

ECM RIFLING TOOL DESIGN AND MANUFACTURING*

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Abstract– Electrochemical rifling is one of the most effective and well-known methods for barrel rifling in the inner surface of complex shapes. In this research a desirable rifling tool is designed, modeled and manufactured via electrochemical theories. Then the manufactured tool electrode is tested and the theoretical and experimental results are compared with each other. This comparison shows a very good agreement, confirming that the desired processes can be theoretically analyzed via electrochemical basic theories on one hand, and also effective machining parameters determination on the other. This method can easily replace the high cost trial and error methods commonly in practice.

Keywords– Electrochemical machining, simulation, rifling

1. INTRODUCTION

Electrochemical machining (ECM) is a well-established non-traditional manufacturing process nowadays. It is a good and effective method in machining complex shapes [1]. ECM is based on shaping by controlled anodic dissolution with high current density. This process is carried out by passing an electric current through an electrolyte flowing within the inter electrode gap between the tool (cathode) and the workpiece (anode). Since this machining method is achieved by electrochemical reaction, hard and difficult-to-cut materials can be machined effectively [2]. Various variants of ECM like: electrochemical sinking, ECM with numerically controlled tool-electrode movement, ECM with orbiting tool-electrode, pulse ECM, electrochemical deburring and electrochemical polishing are used in industrial practice [3]. Moreover, the surface of the workpiece machined by any of the ECM processes is of high quality and stress free. Therefore, usage of ECM for the production of dies, parts of turbine, high compression engines, medical implants, parts for electronic and military industries, etc. is well justified [3]. The form of the gap, and in particular the dependency on gap from with time and process parameters, can be used to determine process characteristics and to define the shape of the workpiece surface relative to the tool surface [4]. Besides, a new variant of ECM in which a universal tool electrode of simple shape (e.g. flat or cylindrical) moves along the workpiece surface to obtain a required shape with no congruency to the workpiece shape, is developed [5]. Various EC machining methods are characterized by high efficiency and lack of tool wear ratio [6]. Pulsed electrochemical machining (PECM) involves the application of current or voltage pulses instead of DC current or voltage in the ECM process [7]. In recent years, numerous research and development activities have shown that electrochemical micro-machining is a promising technique with flexibilities in micro-electrochemical systems and some advanced manufacturing areas [8]. Although the numerical method is one of the most important ways to optimize engineering problems, it is not the objective method in manufacturing and machining processes [9]. In the

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area of tool design, some numerical analyses have been developed that utilize process parameters to predict a tool-shape from a desired workpiece shape [9]. In this research the inside rifling of a special gun-pipe is under consideration. Broaching is an ordinary and well-known method in rifling, but it is not convenient from the economic and precision points of view since the tool holder and knocking jaws are quickly damaged. This process is very slow with low precision; therefore, it is expensive and a low risk trusting method. Moreover, this method cannot be easily used in trapped places such as the inside surface of a gun-pipe. For these reasons, the electrochemical method, which is the best candidate for manufacturing a rifling tool, is modeled, manufactured and tested in this research.

2. SPECIAL ELECTROCHEMICAL RIFLING SYSTEM

Tests are carried out on EC machine model TC-1C from Hungarian Everite Co. equipped with 1500A rectifier, 16V voltage, 30 bar pump pressure and 5 mm/sec linear speed (Fig.1). The workpiece as a pipe and the tool inside are designed and manufactured. These electrodes are fixed between two chucks (Fig. 2). A supplementary system with special components is designed and manufactured (Fig. 3). Coordinate measuring machine (CMM) is used for dimensional control before and after each test. That is to say that the diameter of the pipe and the depth of the rifle are measured via this system. The samples are cleaned via an aqueous solution of tetra ethylene chloride and dried by pressurized air before machining operation. V-blocks are used to support the testing pipes (Fig. 3a). These V-blocks are made from copper with good electrical conductivity. The testing pipes are pneumatically fixed on V-blocks at two positions. A high pressurized electrolyte is pumped between the gap of the tool and the workpiece during machining operation. Since the strong resulting force may cause the displacement of the pipes, two pneumatic clamping plates are used on the situation of V-blocks to damp vibrations of the pipes (Fig. 3b). A fan belt is used to produce various feeding speeds of the tool so that the rotational motion is transmitted to a gear box via this fan belt, and finally it is converted to a linear motion by a long lead screw and then transmitted to the table of the system. Five pulleys are designed in order to produce five different feeding speeds. The pulleys are made of aluminum alloy and produced by casting method. The template of the system is a long slotted straight edge which is angularly adjustable (Fig. 3c). This template can be tilted in any desirable direction of helical angle. The adjusting angle is the helical angle of the rifle. The angular motion of the tool is provided via a long brass pipe which is moved into the slot of the template. The template with the rack and pinion gear on its carriage provides the desired rotational and linear motions. An aqueous solution of NaCl with a concentration of 120% is used as electrolyte. The basic testing parameters are shown in Table 1.



