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Designing, Building and Testing of an Electropolishing Cell

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Abstract: During the work of this research, designing, building and testing of an electropolishing cell has been carried out. Various tests have been performed for three different materials namely, steel, aluminum and brass at different environment conditions in order to a better evaluation of electropolishing. These conditions include the effect of concentration of electrolytes, electrolytes temperature, power supplied and machining time. The results of these tests have been analyzed and performance curves have been drawn. The optimum temperatures and the optimum time have been obtained at which the maximum metal removal and the best surface quality is achieved. These temperature and time for Aluminum, Brass and Steel are T = 60, 50 and 75°C, t = 20, 40 and 50 min, respectively. Surface roughnesses of the specimens have been measured before and after electropolishing. The results showed a significant improvement that effect positively on strength, fatigue resistance and corrosion resistance. Many important conclusions have been extracted from these performance curves and some recommendations have been noted to help in future works.

Key words: Electropolishing, metal removal, surface roughness, concentration, temperature and optimum time

INTRODUCTION

Electropolishing (EP) is normally used to remove a very thin layer of material on the surface of a metal part or component. The process is of interest because of its ability to enhance the material properties of a workpiece in addition to changing its physical dimensions. Therefore, by means of electropolishing, the machining stress produced by grinding and the surface particles resulting in fatigue can be removed, so that the fatigue state of the metal surface is changed. It is obvious that electropolishing increases the machine element life and its effective efficiency is higher than that of machine grinding. EP produces a number of favorable changes in a metal part, which are viewed as credible benefits. These include: brightening, burr removal, total passivation, oxide and tarnish removal, reduction in surface profile, removal of surface occlusions, increased corrosion resistance, increased ratio of chromium to iron, improved adhesion in subsequent plating, reduced buffing and grinding costs, removal of directional lines, radiusing of sharp edges, reduced surface friction, stress relieved surface and removal of hydrogen (Wu *et al*., 2007; Kalpakjian and Schmid, 2007). According to Durkee (2003), another advantage of electropolishing can be raised. He said, EP can be considered as the ultimate cleaning technique. What he called the combination of removal of imperfection like stains and surface corrosion, heat discoloration, oxide films, localized stresses, weld mark, scratches, particles of all sizes, organic films and biological debris. An EP treatment removes the surface and everything which is on, or in it. Naturally, any debris on the surface removed as well. That's how the cleaning is done.

EP has many applications in industry. Long list of applications can be extract form open literature (Landolt *et al*., 2003; Hollywood, 2006; MPC, 2007; Kalpakjian and Schmid, 2007; Yu *et al*., 2007). As a summery from these references, EP can provide services for a wide range of industries, including: aerospace, biotechnology, cryogenics, food and beverage processing, foundries, hydraulics, marines, medical, nuclear, petrochemical, pharmaceutical, semi-conductor, waste water systems and vacuum technology. It can be used with a wide range of systems, sizes and shapes that includes air-sampling canisters, bolts and fasteners, clean-room equipment, filters, gas delivery systems, gears, hardware, heat-exchangers, investment castings, medical implants, pumps, pressure vessels, springs, stampings, surgical instruments, tanks, tubing and pipes, vacuum chambers, valves and fittings, water purification systems and wire products (Hollywood, 2006).

Almost any metal can be electropolished (Lee and Lai, 2003; Hu *et al*., 2003; Kao and Hocheng, 2003; Guo and Johnson, 2004; Jones, 2004; Andrade *et al*., 2005; Wynick and Boehlert, 2005; Aspart *et al*., 2006; Fushimi *et al*., 2006; Abbott *et al*., 2006; MPC, 2007). The metal can be ferrous or non-ferrous. Typical listings of metals and alloys that can be electro polished are shown in Table 1 with some practical limitations.

