Electrochemical Alternatives to Traditional Mechanical Operations

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Electrochemical processes should be considered when processing simple or specialized components. Whether the task is to deburr, drill, contour, or impart a smooth surface, there are electrochemical processes available that can perform these operations. These operations are often used to replace manual hand deburring, to drill holes in exotic materials where conventional drills cannot penetrate, to impart sweeping contours quickly, and to provide superior corrosion resistant surfaces. These operations can be tailored to suit the specific needs. They can also be cost effective, and highly reproducible. This paper outlines the common electrochemical techniques: electrochemical deburring (ECD), electrochemical machining (ECM), and electropolishing (EP). An overview of each process, typical applications, results, and benefits will be presented.

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Introduction

Electrochemical processes are often used when traditional mechanical operations are determined to be either too costly or impractical. Three widely used electrochemical processes - electrochemical deburring (ECD), electrochemical machining (ECM), and electropolishing (EP) are often the processes used in lieu of the mechanical methods. ECD frequently replaces manual hand deburring for its ability to quickly and consistently deburr a component whereas manual deburring varies from person to person and job to job. ECM is the method of choice when exotic alloys cannot be machined any other way. EP enhances the corrosion resistance of a surface, a cleanliness that is difficult to match via mechanical operations. There are similarities between all three electrochemical processes; emphasize different electrochemical properties to achieve the various results desired.

Process Basics

ECD, ECM, and EP are anodic processes and the reverse of plating. Instead of transferring metal ions from an electrolyte bath to add onto a surface as in plating, stock material is removed from the part and transferred to the electrolyte. The part is electrically positive while the electrode (cathode) is negative. The electrolyte is the conductive medium that carries the dissolved ions away from the processed part. Note that these processes are different than electrical discharge machining (EDM) or laser based processes. Laser and EDM are thermal based processes that melt the material instead of dissolving it into the electrolyte. These processes leave behind a recast layer that can require additional cleaning. Conversely, electrochemical dissolution processes do not deposit recast residuals.

A typical electrochemical system contains a power supply, electrolyte, electrolyte handling equipment, and fixturing. Figure 1 is a simplistic diagram of the basic components. Depending on the application, fixturing complexity and the number of related components such as heaters or chillers to control electrolyte temperatures, post rinses to remove electrolytes, electrolyte filters, and operating controls will vary. Fixturing can be as simple as a cathodic plate or a highly engineered tool requiring exact tolerances to be used in a CNC controlled machine. Good electrical contacts are required since these processes require high currents. Poor electrical contact can damage a part from an electrical burn or arc. Contact material and cathode material are often made from copper or brass for their excellent electrical conductivity or other corrosion resistant metals like stainless steel since electropolishing is performed in strong acids.

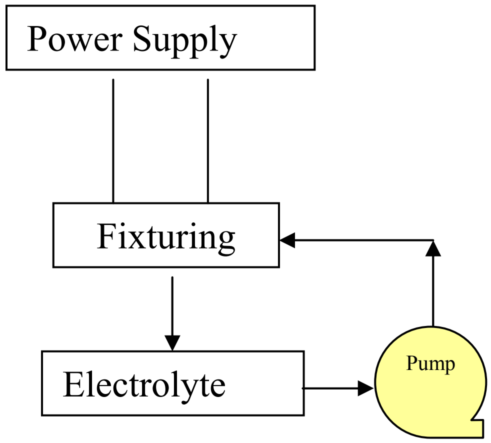

Figure 1 – Simplified components

During ECD and ECM applications, the electrolyte is forced between the part and electrode gap. This circulation removes dissolved material and gases away from the work surface while also removing heat generated by the process. In electropolishing, this may or may not be the case, but generally some form of agitation is used to remove gases from the surface if the gas cannot freely escape.

