Electrically Mediated Edge and Surface Finishing: Application to Industrial Parts

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This paper will present an electrically mediated edge and surface finishing process for industrial parts. Electrical mediation controls the electrochemical surface finishing process through adjustment of parameters such as on time and peak current or voltage of the electric field. The advantages of this approach over conventional chemically mediated electrochemical finishing include higher efficiency, the use of environmentally benign electrolytes, and control of oxide film formation. Results will be presented for edge and surface finishing of passive alloys, such as titanium. Parts that will be discussed may include medical parts (including staples) as well as specialized finishing of golf club heads.

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Introduction:

As the use of hard, passive alloys increases in manufacturing, the need to provide edge and surface finishing of these materials is critical. As the design complexity of parts increase, the need for cost effective, advanced techniques also increase. Edge and surface finishing has a wide range of applications in the aerospace, semiconductor, and medical industries as well as an increasing demand in the industrial and consumer markets. One conventional technique to meet this demand is manual finishing. Manual finishing is extremely costly because it is labor intensive and the employees are highly skilled. Despite the skill developed by the laborers, the process is not reproducible and complete finishing is nearly impossible to achieve especially for complex geometries.

Many edge and surface finishing techniques have been introduced to replace manual finishing. The goal is to provide superior results with an automation capable process (thereby providing reproducible results). Examples of such techniques are abrasive flow finishing, thermal energy deburring, and electropolishing.

This paper looks at high current electrochemical processes as a source for edge and surface finishing. Electrochemical processes: (1) have been proven successful in processing difficult to machine materials, (2) have relatively high material removal rates (0.1 – 10 mm/min), (3) have no tool wear, (4) can finish complex shapes and contours, (5) use environmentally friendly electrolytes (e.g. NaCl and $NaNO_3$), and (6) are capable of automation. The challenges associated with the application of electrochemical processes are dimensional accuracy limitations due to non-uniformities in the electrolyte (e.g. waste products and heat) and surface finish limitations due to high electrolyte flow rates.

Faraday Technology Inc. has been developing an electrically mediated process that incorporates the advantages of typical electrochemical processes while addressing the challenges. Other electrochemical techniques have been developed to address these issues; however, complex chemistries are often used to control the electric field. These complex chemistries are often proprietary baths that limit the user's ability to develop specific applications without relying on chemical suppliers. Faraday's new process simplifies the chemistry through the use of simple, neutral salt solutions and relies on an asymmetric, interrupted square waveform to control the metal dissolution rate and location. As opposed to chemically mediated processes, electrical mediation introduces additional parameters such as peak voltages (or currents), on times, and duty cycles, which provides the user with the ability to tune the waveform for a particular application. For example, polishing is typically achieved with long anodic on times and high duty cycles. Deburring on the other hand typically requires short anodic on times and low duty cycles. This particular process also introduces a cathodic pulse into the waveform whose primary purpose is to control or eliminate oxide film formation during relaxation periods. This concept greatly enhances the process and allows it to be used successfully on hard, passive alloys such as stainless steel, titanium, and nickel based alloys.

Electrically Mediated Process Parameters

Electrically mediated processes are characterized by the application of a non-steady state voltage (or current). This waveform (shown in Figure 1) consists of an anodic voltage and on time (V_a and t_a), cathodic voltage and on time (V_c and t_c), and an off time (t_{off}) where no