Fig. 1. Schematic of the ECM system



Fig. 2. Pipe cross section (workpiece) with the tool inside

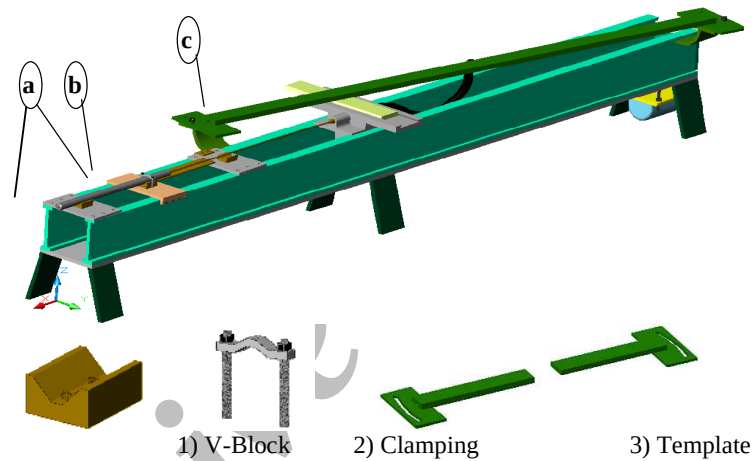


Fig. 3. Schematic view of a special rifling system and its main parts

Table 1. Some setup parameters in machining process

Items	Description	
Mean diameter of tool ($2\bar{r}_0$)	12.40 mm	
Initial diameter of pipe ($2r_1$)	13.02 mm	
Electro-negativity between cathode and anode	-0.78 V	
Tool material	Brass-C28000	
Workpiece material	Steel 1.2726	
Electrolyte	Material	aqueous solution of NaCl
	Concentration	120 g/lit
	Temperature	32°C
	Pressure	25 bar
	Electrical Conductivity	(1/Ω.mm) 0.017
Machining capability of Workpiece	$(K_v)_{\min}$	0.023 (mm ³ /A.S)
	$(K_v)_{\max}$	0.035 (mm ³ /A.S)
	$\bar{K}_v$	0.028 (mm ³ /A.S)

According to the high accuracy and sensitivity of the settle down method of the tool inside the pipe due to the small gap between them, it is necessary to use a special mechanism. This mechanism is a special fixture which is installed on the system after design and manufacturing so that a special ball rail-rolling mechanism is used to prevent the tool electrode from any lateral clearance and contingent contact. In this mechanism, the tool set is fixed on one head of the fixture and then the pipe as the workpiece moves towards the tool along its longitudinal axis to become coaxial with the tool. After inserting the tool inside the pipe, the moving set is fixed by a screw which is located on the chuck casing and moves into a slot. The function of this screw is to inhibit the lateral motion of the pipe while the electrolyte is being pumped. In this system, the tool and workpiece should not be in contact at all, therefore, some parts of the tool are isolated. The details are shown in Fig. 4.

Filter plays a very important role during polishing. According to the high accuracy and sensitivity of the process, filter usage is not avoidable. The analysis of grown up spots, usually at the beginning of the pipe, shows that they are mostly created by the electrolyte. In other words, the problem is the particles of the electrolyte which are brought from an electrolyte tank or from the transmission line and sprayed to the machining gap. The existence of a convenient filtering system at the entrance of the electrolyte into the tool is the only way to solve this problem. An ordinary filter with approximately 0.03 mm mesh is considered to be suitable. Due to the high pressure of the electrolyte into the filter chamber and its serious corrosion, the selection of the shape and the material of this filter is vital. Hence, a bronze cylindrical chamber with a convenient thickness is considered herein. Filtering operation is done by an internal brass strainer which is fixed on a galvanized perforated cylindrical case. When the high pressure electrolyte is forced rapidly through the strainer case, the latter strengthen the strainer against crumpling. The set of the case and strainer with a diameter less than that of the internal housing and with holes on two bottoms is fixed to the internal bottom of the housing as one set with its flank. A bronze disk is tangent to the other bottom of the strainer and the inlet of the filter case is sealed and screwed. In this filter, the electrolyte goes through a hole arranged on the flank of the cylindrical case and reaches the disk center hole after passing through the strainer and the space between the flank of the cylindrical case and the external space of the strainer. The fresh electrolyte is transferred to the polishing zone via some connectors. The designed and manufactured filter is installed at the end of an electrolyte transmission pipe line, and before the entrance of the electrolyte to the back of the tool. The aim for installing such a filter immediately before the tool is to assure that the electrolyte contaminations does not go to the machining zone to prevent spark creation between the tool and the internal surface of the pipe.

