ACCURACY IN ELECTROCHEMICAL MACHINING: A STUDY OF CASE

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Abstract: *Electrochemical Machining (ECM) is a non-traditional machining (NTM) process in the electrochemical category. ECM can be thought of a controlled anodic dissolution at atomic level of an electrically conductive workpiece by a shaped tool using a high current flow at relatively low potential difference through an electrolyte which is quite often water based neutral salt solution. The main purpose of this work is the experimental study of the accuracy in electrochemical machining in which many variables influence the electrochemical machining finish of the workpiece. Lateral overcut and roughness were studied. A prototype developed at the Federal University of Uberlândia was used. Four parameters were changed during the experiments: feed rate, electrolytic solution, electrolyte flow rate and voltage. Forty-eight experiments were carried out using the equipment developed. Two electrolytic solutions were used: sodium chloride (NaCl) and sodium nitrate (NaNO3). Electrochemical machining with sodium nitride had the best results for surface roughness and overcut.*

Keywords: *Electrochemical Machining; Accuracy; Roughness; Lateral Overcut.*

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 electrolyte is pumped through the cutting gap between the tool and workpiece, while direct current is passed through it at a low voltage to dissolve metal from the workpiece (Metals Handbook, 1989). The most appropriates electrolytes are aqueous sodium nitrate ($NaNO_3$) and sodium chloride (NaCl). A small voltage of 10 – 15V is applied between the electrodes, metal dissolves 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. Fe^{++} iron ions leave the surface of the anode and are attracted to the negative ions in the electrolyte:

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

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

$$2Fe + 4H_2O + O_2 = Fe(OH)_3 + H_2 \tag{2}$$

Hydrogen gas evolves on the cathode. The material removed from the workpiece is flushed away by flow of the electrolyte (Tlusty, 2000). As shown in Figure (1), both reactions are consequences of applied potential difference, that is, voltage, from the electric source. A cation reaching the cathode is neutralized, or discharged, by negative electrons on the cathode. Since the cation is usually the positively charged atom of a metal, the result of this reaction is the deposition of metal atoms. To maintain the cathode reaction, electrons must pass around the external circuit. These are obtained from the atoms of the metal anode, and these atoms thus become the positively charged cations which pass into solution. In this case, the reaction is the reverse of the cathode reaction (McGeough, 1988).

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

The main objective of ECM is to achieve the required shape workpiece within given specifications of shape and dimensions. In the most common operation of ECM, cavity sinking, a required workpiece shape can be obtained using a cathode-tool electrode with a shape that is geometrically close to the final shape of workpiece that moves toward the anode (Kozak et al, 1998).

The difficulties in cutting super alloys and other hard-to-machine materials by conventional process have been largely responsible for the development of the ECM process. The process is highly applicable in the field of forceless cutting of conventional material types, especially for complex geometry or when several pieces have to be finished by a single stage operation (Bhattacharyya, 1973), (Bannard, 1978)

Others advantages of ECM are that there is no wear on the tool electrode, therefore, the cost of tool replacement is saved. The required workpiece can be obtained using a tool electrode with a shape that is not congruent with the workpiece shape, Domanowski and Kozak (1998). The objective of this work is the experimental study of accuracy in electrochemical machining in which many variables influence electrochemical machining finish of the workpiece. Lateral overcut and roughness were studied.

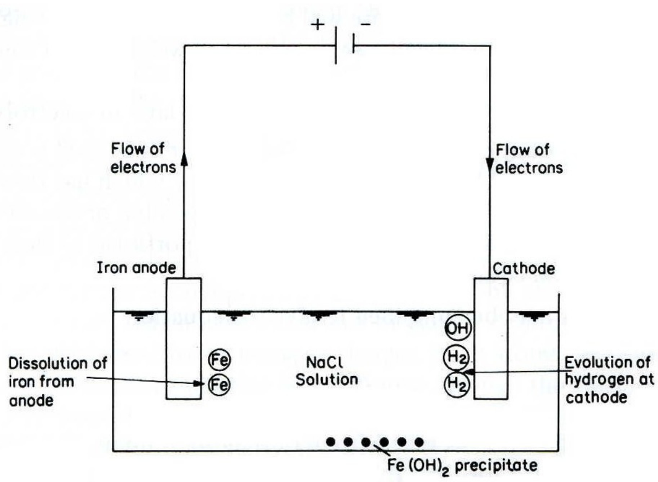

Figure 1. Electrolytic dissolution of iron, McGeough (1988).