A widely used material that is processed via these three techniques is stainless steel. Sodium chloride- and sodium nitrate-based, as well as some ethylene glycol-based electrolytes are commonly used in ECD and ECM while strong inorganic acids such as phosphoric and sulfuric acids are often used in the EP process. Various reactions occur at the part, cathode, and in the electrolyte. Below are reactions involving the dissolution of stainless steel. Figure 2 is a conceptual view of what occurs during the dissolution process. Listed below are theoretical reactions at each area.

Cathode
$2H + 2e^- \rightarrow H_2$ (hydrogen gas is developed)

Electrolyte
$2H_2O + 2e^- \rightarrow H_2 + 2\ OH^-$ (dissociation of water)

Part (anode)
Iron, nickel, chromium metals are dissolved into the electrolyte
$Fe \rightarrow Fe^{2+} + 2e^-$
$Fe \rightarrow Fe3^+ + 3e^-$
$Ni \rightarrow Ni^{2+} + 2e^-$
$Cr \rightarrow Cr^{6+} + 6e^-$
$4OH^- \rightarrow 2O_2 + 4H^+ + 4e^-$ (oxygen gas is formed)

Estimates of material removal and removal rates for these electrochemical processes can be estimated using Faraday's Law of Electrolysis. The weight of material removed is proportional to the time and current applied during the process.

$M = I * T * EE$

M = grams of material removed
I = current (amperes)
T = time (seconds)
EE = electrochemical equivalent (atomic mass / # moles of electrons transferred)/Faraday's #

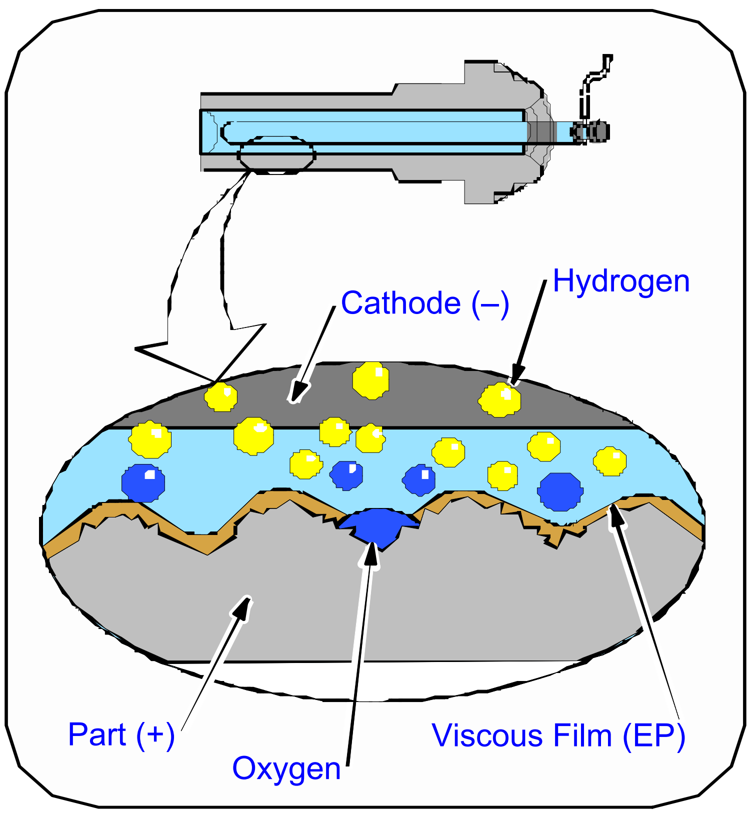

Figure 2 – conceptual view of dissolution

Process Comparisons

While ECD, ECM, and EP remove material from the part being processed, there are differences in how dissolution is achieved. All three processes can be considered high current / low voltage (usually under 30 volts) applications. ECD and ECM are similar when comes to metal removal; both use an aqueous salt-based electrolyte. ECD is a localized process (Figure 3), focusing on a burr and its adjacent edges while ECM is used to drill a hole or removing large quantities of material. The amount of power required in either application is dependent on surface area being worked upon at a given time and the desired rate of metal removal. Pulsing the applied power is often used to improve efficiency, but is limited by the amount of power being used.