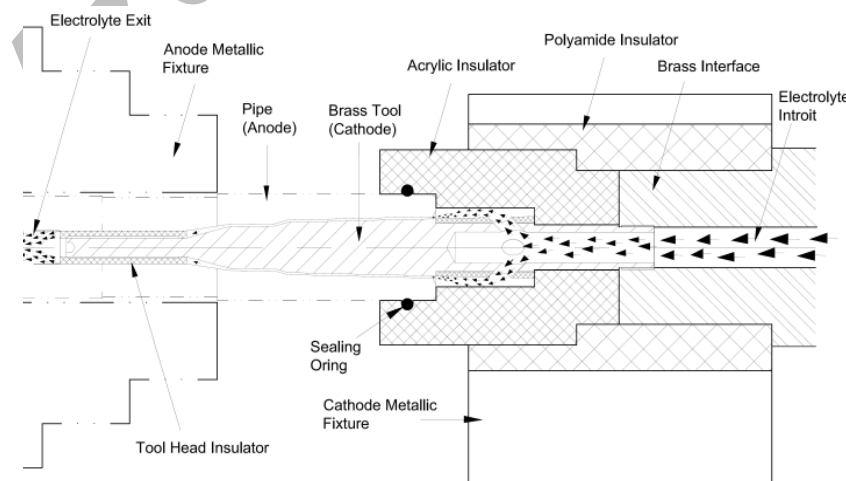


Fig. 4. Method of electrolyte passing through the specially designed fixture

3. GUN-PIPE PREPARATION

Fifty gun-tubes are prepared via a gun drill system for testing. Dimensional measurements and controlling sequences are carried out via CMM before and after each machining operation. The inside diameter of the pipes are to reach 40.06 mm via two reaming steps. To achieve the desirable inner surface finishing of the tubes after drilling, three reaming and two honing operations are necessary. This, herein, is achieved via an electrochemical polishing operation with a special polishing tool before rifling.

4. ELECTROCHEMICAL TOOLS

In order to optimize the output electrochemical machining parameters, the input parameters selection on the one hand and the design with good isolation of the tool on the other hand, are very important [1]. This tool design regarding control of the dimensional accuracy of the workpiece, machining cost and also the flexibility limitation in manufacturing systems, are the major difficulties [2]. Rifling and polishing tools are designed theoretically and practically. In the theoretical step, using basic electrochemical theories and a mathematical model, it is attempted to select the input parameters of the system such that the machining time is minimized. In this case some tool parameters such as its effective length and also its gap with the inner surface of the pipe are determined. In the practical step, according to the desired clearance between the tool and the pipe in rifling and polishing operations, some other tool parameters such as geometrical positioning are also defined. There are two rifling and polishing sets of tools. The main brass body of the tool is engaged in machining operation (Fig.4). In order to have a closed clearance between the tool and the inner surface of the pipe, and also to prevent some areas of the tool's body from machining operations, the two ends of this tool are isolated (Fig.4). The main brass body and isolated parts are prepared after various machining operations. Electrolyte can pass through the center line axis of the tool and reach the machining gap via some holes which are provided on the rear of the tool's tail. On the rear of the tool, two sealing o-ring slots are established to prevent the flow of the electrolyte to the rear part of the tool (Fig. 4).

a) Polishing tool

The inside of the gun-pipe is out of view and its surface finishing quality has to be high. The main body of the tool is brass with two acrylic ends which are prepared under turning, drilling, threading and grinding operations (Fig. 5). The main middle part of the tool, used as the machining tool section, is ground. Then, the isolated parts are assembled on the ends of the main body, and in order to fit inside the pipe are ground to 0.01 mm precision. Finally, the exhaust electrolyte holes are provided via a coordinate milling machine. Eight holes are drilled around the pipe to exhaust the electrolyte (see Fig. 5a). The machining depth is considered to be 0.62mm; therefore, the outer diameter of the plastic insulator bush on the head of the tool will be equal to the final inner diameter of the pipe (see Fig. 5b-3). This is due to the needed close fitness between the tool and the pipe. This section of tool is a hexagonal part with six electrolyte exhaust slots. This fitness is very important, otherwise the free end of the tool will vibrate and the inner diameter of the pipe will be out of precision.