2. EXPERIMENTAL PROCEDURES

2.1. Electrochemical machining equipment

A state-of-the-art ECM system is an assembly of equipment that includes the ECM machine itself, a power supply, a process parameter control system, and a system for electrolyte preparation, feeding and purification. The parts that are machined by ECM usually widely differ in shape and size, amount of stock to be removed, and in lot size. This in turn affects the design of ECM machines. They may be universal, special-purpose and single-operation. Universal ECM machines, as their name implies, are capable of performing a wide range of operations.

These include duplicating and duplicate hole-drilling machines. When designing these machines, it is important to consider workpiece size because this factor determines the forces that will act upon the machine elements during ECM. The tooling scheme should be chosen according to rigidity of the base, feed drive form and some other aspects. It is important that the operator feel comfortable when he sets up or takes down a workpiece, clamps it in a fixture, etc. The above factors should be considered when making the decision to arrange the machine horizontally or vertically, to use a fixed or a movable (extendable) machine table, and where to locate the feed drives.

The degree of automation to be provided in a machine usually depends on the contemplated lot size. Fully automated facilities are recommended for large-size manufacturing, such as for deburring in the automotive industry. Units have been developed in which all operations, from blank feeding to applying a rust-preventive compound to finished parts, are automated. Such units can turn out as many as several hundred parts per hour (UNL, 2007).

Most ECM machines operate in what can be called a semi-automatic mode in which the ECM cycle is automated, but blanks are set up, aligned and clamped, and finished parts are taken down by a human operator.

This work presents a prototype developed in the laboratory of the Federal University of Uberlândia which was used in the experimental procedures. Figure 2 shows the simplified scheme of the tool feed mechanism of electrochemical machining equipment. The feed rate of the tool is determined by the coupled motor rotation in the the tool's reducer. When the electrolyte is present and there is tension, workpiece dissolution occurs. The main functions of an electrolyte in ECM are to create conditions for anode dissolution of workpiece material, to carry electric current, to remove electrochemical reaction debris from the gap, to reduce the heat generated by the machining process, and to maintain a constant temperature in the machining region (Rumyantsev and Davydov, 1989). During electrochemical machining, the electrolyte must be filtered so that it doesn't affect the finish. Figure (3) shows the electrolyte filtration system.

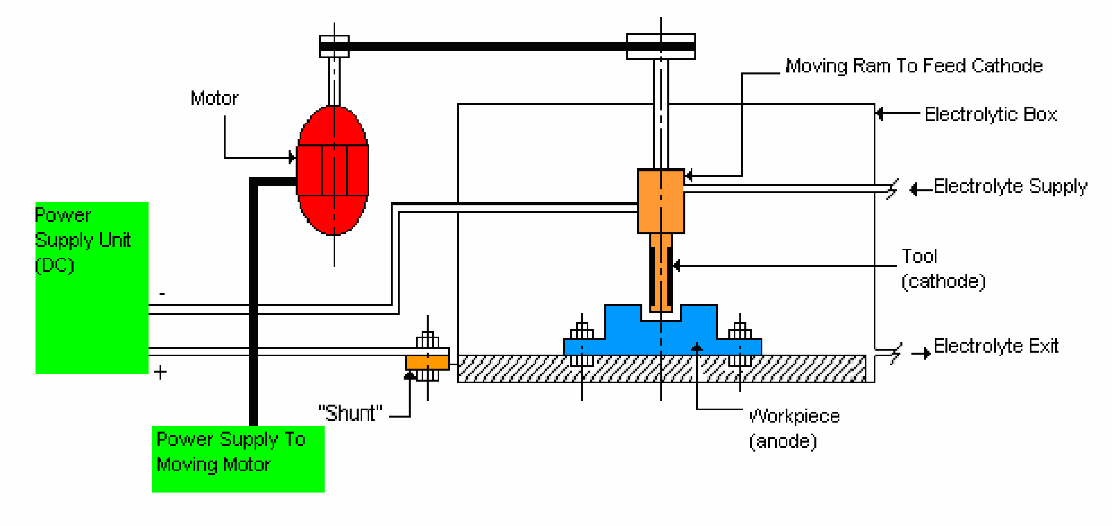

Figure 2. Simplified scheme of the tool feed mechanism of electrochemical machining equipment.