These two processes differ from EP, which is typically considered a finishing process removing less material than either ECD or ECM. In typical applications, ECM removes the most material, where 10,000 amps can remove a cubic inch of metal, while EP removes the least amount of material; surface material removal is generally in the ~0.013 mm (0.0005") range. There are overlaps between processes, as EP can be used to deburr[1] and ECM and ECD processes often produce measurably fine surfaces with a < 0.50 µm (20 µin) Ra lustrous appearance.

When compared to a manual, labor-intensive process, ECD is extremely efficient, especially when evaluating components with multiple areas. ECD is typically performed under a minute. EP is also performed in minutes, but the cycle time is ultimately dependent upon the amount of surface area being processed, applied power, and the desired outcome. When comparing process time, ECM is best compared to traditional machining instead of ECD or EP. For example, using stainless steel, drilling a 25 mm (1") deep hole 6.3 mm (¼") in diameter using a conventional drill may take approximately 20 seconds. Depending on the requirements, ECM typically takes between 1 – 15 minutes to perform the same job.

During the ECD and ECM processes, electrolyte passes at high velocities through the narrow gap between the tool (cathode) and the part. Typically, this gap is between 0.25 mm (0.010") – 1.3 mm (0.050"). High flow rates are necessary to sweep away dissolved metals and remove heat and gas generated during the process. On the other hand, depending on the amount of power used, EP only requires sufficient agitation to carry away evolved gases to ensure even processing across the desired surface. During EP, when power is applied, a viscous layer forms on the surface of the part. This diffusion layer between the part and the acid is where oxygen and metals diffuse through is unlike a polarized ECM or ECD surface. This film layer acts as a buffer, limiting the speed of the process.

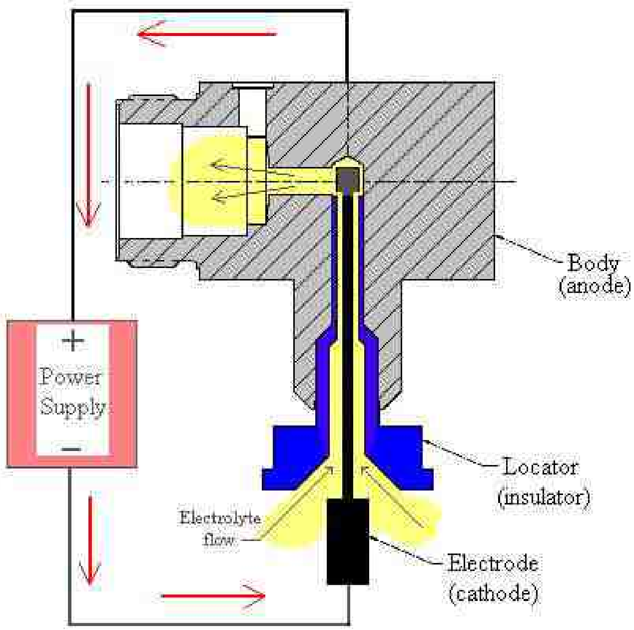

Figure 3 – ECD fixture example

Applications and Results

Since these electrochemical processes work by dissolving away the part surface, the base material being worked on is revealed. This is usually a positive result, eliminating stresses and contamination that might typically be found with any method that touches the surface. Below are examples of industry applications of each of the three processes and why they are being used.

Electrochemical Deburring (ECD) – This operation is probably the most widely used, the main benefit being cost reduction. ECD is used in almost all industries, automotive, medical, valves & fittings, and aerospace are just a few examples. Virtually any traditional machining method will produce a burr or burr ridge. ECD is a highly repeatable, fast process, replacing the need to deburr by hand. In addition, ECD is able to deburr hard to reach locations.