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Table 1: List of metals and alloys that can be super-finished by EP

Aluminum non-silicon and wrought	Hastelloy alloy	Nickel silver	Stainless steels	Titanium	Steels
Beryllium-copper alloys	Gold	Bronze	Copper	Brass	Nickel

The aim of this research is to study of an electropolishing Cell (EPC). This study explain the theory of electropolishing process that includes the basic principles and the general steps of the process. A simplified view of the theory has been presented that includes the mechanisms, problems, quality control and costs. The third section deals with the experimental setup and how the rig has been prepared in order to get the required results. These results are explained in details in the fourth section with there performance curves and the optimum values of temperature and time. Finally, the conclusion and discussion are presented in the last section and some recommendations have been given.

THEORY OF ELECTROPOLISHING (EP)

EP is the electrolytic removal of metal in a highly ionic solution by means of an electrical potential and current. EP is normally used to remove a very thin layer of material on the surface of a metal part or component. EP is often referred to as a reverse plating process. Electrochemical in nature, EP uses a combination of rectified current and a blended chemical electrolyte bath to remove flaws from the surface of a metal part. The typical EP installation is deceptively similar to a plating line. A power source converts AC current to DC at low voltages. A tank typically fabricated from steel, glass and rubber-lined is used to hold the chemical bath. A series of lead, copper or stainless steel cathode plates are lowered into the bath and installed to the negative (-) side of the power source. A part or groups of parts are fixtured to a rack made of titanium or copper or bronze. That rack in turn is fixtured to the positive (+) side of the power source. As the adjoining illustration depicts, the metal part is charged positive (anodic) and immersed into the chemical bath. When current is applied, the electrolyte acts as a conductor to allow metal ions to be removed from the part. While the ions are drawn towards the cathode, the electrolyte maintains the dissolved metals in solution. Gassing in the form of oxygen occurs at the metal surface, furthering the cleaning process. Once the process is completed, the part is run through a series of cleaning and drying steps to remove clinging electrolyte.

The amount of change to the metal is highly dependent upon the metal itself and how it has been processed up to the point where it is electro polished. The EP effect occurs because as the current is applied, the EP film at the surface of the metal changes its characteristics. As the current is applied to the workpiece, the EP solution becomes thicker and becomes an insulator or resister. During electrolysis, the thickness of the salt film forming on the workpiece surface varies with the surface aspect, i.e., the film at raised parts is thin, but is thick at dented parts. The surface is smooth because the dissolve rate of raised parts is faster than that of dented parts. At the same time, an oxide film is generated on the machined surface. This film has certain stability and makes the surface be in the lightly passivating state. Then, the machined surface is bright. The resultant surface is clean and bright. The quantity of metal removed from the workpiece is proportional to the amount of current applied and the time. Other factors, such as the geometry of the workpiece, affect the distribution of the current and, consequently, have an important bearing upon the amount of metal removed in local areas (Hocheng and Pa, 2000, 2002, 2003). Figure 1 shows both high and low current density areas of the same part and notes the relative effects of electropolishing in these two areas (Roy *et al*., 2007; MPC, 2007). The principle of differential rates of metal removal is important to the concept of deburring accomplished by electropolishing. The optimum combination of quality, effectiveness and cost can be found by the proper control of the electrolytic process parameters. Fine burrs become very high current density areas and are, subsequently, rapidly dissolved. Low current density areas receive lesser amounts of current and may show negligible metal removal. The general relationship between applied current and voltage for a typical electropolishing system is shown in Fig. 2. An understanding of the combined effects of current and voltage is a key to the production of high quality electropolishing.