b) Rifling tool

The manufacturing process of a rifling tool is the same as a polishing one. Helical grooves with very high accuracy are made on the main body of the tool. Therefore, the inside surfaces of these grooves are isolated (Fig. 6). Due to the complexity of the tool, its isolation is very difficult. In isolation, by coating method the protection of the machining section of the tool against the coating operation is not easy since the form of the grooves are helical. The best method of isolation is using plastic parts and assembling them on the tool (Fig. 6b). This isolation is done via a number of bushes and some belt-type pieces and

also two plastic nuts. These belt-type pieces are fixed into the helical slots and the remaining portions that have to be machined are on the outside of the slots. Then, a combination of the main body, bushes on the tails of the tool and plastic nuts on its ends are matched. It is noteworthy that the outer diameter of bushes and also the upper surfaces of the belt-type pieces are sized by grinding after the assembly. The profile section of the pipe with eight rifles is shown in Fig. 7. In this figure the main parameters are as follows:

B: The width of rifle

Φ_1 : Inner diameter of rifle

Φ_2 : The diameter of the rifle at the bottom

$a = (\Phi_2 - \Phi_1)$: Machining depth

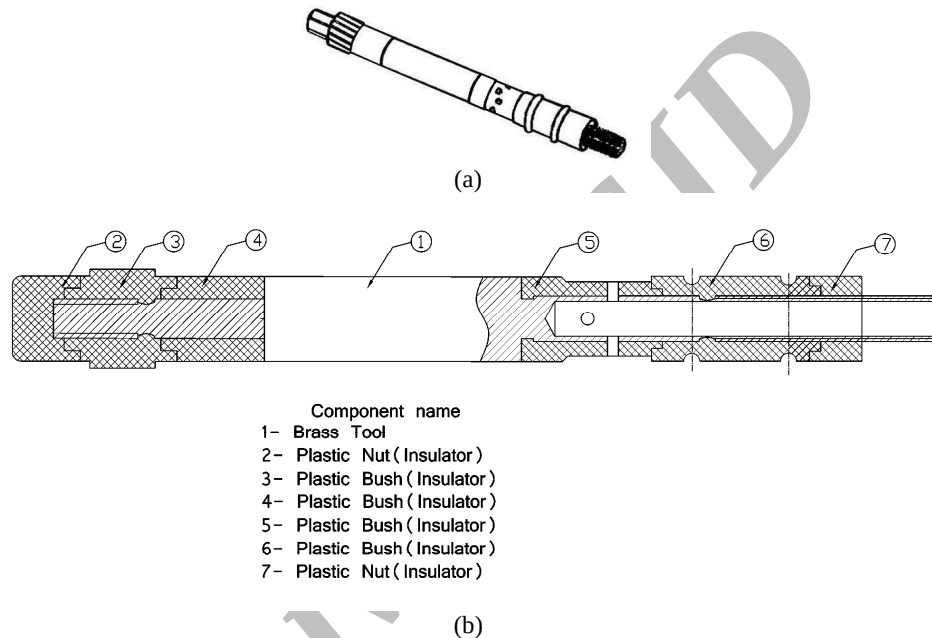


Fig. 5. Three dimensional (a) and assembled (b) models of electro polishing tool

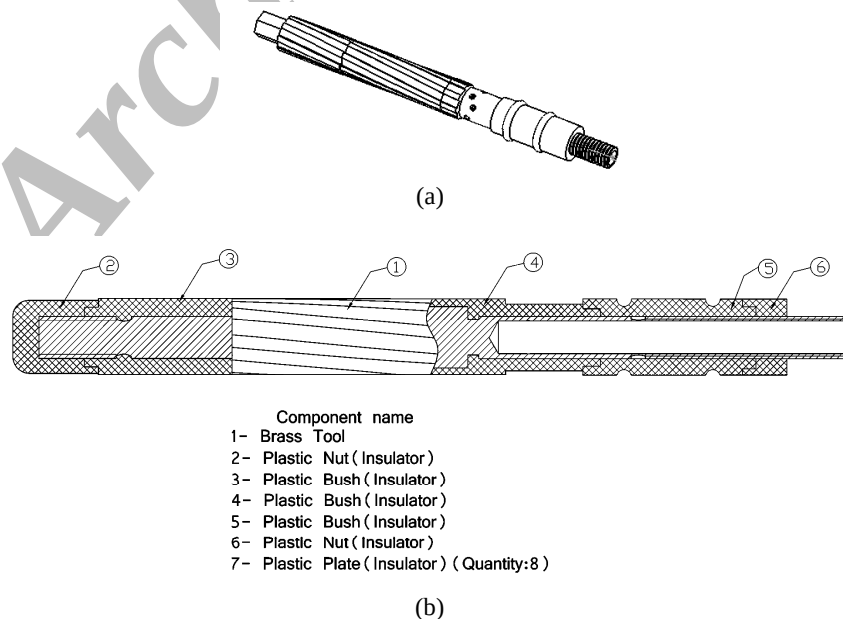


Fig. 6. Three dimensional (a) and assembled (b) models of rifling tool

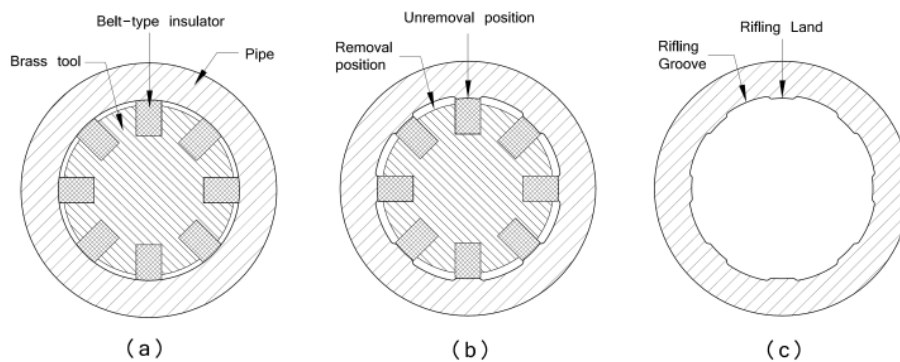


Fig. 7. The cross sections (a), (b) and the profile of the rifled section of the tool

5. RIFLE'S DEPTH CALCULATION