It is a suitable high volume process where, for example, thread damage via a tumbling operation is a concern. A fixture/machine can be designed to fit the number of parts or number of areas on one part requiring deburring. Much of the time is spent on developing fixturing for each type of part. There are not any industry-wide ECD standards. A typical specification on the use of ECD is customer driven with interpretations of ECD acceptability, however, there are industry specific standards covering edge and burr conditions.

The customer requirements will dictate the level of fixture complexity needed. If the requirement is simply to deburr the surface and a light etched appearance around the adjacent area is satisfactory, then a tool can be developed without the need to mask other areas. If the desire is to limit the area affected and reduce smut (post process discoloration), then the process parameters such as electrolyte type, concentration, applied power, along with fixturing are optimized for the process.

Two prerequisites are needed prior to ECD. First, the parts need to be clean, typically a degreasing operation is sufficient. If cutting fluids or contaminants are left on the surface, they can produce uneven results, unintentionally mask off areas[2], and shorten electrolyte bath life. Second, the burr areas need to be qualified – excessively large burrs, often called cap burrs, need to be removed. If a burr is not qualified, the burr[3] will connect the part and cathode, creating a short circuit and a burn that usually will cause the part to be scrapped. Many systems will incorporate a function, which tests for a short circuit prior to starting the actual process. Figures 4 and 5 are examples of an ECD fixture block, electrode/locator close-up, and workstation.

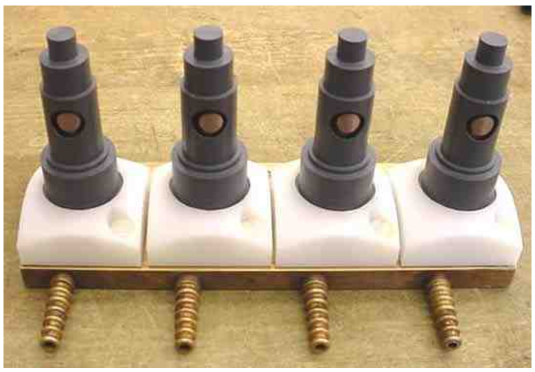

Figure 4 – ECD fixture block

Figure 5 – ECD electrode / locator

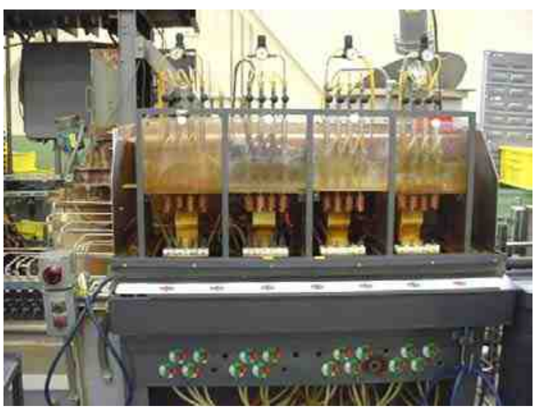

Figure 6 – ECD workstation

Electrochemical machining (ECM) – This process has a wide range of use, including large aerospace components, automotive components, and medical instruments—areas where traditional manufacturing techniques are impractical. ECM can remove a large amount of metal; comparable to the amount of chips produced via a traditional machining process. An even greater amount of by-product is produced for every pound of metal dissolved; over 5 pounds of metal hydroxide/salt composite will form during electrolyte treatment.

ECM requires the largest capital investment and supporting equipment of the three electrochemical processes. CNC controlled machines are matched with electrolyte systems incorporating pressurized, high electrolyte flow rates, along with large power supplies. ECM is capable of drilling holes, embossing external features, and placing contours into a part.

Like ECD, much of the ECM related specifications are customer driven. Currently, the only standard is being developed by the National Aerospace and Defense Contractors Program (NADCAP), which is an accreditation system for the ECM process. ECM is a logical option when manufacturing hardened alloys, complex geometries with contours such as the rifling of a barrel, or when faced with the need to process numerous locations in one operation. A surface will typically be under 0.50 µm (20 µin) Ra and tolerances in the 0.35 mm (0.015”) range are common. Figure 7 is an example of an aerospace component where the features are machined onto the outer surface. An overview article on ECM can be found in the July 2003 issue of Plating and Surface Finishing[4].