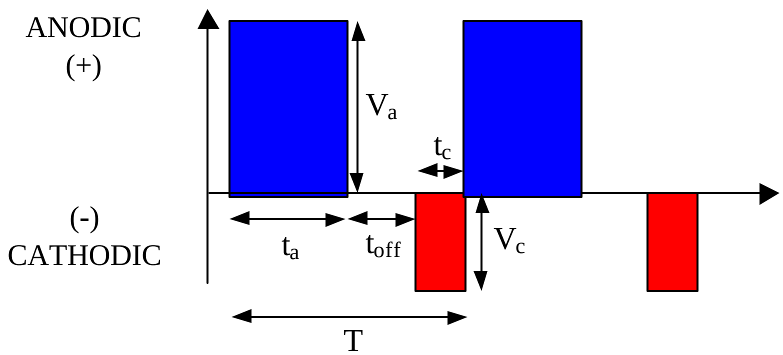

Figure 1: Schematic of electrically mediated waveform

current is passed. The period of the waveform, T, is a summation of the anodic, cathodic, and off times. The frequency of the waveform is the inverse of the period. The duty cycle of either the anodic, γ_a, or cathodic, γ_c, pulse is the ratio of its respective on time with the period. The average voltage, V_{ave}, is defined as:

$$V_{ave} = V_a \tilde{a}_a - V_c \tilde{a}_c \qquad (1)$$

where,

$$\tilde{a}_a + \tilde{a}_c \leq 1 \qquad (2)$$

The average voltage influences the material removal rate, the dimensional accuracy, and the surface quality.

Unlike traditional direct current electrochemical machining (DC-ECM) that is limited to only one process variable (the steady-state voltage or current), electrically mediated processes have nearly an infinite number of process parameter combinations. By applying various combinations, the user can strongly influence the mass transport rates, the current distribution, and the hydrodynamic conditions during metal removal. Each of these process conditions and the means by which they are influenced will be discussed in detail in the following paragraphs.

Mass Transport

In electrically mediated processes, mass transport is a combination of steady state and non-steady state diffusion processes. The theory of mass transport during non-steady state electrolysis has been discussed previously.[1,2,3] In DC processes, the diffusion layer thickness, δ, is time invariant and is defined by the electrode geometry and solution hydrodynamics. In electrically mediated processes, δ varies from 0 at the beginning of the pulse to its steady state value when the Nernst diffusion layer is fully established. This suggests that the diffusion limiting current density would be infinite at t = 0 and would eventually decrease to a steady state value equivalent to the DC limiting current density. In electrically mediated processes, the current is interrupted before δ has a chance to reach its steady-state value. During the period of zero current, the reacting ions diffuse back to the electrode surface and replenish the surface concentration to its original value. Therefore, the concentration of the reacting species, in the vicinity of the electrode, pulsates with the applied waveform. By selecting the appropriate duty cycles, the concentration profile of the reacting species at the beginning of each pulse remains the same.

During the electrically mediated finishing process, a “duplex diffusion layer” consisting of a pulsating layer, δ_p, and a stationary layer, δ_s, has been proposed.[4] By assuming a linear concentration gradient across the pulsating diffusion layer and conducting a mass balance, the pulsating diffusion layer thickness (δ_p) was derived:

$$\delta_p = \left(CDt_c\right)^{0.5} \qquad (3)$$

where *C* is a constant and *D* is the diffusion coefficient. The limiting current density i_l, in electrically mediated electrolysis, is:

$$i_{pl} = nFD\left(C_s - C_b\right)/\eta_p \delta_p \qquad (4)$$

Compared to the limiting current density in the steady state condition:

$$i_l = nFD\left(C_s - C_b\right)/\eta\delta \qquad (5)$$

the relationship between the limiting current in the steady and non-steady state condition is:

$$i_{pl} = i_l\left[\delta_p/\delta\left(1 - \gamma_a\right) + \gamma_a\right]^{-1} \qquad (6)$$

Because $\delta_p \ll \delta$, a much higher limiting current density can be applied in the electrically mediated process, as compared to steady state conditions (DC), resulting in higher removal rates.