Figure 3. Electrolyte filtration system.

2.2. Experimental set-up

Experimental set-up is very important in ECM. Among others elements, it consists of a specially developed tool which allows the formation of a gap with the workpiece. There are two aspects of cathode (tool) design for ECM.

The first aspect deals with determining cathode shape along with the optimal machining conditions to produce the required work shape. In general, cathode shape for ECM is designed using trial and error, which is 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, and insulating certain parts of the tool to prevent overcut in the undesired region. Design requirements for some of these aspects may conflict and may require tool geometry to be modified (Reddy et al., 1988).

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

In this work, tool attachment set-up was produced in 304 stainless steel to resist environmental corrosion where machining occurs, as shown in Figure (4). The workpiece is between two insulation plates to minimize electrolyte jet deviation and prevent overcut. The operation was carried out with and the tool moving against a stationary workpiece.

The electrolyte was fed into the workpiece-tool interface. The tool was made of electrolytic copper. The external diameter of the tool was 9.25 mm and internal diameter was 3 mm. The external part of this tool had a 0.20mm commercial nylon insulating coating. Fast cure glue was used on the tool coating. The operation was electrochemical drilling. Tests were carried out in an electrochemical machining prototype developed at Federal University of Uberlândia (Malaquias, 2000). Figure (5) shows the electrochemical tool (without insulation, left) and support for securing the workpiece (right) (Silva Neto, 2004).