*Figure 7 – Engine case**

* Courtesy of Sermatech Manufacturing Group

Electropolishing (EP) – This process is found in a traditional plating shop whereas ECM and ECD might be found more in a machining environment. Since the electrolyte is often acid based, phosphoric/sulfuric acid being a common blend, shops require more attention to operator and facility safety than is usually required with salt-water electrolytes. EP does not remove as much material as the other two, but is used to improve the corrosion resistance of a surface for high purity applications, or the cosmetic appearance of a component. Examples of electropolished components are valves and fittings used in semiconductor fluid delivery systems and medical processing vessels and instruments.

Electropolishing produces a surface that is microscopically clean and smooth, removing the mechanically disturbed surface that could contain machining contaminants. Figures 8 – 10 are examples of before and after electropolishing. The surface Ra can be improved by as much as 50%, depending on the initial roughness. The amount of material removed generally does not change functional dimensions, typically less than 0.025 mm (0.001”). Figure 11 is a depiction of how EP smoothes the surface.

The amount of power or current density typically used for EP is less than the other two processes. The equipment needed can be basic compared to ECD or ECM. Since electrolyte high flow rates are not required, often simple part agitation is sufficient. A basic system would be composed of a processing tank, fixturing, power supply, and rinses. More often, EP systems include heaters, pumps, and fixture/electrolyte controls. There are more specifications available that cover EP than are available for ECM and ECD. EP relevant specifications can be found in ASTM, BPE, and SEMI standards.