In order to theoretically calculate the depth of the rifle two methods can be used; 1) The method based on simulation and modeling. 2) A new method based on theoretical calculations. The second method is developed herein and is compared with the first one. The general characteristics of the process are shown in Table 1. Since the surface between slots which have to be machined are small in depth and length, the effect of hydraulic parameters, electrolyte temperature variations and also hydrogen bubbles creation can be neglected. In the rifling process with electrochemical machining the tool moves with respect to the pipe. In this method it is assumed that the starting point of the machining is where the non-machined length of the tool reaches a special point inside the pipe. The location of this point can be wherever the inside of the pipe in which the remaining portion of the pipe is larger than that of the tool. From this point, the machining starts and continues until the end of the rifling section passes through this point. This is called the start and the end of the machining process. The machining time can be changed with the linear motion of the tool. Hence, when the feed speed of the tool increases, the machining time decreases and vice versa. The effective machining length of the tool is 60mm, and due to its linear speed variation the machining time can be calculated. Calculations and theoretical analysis are based on the Laplace's equation, Ohm and Faraday's laws of electrolysis. According to the Laplace's equation

$$\nabla^2 u = 0 \rightarrow \text{Div}(\text{Grad } u) = 0 \quad (1)$$

By solving this equation the value of potential u can be determined at any electrolyte point, especially on electrode surfaces. The boundary conditions are as follows (Fig. 8):

$u = 0$ on the surface of the tool (Cathode)

$u = V = U - E$ on the surface of the pipe (Anode)

where V , U and E are effective potential, the voltage between two electrodes that supply via rectifier of the system and electro-negativity of the electrodes respectively. This electro negativity can be calculated as follows:

$$E = E_a - E_c \quad (2)$$

where E_a and E_c are the electro negativity of anode and cathode electrodes.