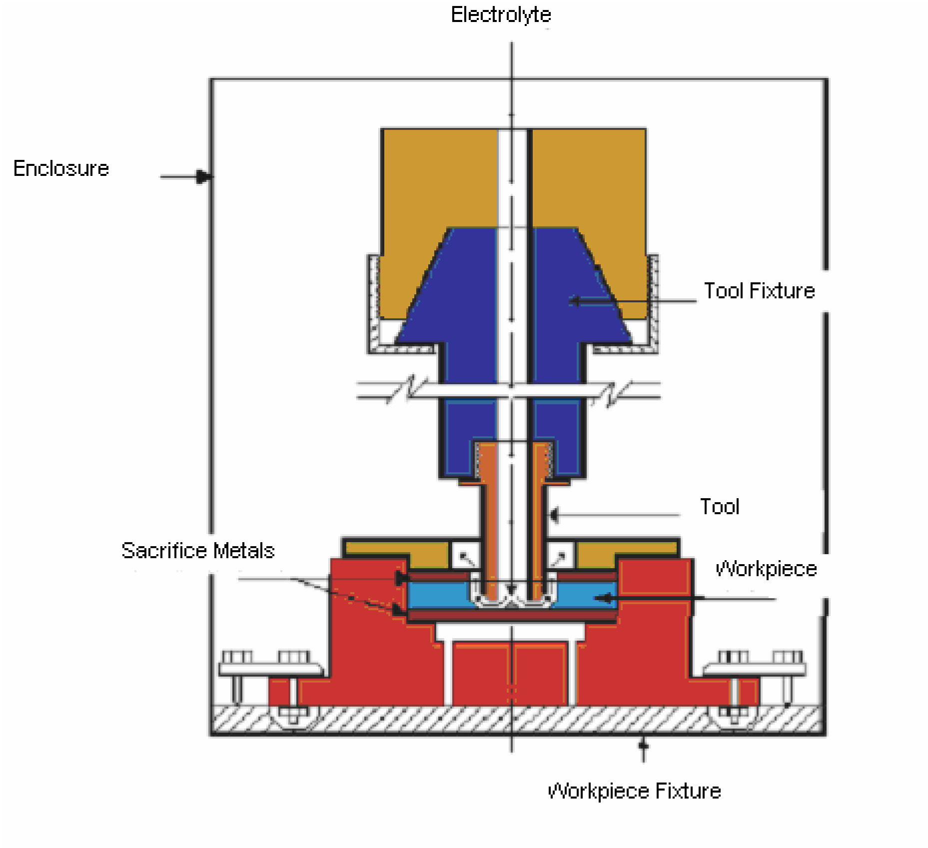

Figure 4. Schematic diagram of experimental set-up

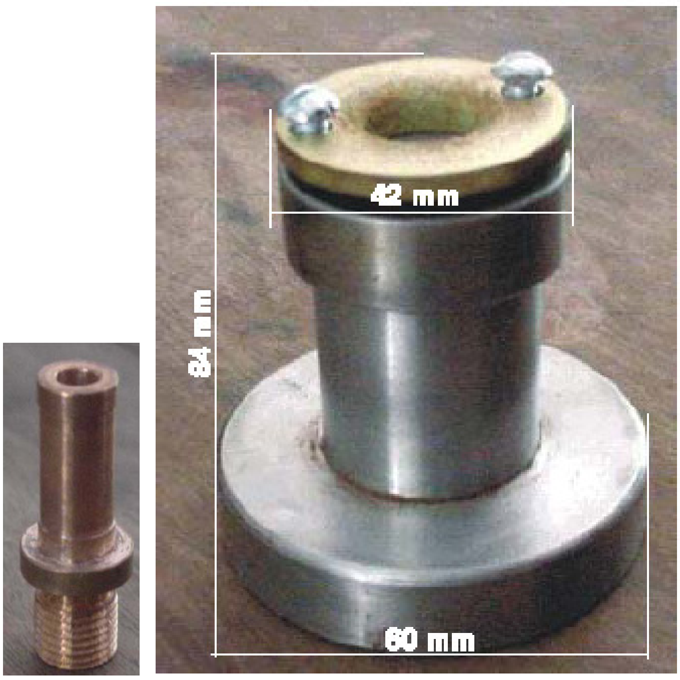

Figure (5). Electrochemical tool (without isolation, left) and support for securing workpiece (right), Silva Neto (2004).

2.3. Machining Parameters

The workpiece was made out of SAE-XEV-S Valve Steel. This steel is used in manufacturing fuel injectors for internal combustion motors. Villares Metals is trying to find an machining alternative method. Chemical composition of this steel is showed on Table (1). Electrolytic solutions were 100 g L^{-1} sodium chloride (NaCl) and 250 g L^{-1} sodium nitride ($NaNO_3$) (Silva Neto, 2004).

Table 1. Chemical composition of SAE-XEV-S Valve 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%

Samples had a thickness of 6 mm. Valve steel was chosen because it has low machinability for conventional processes with significant wear on the tool during cutting. Electrochemical drilling was carried out. Table (2) shows electrochemical parameters for machining the valve steel, where $\mathbf{v_f}$ is feed rate of the tool in mm/min, **Q** is electrolyte flow L h^{-1} and **V** is voltage. Hole diameters were measured with an internal micrometer with 1μm resolution. Forty-eight experiments were carried out using the equipment developed, twenty-four with each electrolyte.

Overcut was calculated by Equation (3), where $\mathbf{D_i}$ is hole inlet diameter and $\mathbf{D_t}$ is tool diameter.

$$Overcut_{inlet} = \frac{D_i - D_t}{2} \tag{3}$$

Table 2. Electrochemical machining parameters

Tests	v_f (mm/min)	Q (L h^{-1})	V (V)
1	0.4	300	10
2	0.5	300	10
3	0.6	300	10
4	0.4	200	10
5	0.5	200	10
6	0.6	200	10
7	0.4	300	15
8	0.5	300	15
9	0.6	300	15
10	0.4	200	15
11	0.5	200	15
12	0.6	200	15

3. RESULTS AND DISCUSSION

3.1. Lateral Overcut Analysis

Overcut is the removal of excess material on the side of the hole. High values can affect accuracy of the workpiece. It occurs because of irregular anodic dissolution of material. Overcut depends on various factors, such as type of electrolyte, tool feed rate, current density, and workpiece material, among others (Rumyantsev and Davydov, 1989).

Figure 6 shows workpieces machined without insulation plates (above) and with insulation plates (below). The workpieces machined without insulation plates had obvious scars in the surface, affecting finish quality. Therefore, these workpieces had larger lateral overcut than those machined with a tool of a different diameter.

Figure 6. Workpieces machined without insulation plates (above) and with insulation plates (below).

Table 3 shows general lateral overcut results. NaCl and $NaNO_3$ electrolytes were used.

Table 3. General overcut results.