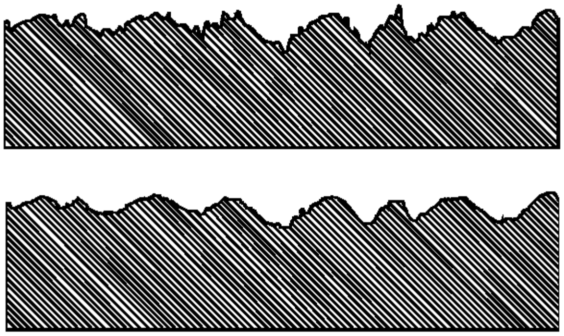


Fig. 1: The variation of the surface texture before and after electropolishing (MPC, 2007)

In the course of electropolishing, the workpiece is manipulated to control the amount of metal removal so that polishing is accomplished and, at the same time, dimensional tolerances are maintained. EP literally

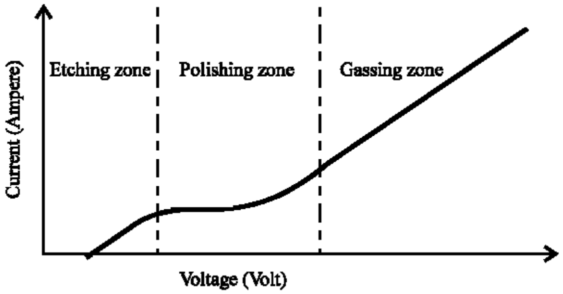


Fig. 2: General relationship between current and voltage in (MPC, 2007)

dissects the metal crystal atom by atom, with rapid attack on the high current density areas and lesser attack on the low current density areas. The result is an overall reduction of the surface profile with a simultaneous smoothing and brightening of the metal surface (MPC, 2007).

To obtain high quality electropolished finishes on most material, it is necessary to process the work through three major operations [more details can be found in (MPC, 2007). These three stages are including metal preparation, electropolishing and post treatment. The aim of the first stage is to remove surface oils, greases, oxides and other contaminants, which interfere with the uniformity of electropolishing. The second stage is designed to accomplish the desired smoothing, brightening and/or deburring of the metal, followed by recapture of the electrolyte to minimize waste treatment. The final stage is to remove residual electrolyte, to remove by products of the electropolishing reaction and to dry the metal to prevent staining.

EP is performed through few controlled mechanisms. These mechanisms work simultaneously in the electropolishing process. A change in any single mechanism can affect the results of the process (MPC, 2007). These mechanisms include; Chemical Saturation Effect, Lightning Rod Effect, The Viscosity Effect, The Osmosis Effect, Gas Mixing/Pump Effect and the Parabolic Mirror or Deep Cone Effect.

The principal chemical reaction occurring at the electrical anode, that is, at the workpiece, is as follows:

$$\text{Metal-electrons} \rightarrow \text{Metal ions} \quad (1)$$

The chemical reaction at the Anodic (+Electrode) is as follows:

$$4(OH)-4(e) \rightarrow 2H_2O+O_2 \quad (2)$$

And the reactions at the Cathodic (- Electrode) are:

$$\text{Metal Ions} + \text{electrons} \rightarrow \text{Metal} \quad (3)$$

$$2H^+ + 2(e) \rightarrow H_2 \quad (4)$$

These reactions state that metal is dissolved from the anodic electrode, passing into the solution to form a soluble salt of the metal.