The current density on the pipe can be calculated after the determination of the voltage, so that [2]:

$$i_A = -K_e \nabla u \quad (3)$$

where K_e is the electrical conductivity of the electrolyte. The machining rate can be also calculated from the following equation:

$$\dot{r}_a = \frac{A i_A}{Z F \rho_a} \quad (4)$$

where, i_a , A , Z , ρ_a and F are atomic mass, atomic number, the density of anode and Faraday's constant respectively. As the electrodes are cylindrical, in order to solve the equations the cylindrical coordinate system is used. The machining is done in radial direction and the normal gap is defined as:

$$d = r - r_0 \quad (5)$$

where r and r_0 are the radius of the points on the inner surface of the chamber and the radius of the tool respectively. In order to determine the current density on the surface of the workpiece a linear approximation of the electrical potential distribution can be used along the machining gap, so that:

$$i_A = K_e \frac{U - E}{d} \quad (6)$$

The following equation can be used to determine the variations of r [1]:

$$\frac{\partial r}{\partial t} = K_e K_v \frac{U - E}{r - r_0} |\text{grad } r| \quad (7)$$

where K_v is the electrochemical machinability coefficient. In cylindrical coordinate this equation can be written as follows:

$$\frac{\partial r}{\partial t} = K_e K_v \frac{U - E}{r - r_0} \sqrt{\left(\frac{\partial r}{\partial r}\right)^2 + \left(\frac{1}{r} \frac{\partial r}{\partial \theta}\right)^2 + \left(\frac{\partial r}{\partial Z}\right)^2} \quad (8)$$

In this polishing condition, the tool electrode is fixed into the pipe without any movement. Besides, the machining rate is constant in all radial directions. Therefore, this equation can be simplified as follows:

$$\frac{dr}{dt} = K_e K_v \frac{U - E}{r - r_0} \quad (9)$$

The solution of this equation is:

$$\begin{aligned} (r - r_0) dr &= K_e K_v (U - E) dt \\ \int_{r_1}^r (r - r_0) dr &= \int_0^t K_e K_v (U - E) dt \\ \left. \frac{1}{2} r^2 - r_0 r \right|_{r_1}^r &= K_e K_v (U - E) t \Big|_0^t \\ r^2 - 2r_0 r + (2r_0 r_1 - r_1^2 - 2K_e K_v (U - E) t) &= 0 \\ r &= r_0 \pm \sqrt{r_0^2 - (2r_0 r_1 - r_1^2 - 2K_e K_v (U - E) t)} \end{aligned} \quad (10)$$

Since $r > r_0$ then:

$$r = r_0 + \sqrt{r_0^2 - (2r_0 r_1 - r_1^2 - 2K_e K_v (U - E) t)} \quad (11)$$

Let $C = K_e K_v (U - E)$, where C is $\text{m}^2 \text{s}^{-1}$, the machining constant for the set of workpiece and electrolyte, then

$$r = r_0 + \sqrt{r_0^2 - (2r_0 r_1 - r_1^2 - 2C t)} \quad (12)$$

Using this equation the radius of the rifle at the bottom (r) is determined and then the machining depth can be calculated. According to the Eqs. (5) and (12), to determine the depth of the rifle two conditions can be considered; 1) The feed speed of the tool is variable. 2) The feed speed of the tool is constant. In the latter case the electrical voltage is variable, but the machining time is constant. In the former case the electrical voltage of the system is 10 V, therefore, the feed speed of the tool is as follows:

$$V_p = \frac{L}{t} \quad (13)$$

where L is the length of the tool, 60 mm, and V_p and t are the linear speed of tool (mm/sec) and machining time (sec), respectively. Figure 9 shows the variations of the rifle's depth with the linear speed of the tool.

In the latter case, the depth of the rifle is determined with various values of voltages so that the linear speed of the tool is equal to 4.97 mm/sec, which is calculated according to the following equation:

$$V_p = npN \quad (14)$$

Where n is the speed of the motor drive shaft 940 rpm, p is the pitch of this shaft 6.35mm and N is gear box ratio 1/20. This value is equivalent to the machining time of 12.08 sec, which is determined experimentally as the optimum machining time. Figure 10 shows the rifle's depth variation with the electrical voltage.