Tests	**T (min)**	**Overcut (mm) with NaCl**	**Overcut (mm) with $NaNO_3$**
1	14.12	1.076	0.796
2	12.57	1.235	0.925
3	9.52	1.040	0.891
4	14.07	1.195	0.923
5	12.39	1.174	0.855
6	9.44	0.892	0.765
7	14.15	1.307	1.008
8	12.49	1.494	0.973
9	9.50	1.216	0.962
10	14.19	1.300	0.686
11	12.32	1.355	0.973
12	9.53	1.235	0.944

According to Table (3), electrochemical machining with the electrolyte flow of 300 L h^{-1}, 10V and NaCl, but electrochemical machining with electrolyte flow of 200 L h^{-1} and NaCl, lateral overcut had a tendency to increase in function of tool feed rate increase. This situation is more favorable according the literature (Benedict, 1987) because increasing the tool feed rate can increase surface finish. Figures 7 and 8 show lateral overcut with 200 L h^{-1} and 300 L h^{-1}, 10V and NaCl.

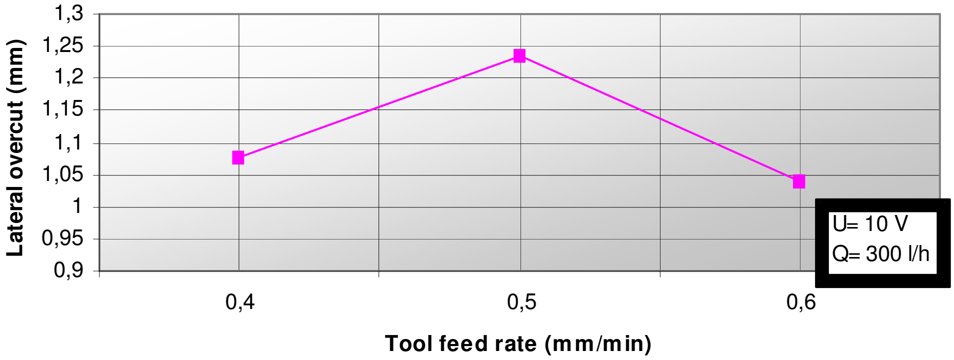

Figure 7. Lateral overcut with 300 L h^{-1}, 10V and NaCl.

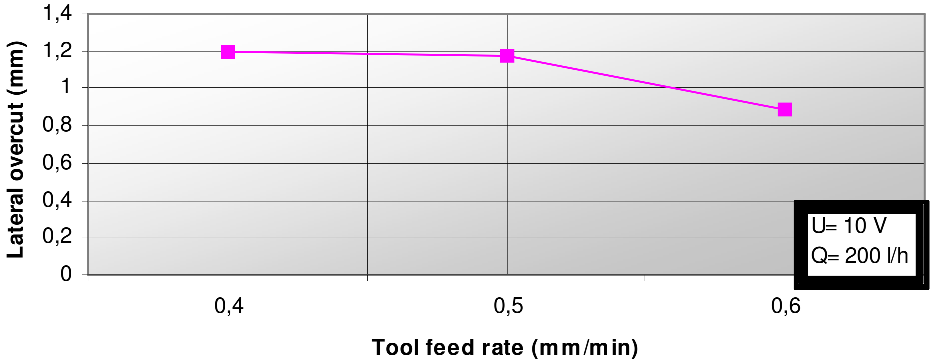

Figure 8. Lateral overcut with 200 L h^{-1}, 10V and NaCl.

In electrochemical machining with electrolyte flow of 300 L h^{-1}, 10V and $NaNO_3$, lateral overcut had a tendency to increase in function of tool feed rate increase. In this case, passivation may have occurred, which is the formation of a thin adherent film or layer on the surface of a metal that acts as a protective coating to protect the underlying surface from further chemical reaction, affecting dissolution. The passive film is very often, though not always, an oxide. A passive film can result in an irregular surface that can affect lateral overcut. During anodic passivation, the current first increases with potential, then falls to a very small value. Figure 9 shows lateral overcut with electrolyte flow of 300 L h^{-1}, 10V and $NaNO_3$.