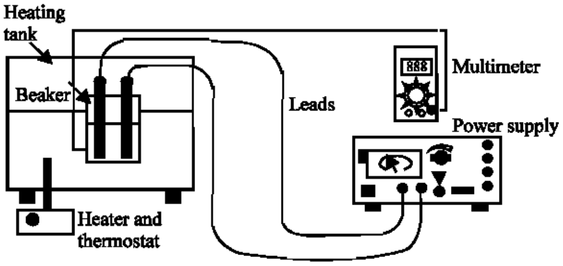


Fig. 3: The designed electropolishing cell

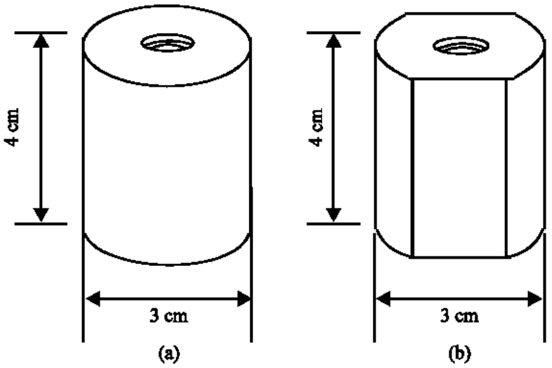


Fig. 4: The dimensions and shape of the two types of work piece

EXPERIMENTAL SETUP

The experimental rig has been designed in a way that allows the user to change the process variable to elaborate their effect on the process in addition to perform the process it self. The designed and manufactured EPC, as any standard cell, consists of the following components (Fig. 3).

Work piece (Anode): This part is the work piece of metal that is being electropolished. This piece of metal is connected to the positive pole of the electrical power supply. The origin shape of this work piece is a vertical cylinder of 30 mm diameter and of 40 mm height as shown in Fig. 4a provided with a threaded hole in order to be fixed to the equipment via a threaded rod. Some of these specimens have been cut, as shown in Fig. 4b, in order to simplify the measurement of roughness.

Cathode: This part is connected to the negative pole of the power supply to receive the metal ions that are

Table 2: The electrolyte that used with each material

Material	Electrolyte
Aluminum	Sulfuric acid (H_2SO_4)
Brass	Phosphoric acid (H_3PO_4)
Steel	Mixing of (H_2SO_4) and (H_3PO_4)

machined from the work piece. The cathode is made out of a shaped in such way to provide even current densities to the work piece surface.

Electrolytes: The Electrolyte is the ionized liquid that provides the right environment to perform the electropolishing chemical reactions that transfer material from the work piece. The different electrolytes that used with each materiel is the recommend one and as indicated in Table 2.

Heating Tank (Container) and Heater: It makes of PVC material with a volume of 96 L (40×40×60 cm). The tank filled with pure water that used to heat the Beaker. A 1 KW heater is used to heat the water within the range 0-80°C. The power and control of this heater is controlled with a thermostat.

Beaker: This glass beaker (scaled from 0-5 L) is located inside the heating tank. Only this beaker has been filled by the electrolytes at this stage of experiments.

Power supply: This equipment supply the cell with a direct current (DC) in the range (0-27.5) Amperes and a voltage between (0-12).

Multi-meter and roughness-meter: These calibrated stranded measuring devices are used to monitor the different required parameters.

RESULTS

The results have been classified into three categories according to the material to be electropolished. Experiments have been carried out for three materials, namely, Brass, Steel and Aluminum. Each of these three materials has been tested under three different operated parameters namely the process time, temperature and concentration of electrolyte. The following is the main results from these runs.

Category 1: The Brass specimen: The brass specimens have been tested under two parameters which are processing time and the temperature. The results of these tests are shown in Fig. 5. and parts of Fig. 6 and 7. It's noted at this stage that the surface finish improved significantly with time until reaching 40 min which considered as the optimum time. At the other hand, the optimum temperature, when it's the only variable, has been found to be around 50°C.

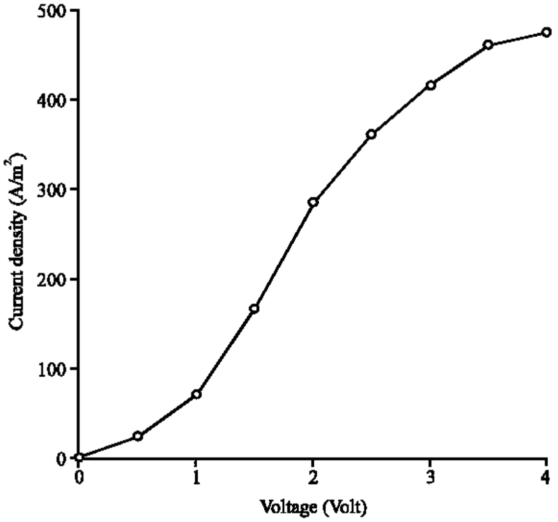


Fig. 5: Effect of applied voltage on the current density for Brass (T = 30°C)