Figure 8 – Before / After EP

Figure 9 – Before / After EP

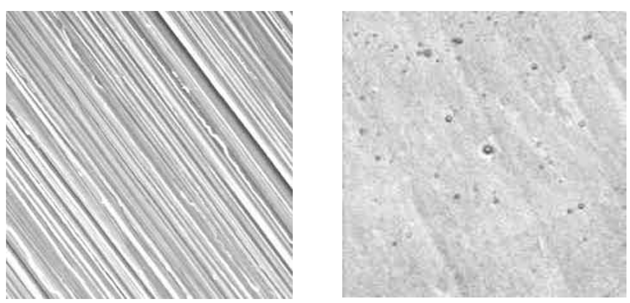

Figure 10 – EP Before / After 1,000x

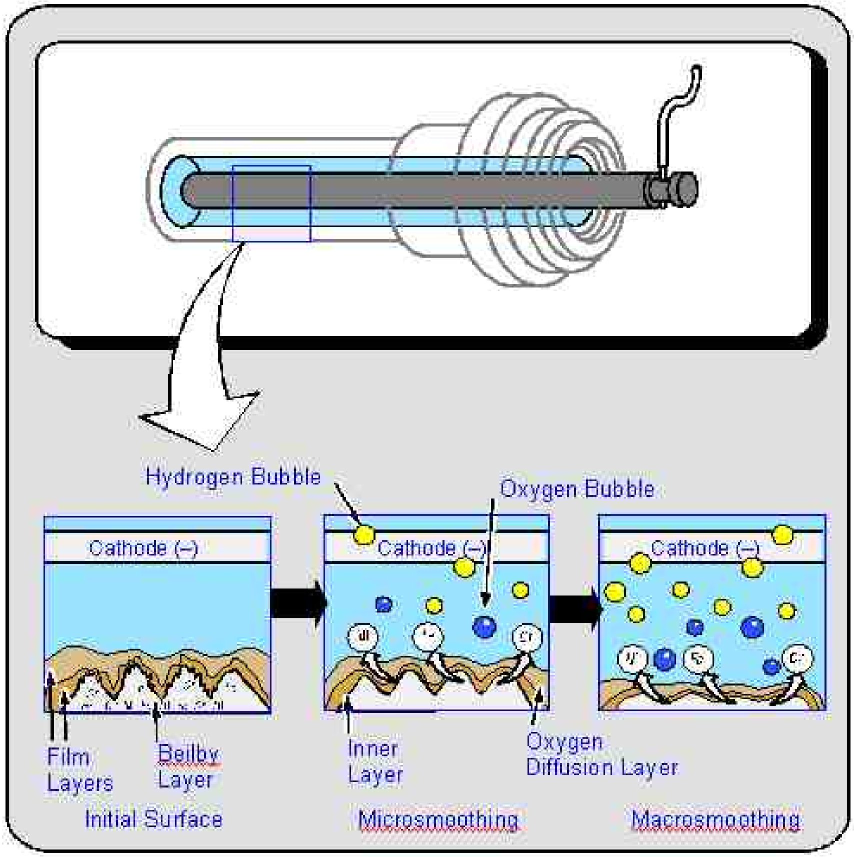

Figure 11 – Surface smoothing via EP

Process Summary

Electrochemical processes have found niches throughout various industries, demonstrating the ability to process a wide variety of components. These processes have been developed and implemented either because there was no alternative or to reduce operating costs. These operations generally need be tailored to suit specific needs, but once developed, they are cost effective and highly reproducible. Table 1 is a recap of various parameters and issues associated with each process.

Table 1 - Common parameters and ranges

	ECD	ECM	EP
Electrolyte	$NaNO_3$, $NaCl$, $C_2H_6O_2$ based	$NaNO_3$, $NaCl$, $NaClO_4$	H_3PO_4, H_2SO_4
Voltage range	<40 V	<30 V	<30 V
Amperage range	<1,000 A	Up to 40,000 A	<1,000 A
Gap distance	0.25 – 1.30 mm (0.010" – 0.050")	0.25 – 1.30 mm (0.010" – 0.050")	0.50 mm+ (0.020"+) (per application)
Process speed	< 30 sec	0.50 mm – 25 mm (0.020" – 1") per min feed rate	30 sec – minutes+ (per application)
Pre process cleanliness	Degreased	Degreased	Spot free, contamination free
Post process rinse	Remove electrolyte, dissolved metals	Remove electrolyte, dissolved metals	Remove electrolyte, dissolved metals
Visual luster	Localized, matte to bright	Satin – bright	Satin – bright
Ra (µin)	N/A	< 0.50 µm (< 20 µin)	0.10 – 0.30 µm (4 - 12 µin)[5] (Per application)
Typical evaluation metrics	Visual	Dimensional	Visual, SEM, ESCA, Auger, CPT, GDOES
Capital costs	$25K +	$100K – 2 million	$25K +
Fixturing complexity	Simple – complex	Complex	Simple to complex
Other equipment that may be required	Cleaning system, wastewater treatment, solid waste processing	Cleaning system, wastewater treatment, solid waste processing	Cleaning system, wastewater treatment, ventilation
Applications	Automotive, medical, general manufacturing	Aerospace, automotive, medical, precision manufacturing	Semiconductor, pharmaceutical, general manufacturing

References

[1] L.K. Gillespie, *Deburring and Edge Finishing Handbook*, SME, Dearborn, MI 1999; p.313 – 321.

[2] L.K. Gillespie, *Deburring and Edge Finishing Handbook*, SME, Dearborn, MI 1999; p.299 – 312.

[3] R. Taufer, *Proceedings, AESF SUR/FIN ® 03',* p.762 (2003).

[4] T. Lievestro, *Electrochemical Machining at Sermatech is State of the Art in Metal Removal*, Vol. 90 No.7, Plating and Surface Finishing Journal (July 2003).

[5] P. Dettner, *Electrolytic and Chemical Polishing of Metals,* Ordentlich Publishers, Tel Aviv, 1988.