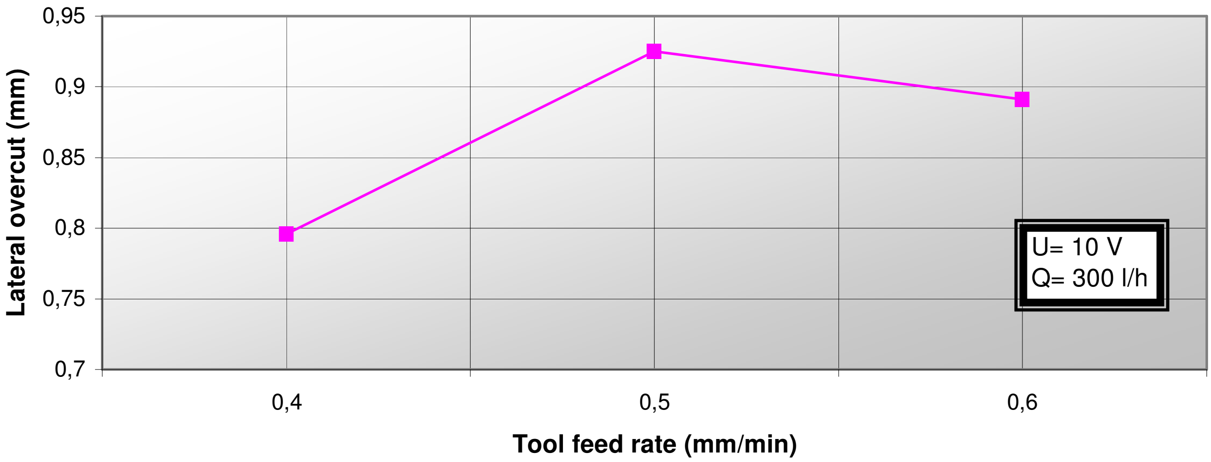

Figure 9. Lateral overcut with electrolyte flow of 300L h-1, 10V and $NaNO_3$.

In electrochemical machining with electrolyte flow of 200 L h^{-1}, 10V and $NaNO_3$, lateral overcut had a tendency to decrease in function of tool feed rate increase. A small deviation of the electrolyte can also occur on the side of the hole. Figure 10 shows lateral overcut with electrolyte flow of 200 L h^{-1}, 10V and $NaNO_3$.

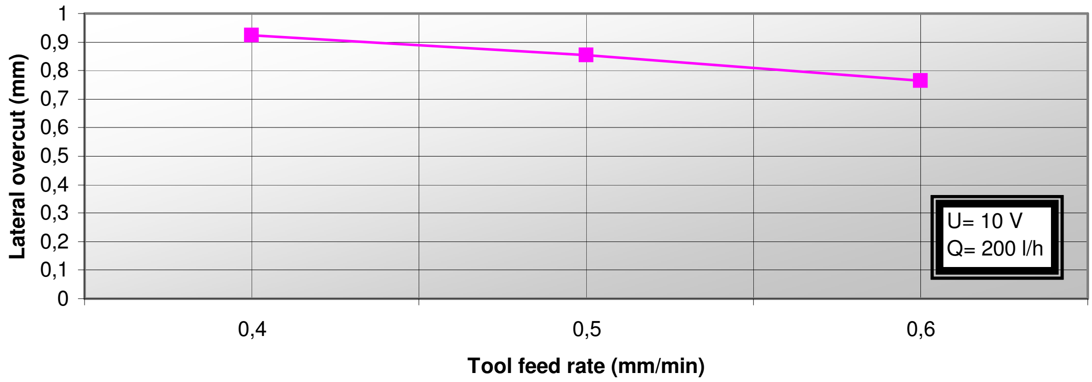

Figure 10. Lateral overcut with electrolyte flow of 200 L h^{-1}, 10V and $NaNO_3$.

In all the tests, electrochemical machining with NaCl had comparatively greater lateral overcut than electrochemical machining with $NaNO_3$. Therefore electrolyte selection is very important to lateral overcut. According to Datta (1993) and McGeough (1988), $NaNO_3$ results in better finish than NaCl. Figure 11 shows comparative results of lateral overcut with NaCl and $NaNO_3$.

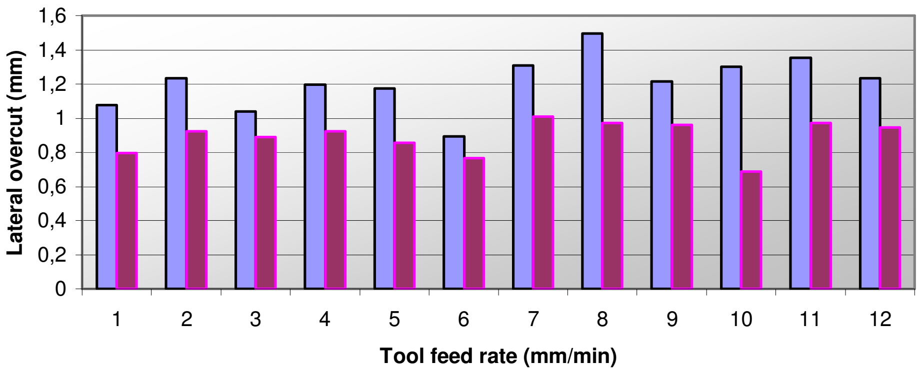

Figure 11.Comparative results of lateral overcut with NaCl and $NaNO_3$.

