971 μm Ra. Figure 6 shows the response surface of the roughness with variable X_3 at level (+1).

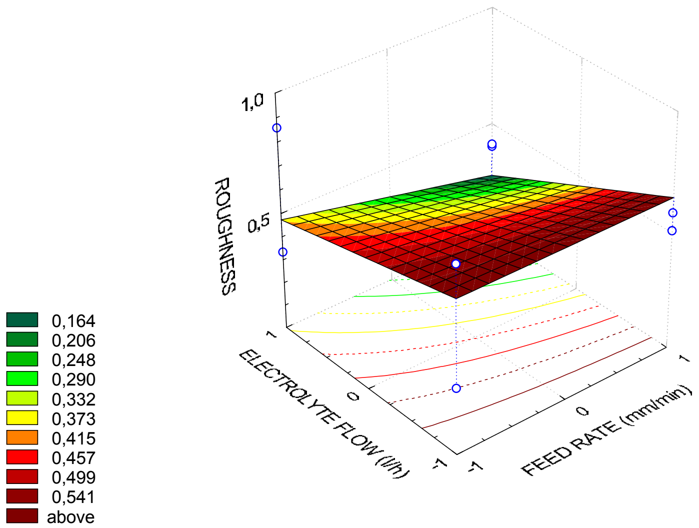

Figure 6. Response surface of the roughness with variable X_3 at level (+1).

By the other hand, the stainless steel did not presented difficulty of machining for the electrochemical machining process. Did not have apparent formation of burrs and tool wear. For its characteristic of material removal of the part atom for atom, the electrochemical machining is considered as a cold machining process much used in the machining of materials of highest hardness or when is desired to machining material of low machinability.

Can be concluded that, in the studied conditions, as the tool does not have contact with the workpiece, and as the material removal occurs for electrochemical reactions, the electrochemical machining process can be considered suited to machining the austenitic stainless steel.

6. Conclusions

- The variables that most influenced in the response were the feed rate and electrolyte flow;
- The accuracy, overcut (end of cut) and roughness were not influenced by the investigated variables;
- The voltage had smaller influence in the response;
- In the studied conditions, the electrochemical machining process can be considered appropriate to machining the austenitic stainless steel.

7. Acknowledgements

The authors thank the Netzsch of Brazil and the Engineer Antonio Felisberto for yielding electrolyte filter. The authors are also grateful to the Villares Metals for the supplying of 4 bars of 500mm of length and diameter of 19,05mm of the stainless steel.

8. References

Aveste Polarit, 2003, "Machinability of Stainless Steels", http://www.avestapolarit.com/template/Page____2151.asp, accessed in 04/13/2003.

Bahadur, S., "Machinability" 2003, http://www.me.iastate.edu/me324_bahadur/Section%203.2/Machinability.htm , accessed in 04/13/2003.

Bannard, J., "Fine Hole Drilling Using Electrochemical Machining", Nineteenth Int. Machine Tool Design Research Conf. Manchester, 1978, pp. 503-510 (MacMillan, London).

Bhattacharyya, A., 1973; "New Technology", Hooghly Printing Company, Calcutta, pp. 89 –140.

De Barr, A. E., Oliver, P. A., 1968, "Electrochemical Machining", McDonald and Company, London.

Domanowski, P., Kozak, J. 1998, "Inverse Problems of Shaping by Electrochemical Generating Machining", International Conference on Advances in Production Engineering, Warsaw, pp. 272.

Engineering Statistics Handbook, 2003, "Two-level full factorial designs", accessed in 03/29/2003, http://www.itl.nist.gov/div898/handbook/pri/section3/pri333.htm.

Kozak, J., Dabrowski, L., Lubkowski, K. e Rozenek, M., 1995, "The Effect of Electrochemical Dissolution Characteristics on Shape Accuracy in ECM", International Symposium for Electromachining, Lousanne, pp. 511 – 519.

Kozak, J., Budzynsky, A. F., Domanowski, P., 1998, "Computer Simulation Electrochemical Shaping ECM-CNC) Using a Universal Tool Electrode", Journal Materials Processing Technology, Warsaw, Poland, pp. 161-164.

Malaquias, E., 2000, "Contribution to Study of Electrochemical Machining of AISI M2 High Speed Steel", Thesis, Federal University of Uberlândia, Uberlândia, MG, Brazil.

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

Metal's Handbook, 1989 "Electrochemical Machining", Ninth Edition Vol. 16, ASM INT, pp. 533 – 550.

Reddy, M. S., Jain, V. K, Lal, 1988, "Tool Design for ECM: Correction Factor Method", Journal of Engineering for Industry, India, Vol. 110/111, pp. 110-117.

Rumyantsev, E., Davydov, A., 1989, "Electrochemical Machining of Metals", Mir Publishers, Moscow, pp. 47.

Silva, A., McGeough, J. A., 1986, "Surface Effects on Alloys Drilled by Electrochemical Arc Machining", Proc. Instn. Mech. Engrs., Endinburgh, Vol. 200, Nº B4. pp. 237.

Strode, I and Basset, M. B., 1986, "The Effect of Electrochemical Machining on the Surface Integrity and Mechanical Properties of Cast and Wrought Steels", Wear, 109, U.K, pp-171-180.

Tlusty, J., 2000, "Manufacturing Process and Equipment", 1st ed, Prentice-Hall, Upter Sadie River, N. Y, (USA).