Current Distribution

During electrically mediated processes, the current distribution consists of primary (geometrical), secondary (kinetic) and tertiary (mass transport) effects, all of which influence the material removal rate, dimensional accuracy, and surface quality. Electrical mediation enhances the kinetic and mass transport effects thereby significantly altering the current distribution as compared to DC electrochemical processes. For example, the current distribution in electrically mediated finishing can be altered by the addition of kinetic (secondary) and mass transport (tertiary) effects through the adjustment of process parameters. Compared to primary current distribution, the addition of kinetic or tertiary effects tends to make the current distribution more uniform. By understanding the influence of electrically mediated electrolysis on current distribution, process parameters can be selected to provide either a localized current distribution for deburring or a uniform current distribution for surface polishing.

Hydrodynamic Conditions

In addition, electrically mediated finishing can achieve uniform hydrodynamic conditions in the gap between the tool and workpiece. Compared to conventional DC-ECM, heat and undesired products being generated by the high current are removed during the off or reverse time with relatively small flow velocities. The nascent gas bubbles generated at the cathode during the forward pulse can be removed or anodically consumed during the off or reverse time. This minimizes the presence of gas bubbles in the electrolyte and reduces the local pH at the tool surface through the following reactions:

Forward modulation (*i.e.*, cathodic reaction at the tool):

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad (7)$$

Reverse modulation (*i.e.*, anodic reaction at the tool):

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \qquad (8)$$

By consuming the nascent hydrogen in the interelectrode gap, the electrolyte density, thermal conductivity, and flow velocity is more uniform. A detailed discussion on the effects that hydrodynamic non-uniformity has on ECM processes has been provided by Kozak et al.[5]

Conclusions

Compared to the DC electrochemical processes, the electrically mediated finishing process: (1) has a higher efficiency, (2) can control the current distribution, (3) can maintain electrolyte hydrodynamic uniformity in the interelectrode gap by removing heat, gas bubbles, and metal precipitation during the reverse and off times, (4) has a high limiting current density to obtain a high metal removal rate, (5) can prevent cavitation on the workpiece by reducing the electrolyte flow rate, (6) can prevent metal hydroxide deposits on the tool by decreasing the pH near the tool during the reverse period, and (7) can minimize oxide film healing on the part surface, thereby allowing the polishing of passive alloys.

Prior Work

In previously reported work, Faraday Technology, Inc. has shown capability in the following areas. Some of these milestones may be presented at the conference:

- Electrically mediated edge finishing of cast aluminum alloy wheels [6, 7]
- Electrically mediated edge and surface finishing of stainless steel valves [7]
- Electrically mediated surface finishing of titanium and titanium alloys [7, 8]

Industrial Examples

The following examples are ongoing work at Faraday Technology, Inc. A brief description of each example is provided. These examples may be presented at the conference:

- Electrically mediated machining of micro grooves in titanium alloys
- Electrically mediated edge finishing of titanium medical clips
- Electrically mediated surface finishing of titanium sputtering targets
- Electrically mediated edge finishing of surgical steel blades
- Engineering study to determine tool life for electrically mediated surface finishing of 316 stainless steel
- Engineering study to demonstrate capability of electrically mediated machining of meso-scale features in stainless steel, titanium alloys, and Inconel®

Electrically Mediated Machining of Micro Grooves in Titanium Alloys

In this project, Faraday Technology, Inc. is machining a semicircular groove into a contoured titanium alloy substrate. The desired radius of the groove cross section is 0.380 mm and the total length is approximately 22 mm. Initial results were achieved using a simple cell design (shown in Figure 2). Grooves measuring 0.89 mm wide (design = 0.76 mm) with a depth of 0.38 mm were achieved. The initial experimental runs conducted revealed a strong coupling between the solution flow conditions and the groove geometry. To address this issue, a new fixture was designed and fabricated to achieve a uniform flow front across the groove. The fixture also provides the capability to apply backpressure to the flow, thereby reducing cavitation effects. Additionally, this fixture has a reusable Teflon® mask to further control the groove geometry. Testing is ongoing to determine the effects of the electrically mediated process on variables such as undercut and surface finish.