3.2. Roughness Analysis

Figure 12 shows a very high degree of roughness in the case of NaCl with a lower feed rate. However, for $NaNO_3$, the roughness had a tendency to reduce with feed rate increase. Very low feed rate can provoke irregular material removal and affect the surface finish. This leads to a gap increase and affects material removal and confinement of anodic dissolution in ECM. The term confinement refers to the requirement that anodic dissolution take place solely within the anodic areas separated from the cathode by a small machining gap. If the machining gap is not maintained at the specified minimal value, the shape of the tool won't be accurately duplicated in the workpiece. In this case roughness can be affected.

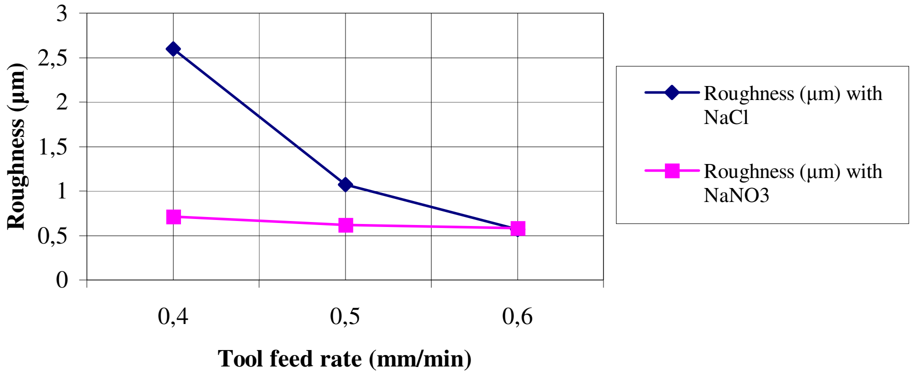

Figure 12. Roughness in function of tool feed rate.

A comparative study of roughness between the two electrolytes verified that in 58% of the tests, NaCl had greater roughness than $NaNO_3$. These results can be seen in Figure 13.

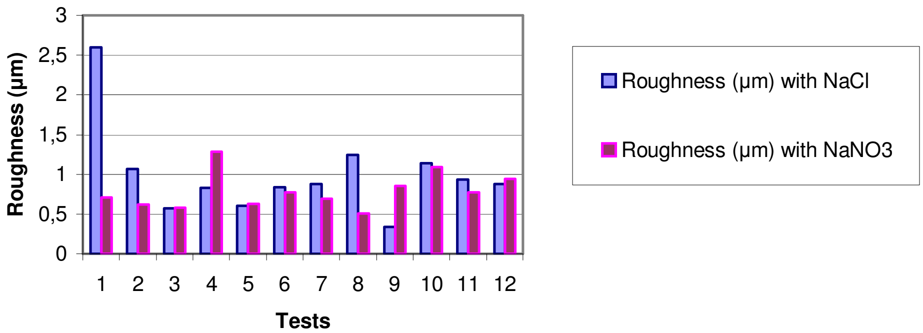

Figure 13. Comparative study of roughness between NaCl and $NaNO_3$

4. CONCLUSIONS

ECM technique removes material by atomic level dissolution of the same by electrochemical action. Thus the material removal rate or machining is not dependent on the mechanical or physical properties of the work material. But many variables affect the process. In this work were making the conclusions:

- This work presented many aspects of the electrochemical machining process;
- Insulation plates can minimize electrolyte jet deviation and prevent lateral overcut;
- Feed rate can affect surface finish;
- NaCl had greater lateral overcut than $NaNO_3$;
- Roughness is very high in the case of NaCl with low feed rate. However, for $NaNO_3$, roughness had a tendency to reduce with feed rate increase;
- ECM accuracy depends on many machining factors.

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