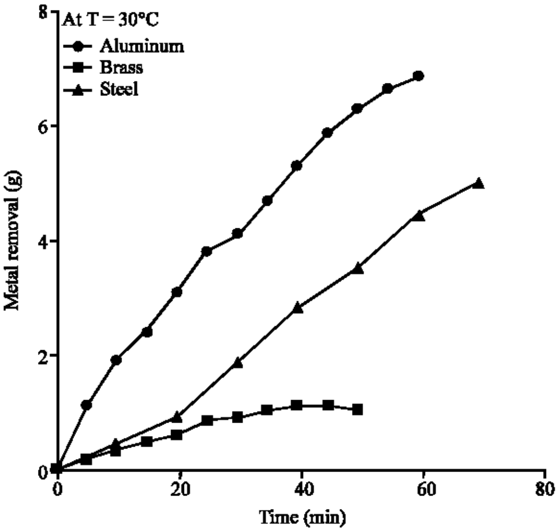


Fig. 6: Effect of the processing time on the metal removal quantity for all materials (T = 30°C)

Category 2: The Aluminum specimen: Similar tests are performed for Aluminum. The results of these tests are shown in Fig. 6-9. It's noted at this stage that the surface finish improved significantly with time until reaching 20 min which considered as the optimum time. The optimum temperature, in this case, is found to be around 60°C as shown in Fig. 8. The effect of the concentration of the electrolyte is tested and the result is shown in Fig. 9 which found in the range of expectations.

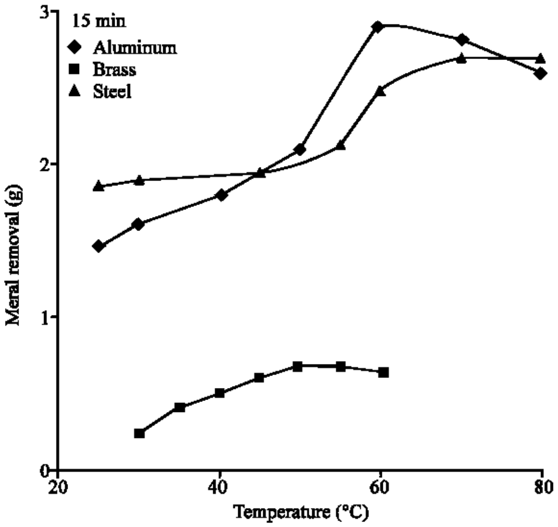


Fig. 7: Effect of the temperature on the metal removal quantity for all materia (Time = 15 min)

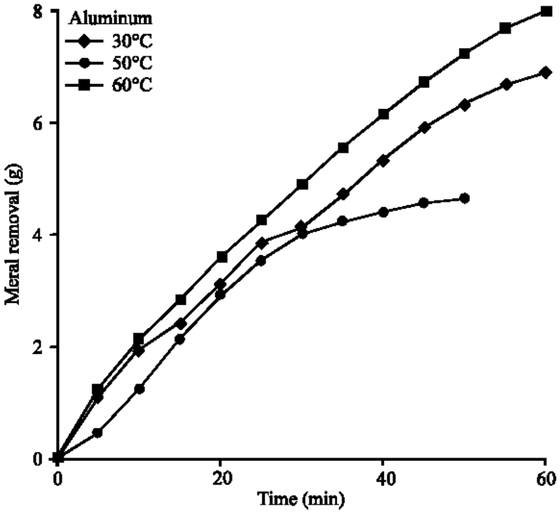


Fig. 8: Effect of the processing time on the metal removal quantity for aluminum at different temperatures

Category 3: The Steel specimen: The steel has been tested under the same parameters, also and the results obtained shown in Fig. 6, 7 and 10. It's noted, here, that the surface finish improved significantly with time until reaching 50 min which considered as the optimum time. The optimum temperature, when it's the only variable, is around 70°C.