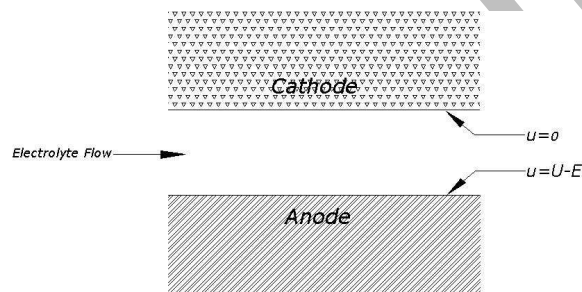


Fig. 8. Schematic of electrochemical machining process

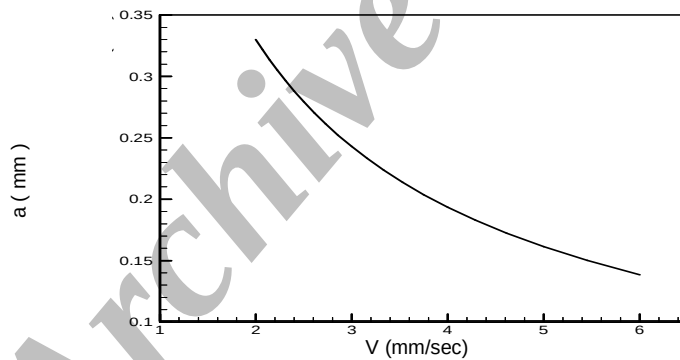


Fig. 9. Rifling depth variations with linear speed of the tool

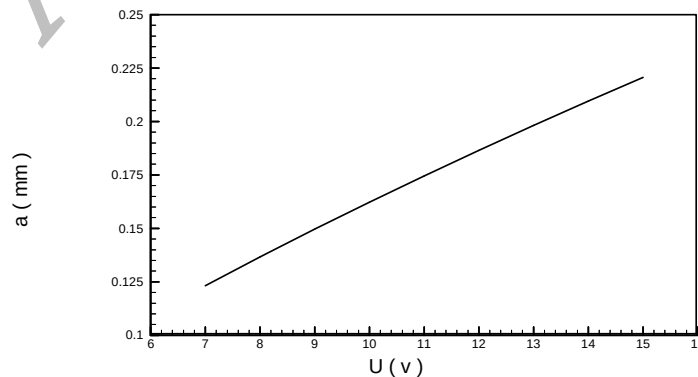


Fig. 10. Rifling depth variations with the electrical voltage

6. EXPERIMENTAL PROCEDURES

a) General conditions

The control of testing conditions during machining operations is very important. The temperature and the density of the electrolyte should be controlled and fixed throughout the tests. The inner surfaces of the pipe in rifling and polishing before and after any process should be clearly cleaned with suitable chemical liquids first, and then emerged into hot and cold water to make sure that the machining contaminations are removed. It is also necessary that the inner surface of the pipes be completely dried after machining operations. It is also necessary, especially in the polishing process, that the inner surfaces of the pipes be clearly degreased after machining operations.

b) Experimental rifling tests

Ten samples of pipes are polished under 1320 A current, 12.5 V voltage and 3 mm/sec linear speed conditions which come from the technical map of the rifle (Fig. 11). The polished samples are dimensionally controlled and their surface roughness are desirable (Fig. 11). In order to optimize the rifling parameters, twenty trial and error tests have been carried out, and these parameters for desired rifling conditions have been obtained. In this step and after rifling, the test procedure for dimensional and surface finishing has been carried out similar to the previous tests for polishing. The width of the rifles has been measured via a pantograph system and the shape of rifles is drawn with 50 times magnification. These shapes are transferred to the Mechanical Desktop 6 area after scanning and then are measured (Fig. 11). The comparison between experimental and theoretical results is shown in Table 2. It is noticeable that the linear speed of the tool and the surface finishing quality are the most important parameters in rifling. From this point of view, 4.97 mm/sec and 10 V are the optimized linear speed and electrical voltage, respectively, in this research.

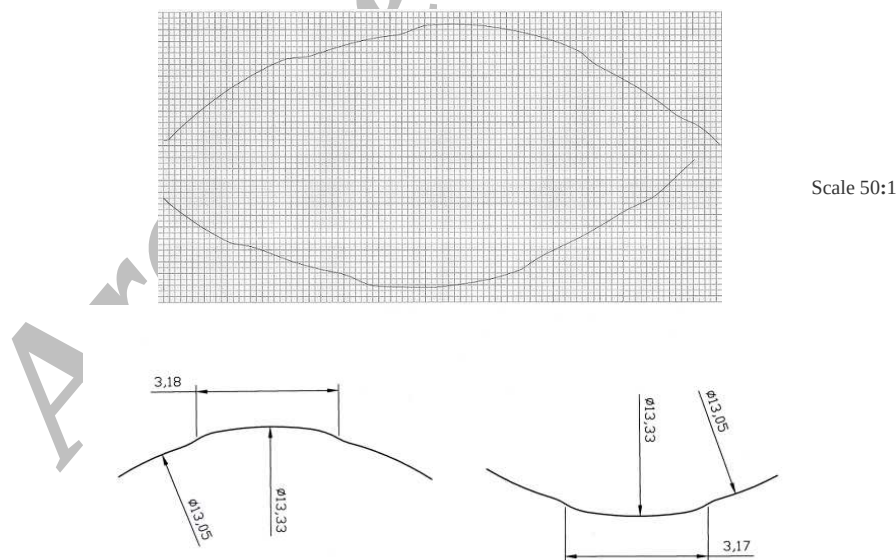


Fig. 11. The graphs obtained from traverse section of rifles and their CAD simulated