Figure 2: (upper left) photograph of workpiece, (upper right) stainless steel tool, (bottom) assembled fixture

Electrically Mediated Edge Finishing of Titanium Medical Clips

In an ongoing project at Faraday Technology, Inc., commercially pure titanium medical clips (please see inset in Figure 3) are edge finished using the electrically mediated process in conjunction with a rotating barrel. The setup is shown in Figure 3. The titanium clips are placed in the barrel along with graphite pellets. The anodic lead is allowed to dangle in the barrel making contact with both the titanium clips and the graphite pellets. The purpose of the graphite pellets is to provide a means of passing current without the need for contact between the titanium clips. The cathode is placed approximately 1 cm from the barrel. The entire setup is immersed in electrolyte with a pump providing a stream of fresh electrolyte into the barrel. Initial results have shown that the process is capable of complete burr removal. Complete results may be presented at the conference.

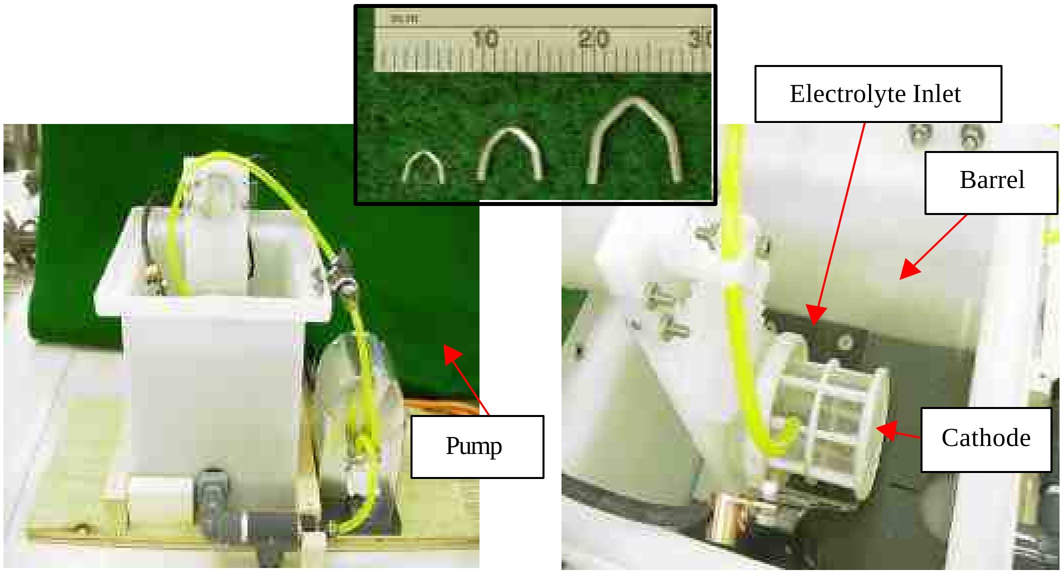

Figure 3: Titanium medical clip samples (insert, above), barrel deburring fixture (left), view of inside of tank (right)

Electrically Mediated Surface Finishing of Titanium Sputtering Targets

The objective of this project is to determine the capability of the electrically mediated process to finish the surface of ultra pure titanium sputtering targets. Initial tests are being conducted using a rotating disk electrode and a mesh cathode. By using a rotating disk, a uniform hydrodynamic diffusion layer is developed on the surface of the rotating disk and can be quantified using the Levich equation. Once a stable process is realized, a pilot scale fixture will be fabricated to transition from coupons to full sized targets.

Electrically Mediated Edge Finishing of Surgical Steel Blades

This ongoing project is investigating the feasibility of using the electrically mediated edge finishing to debur surgical blades. Each blade measures 5.6 mm wide and 0.5 mm thick. The feasibility of the process was proven using a very simple fixture. The total processing time required for complete burr removal was 2 seconds. Figure 4 shows the "as received" knife edge and the edge after processing.