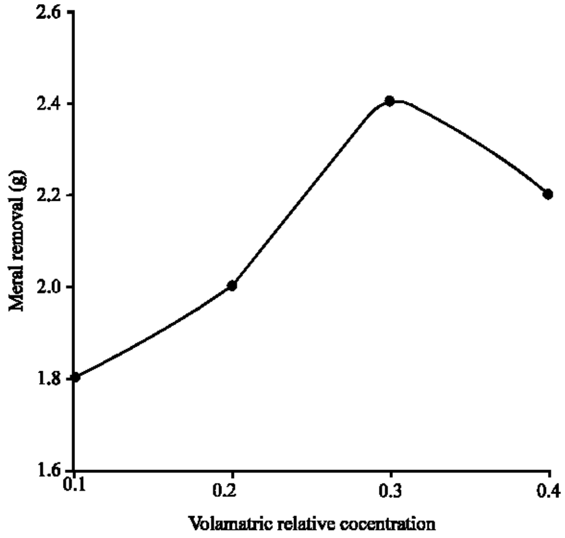


Fig. 9: Effect of the acid concentration on the metal removal quantity for aluminum at (T = 30°C and time =15 min)

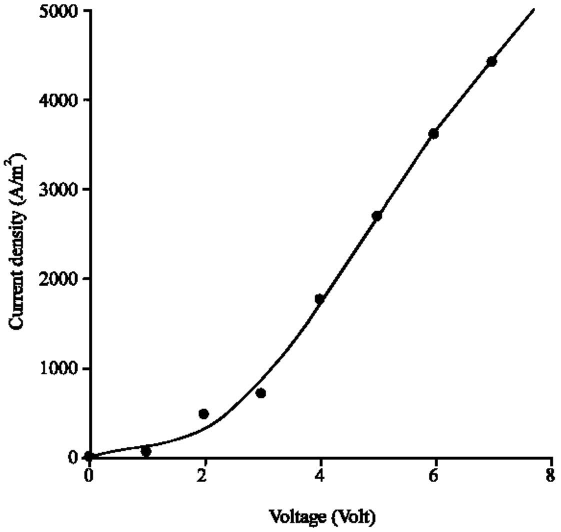
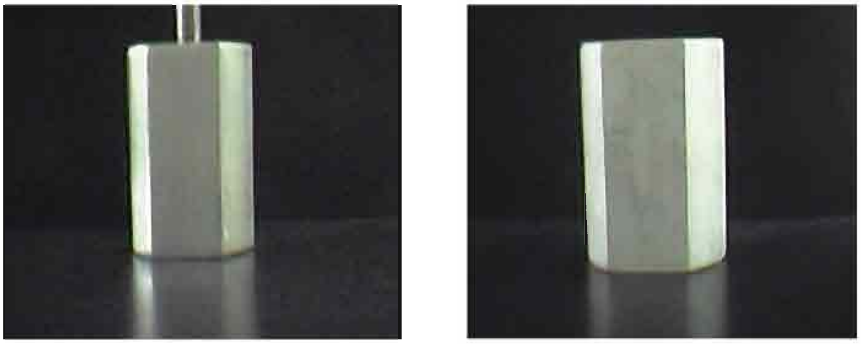


Fig. 10: Effect of applied voltage on the current density for steel (T = 70°C)