Table 2. Comparison between various output parameters in rifling

Voltage (V)		8.5	9.25	10	11.5	14
Rifling depth (mm)	Solution 1 (Computer simulation)	0.142	0.151	0.160	0.178	0.207
	Solution 2 (Electrochemical theories)	0.143	0.152	0.162	0.174	0.209
	Experimental data	0.135	0.150	0.165	0.174	0.215

7. DISCUSSION AND CONCLUSION

In this research a rifling tool is designed and manufactured according to electrochemical basic theories. The results are compared with those of simulation and experimental methods. The linear speed of the tool and the depth of the rifles are compared with the results of simulation and experimental methods. The linear speed of the tool and also the depth of the rifle, as two major machining parameters, were under consideration. Increasing the linear speed of the tool decreases the machining depth (Fig. 9). This increasing causes the reduction in machining time and subsequently decreases the machining depth. It can be inferred that increasing the voltage decreases the machining depth (Fig. 10). The theoretical and experimental rifling depth variations are shown in Figs. 12 and 13. Comparison between the two shows a difference in the range of 0-0.025mm. The tolerance domain for this depth, as indicated in Fig. 12, is 0.06mm. This difference is very small and can be neglected. This means that the theoretical and experimental values are almost the same. The error could be due to: 1) Reading voltage and current values from analogue systems are not precise. 2) Different linear speed of the tool is obtained via the variations in the gearbox and also transmission speed pulleys from the motor to gearbox. This speed is calculated via the measurement of the distance and time which have their own cumulative errors. 3) The spiral shape of rifling depth is complex and the measurement of these slots is prone to errors. 4) The setting up of some machining parameters such as the density and the temperature of electrolyte and their control during the machining process. Two theoretical and one experimental result show a very good agreement (Fig. 12 and 13).

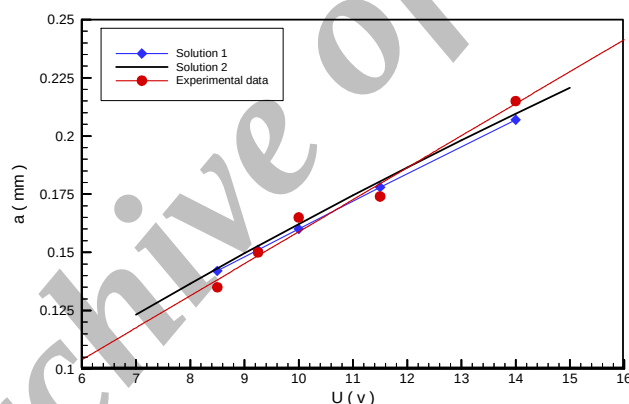


Fig. 12. Rifling depth variations with electrical voltage according to; Computer simulation (solution 1), Electro chemical theories (solution 2), Experimental results

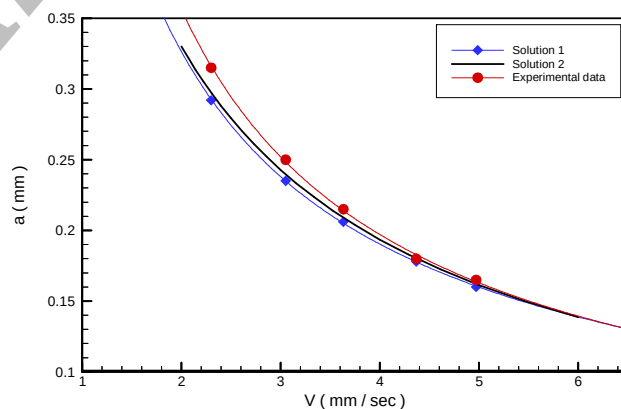


Fig. 13. Rifling depth variations with linear speed of tool according to; Computer simulation (solution 1), Electro chemical theories (solution 2), Experimental results

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