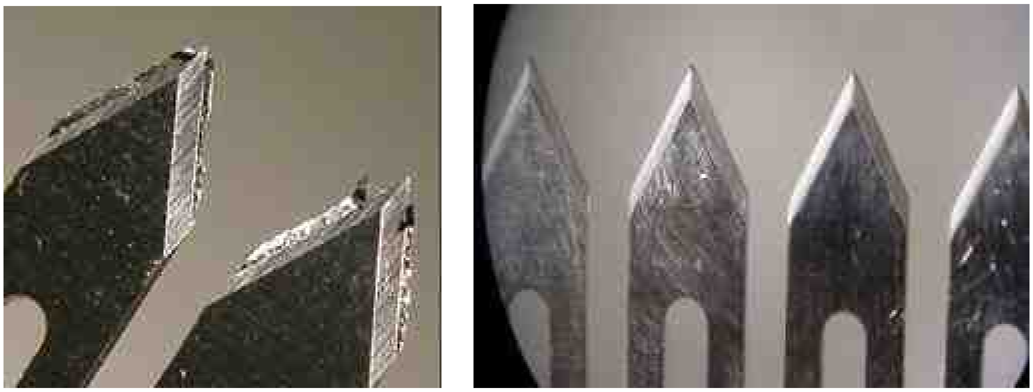

Figure 4: (left) knife edge "as received" (5.6 mm wide x 0.5 mm thick), (right) after electrically mediated edge finishing

Engineering Study to Determine Tool Life for Electrically Mediated Surface Finishing of 316 Stainless Steel

The purpose of this study was to determine the life of various tool materials during electrically mediated surface finishing of 316L stainless steel. This study also investigated the influence that gold or platinum coatings would have on tool life. Table 1 shows a matrix of the materials tested. The characteristic of most interest in the study was the reduction in the diameter of the tool as a function of the number of polishing cycles. Figure 5 shows the results for the *uncoated* materials. This data suggests that the performance of the titanium alloy and the copper impregnated graphite were significantly better than the stainless steel tool. Both of these materials, however, generated excessive amounts of heat because of their relative high electrical resistance. In achieving a balance between heat generation and diameter loss, the copper-tungsten alloys had the best performance.

Table 1: List of Electrode Materials Investigated

Material	Uncoated	Gold coating	Platinum coating
304 Stainless Steel (baseline)	X	X	X
Tungsten	X	X	X
15% Copper, 85% Tungsten Alloy	X	X	X
30% Copper, 70% Tungsten Alloy	X	X	X
Titanium 6Al-4V	X	X	X
Copper Impregnated Graphite	X		
Brass		X	X

This study has also shown that the application of a platinum coating to the base tool materials did not significantly enhance tool life. The gold coating did, however, increase the performance. In particular, the gold coated, stainless steel tool did not shown any signs of degradation until approximately 400 cycles. In contrast, the uncoated and platinum coated electrode showed signs of wear within a few cycles.