Table 3: Effect of the electropolishing on roughness

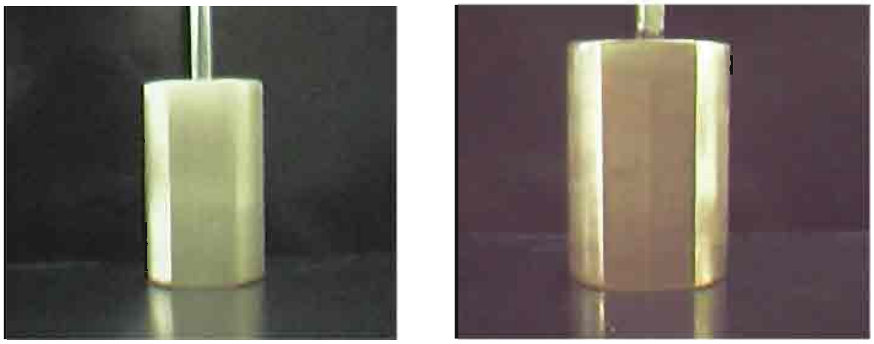
Metal	R_a before (μm)	R_a after (μm)	Reduction (%)
Brass	1.5	0.7	53
Aluminum	2.2	1.0	55
Steel	2.4	1.3	46

In general and for all of the three materials, the measured roughness of the surface improved significantly and decreased with around 50% with respect to before electropolishing and the results are summarized in Table 3. Photographs of the three different specimens before and after the electropolishing are shown in Fig. 11.



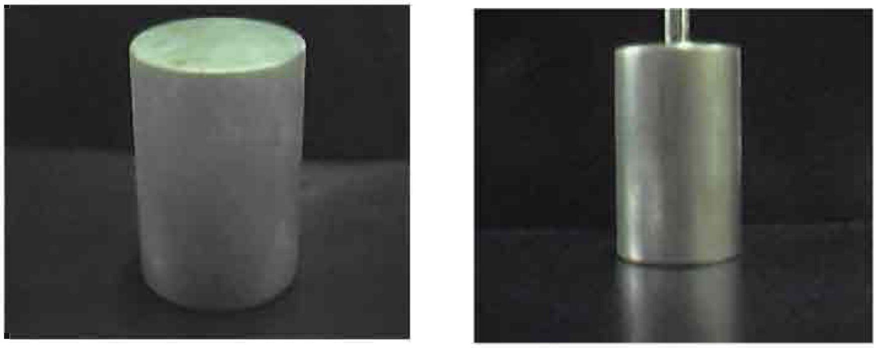
Aluminum before electropolishing

Aluminum after electropolishing



Brass before electropolishing

Brass after electropolishing



Steel before electropolishing

Steel after electropolishing

Fig. 11: A photographs of the three different material before and after electropolishing

DISCUSSION

Many lessons have been learned after carrying out the tests of electropolishing on the (Aluminum, Brass and Steel) specimens with different parameters that affecting the electropolishing process. These parameters include current density, voltage, solution's concentrations, time and temperature. These factors affect the quantity and the quality of metal removal from the specimens. The optimum conditions are the aim of this study. The first important conclusions that extract from these comprehensive tests are shown in Table 4.

Table 4: Summary of the optimum results for the three materials

Metal	Temperature (°C)	Time (min)
Brass	60	20
Aluminum	50	40
Steel	75	50

The improvement of the surface roughness by the process has been improved many mechanical properties of the material (Callister, 1997; Durkee, 2003). These improvements include the decrease of friction coefficient, wear resistance, bearing stresses of contact, fatigue life and stress concentration.

Many problems have been faced during the work and in all of its stages. Solving these problems gives strength to the results and improves the technique of electropolishing. Examples of these problems and not restricted to, are the cost of operation, materials selecting, the shape of the work piece, roughness measurements, post processing of the work piece and post processing of data. One important point to be raised here, is that work with brass needs accurate procedure. It is noted that the EP effect in the zinc more than that of copper. This type of depletion may change the properties of surface if the procedure is not followed accurately.

Cost estimating of the process has been carried out and good results were obtained. For example, the cost of electropolishing of 1 m^2 of Aluminum is around 60 JD (approximately 85$).

Finally, many lessons have been learned during the research time but other improvements could be added to the future work like, ventilation system, circulating pump for the heating tank, work piece rotating inside the cell, multi cathodes system and multi tank system.

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