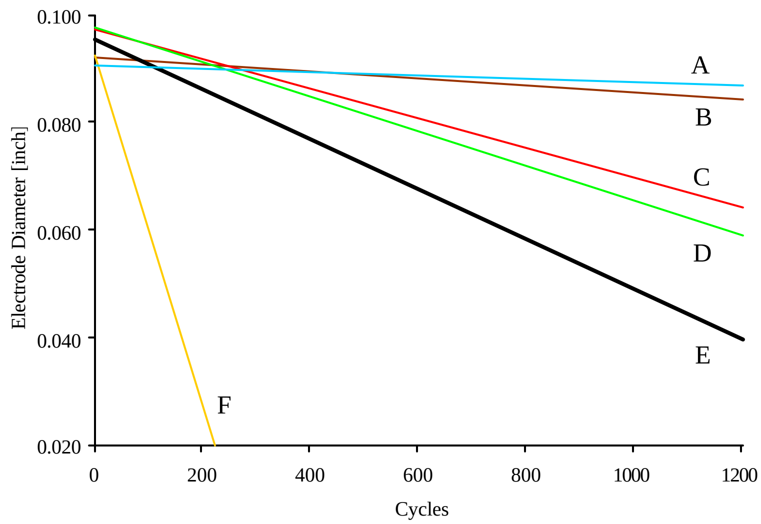

Figure 5: Electrode diameter of uncoated tools as a function of polishing cycles, (A) copper impregnated graphite, (B) titanium 6Al-4V, (C) 30% copper-70% tungsten alloy, (D) 15% copper-85% tungsten alloy, (E) 304 stainless steel, and (F) tungsten

Engineering Study to Demonstrate Capability of Electrically Mediated Machining of Meso-Scale Features in Stainless Steel, Titanium Alloys, and Inconel®

The objective of this study is to demonstrate the capability of the electrically mediated machining process to produce meso-scale features. A zoomed view of the tool and a view of the assembled fixture are shown in Figure 6. The machine that is being used is capable of feeding the tool. The materials of interest are: stainless steel 17-4 PH, titanium 6Al-4V, and Inconel® 718. Work is ongoing and may be presented at the conference and in future publications.

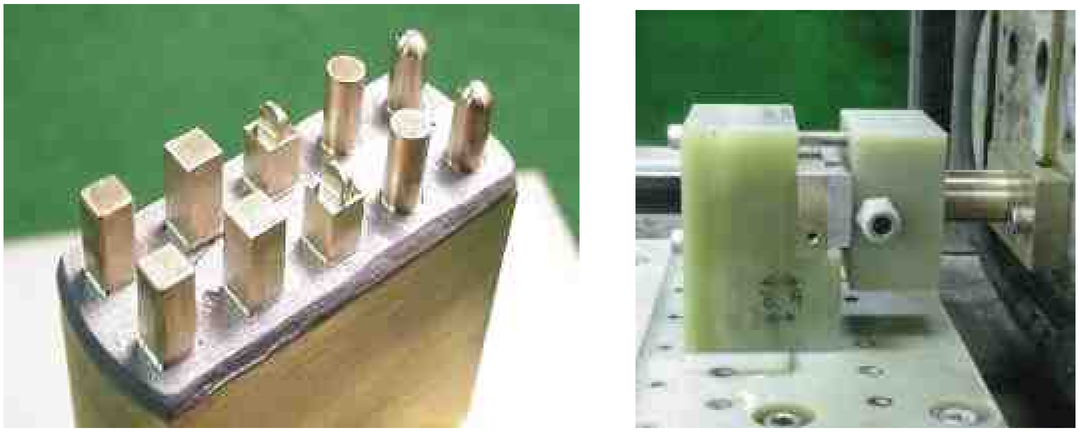

Figure 6: (left) tool for meso scale feature study (characteristic dimension of features is 2.5 mm), (right) fully assembled fixture

Conclusions

Reported work has shown the capability of the electrically mediated process for edge and surface finishing of aluminum alloys, titanium alloys, and stainless steel.

Ongoing work is investigating the feasibility and expanding capability of electrically mediated processes to surface finish titanium alloys, to machine meso-scale features in titanium alloys, stainless steel, and Inconel®, and edge finishing of titanium alloys, stainless steel, and surgical steel. Studies have also been conducted to further enable the commercialization of electrically mediated surface finishing of stainless steel by quantifying tool life for various materials.

In summary, the electrically mediated finishing process is a robust process for surface finishing a variety of metal alloys, especially hard passive alloys including titanium, stainless steel, and aluminum alloys.

Acknowledgements

Faraday Technology, Inc. acknowledges the financial support of the National Science Foundation and private clients.

The authors acknowledge the efforts of P. Miller for technical editing of the manuscript. The financial support of Faraday Technology, Inc. corporate R&D is also gratefully acknowledged.

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