Electrically Mediated Edge and Surface Finishing: Application to Industrial Parts and Effect on Mechanical Properties such as Fatigue Life

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ABSTRACT

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 showing the effect of electrically mediated surface finishing on mechanical properties will be presented. Specifically, the benefit of electrically mediated finishing for improving the fatigue life of engineering alloys, such as carbon steels, nickel-based and titanium-based alloys, and stainless steels, will be discussed.

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Introduction

For DC electrochemical finishing processes which operate at very low applied currents, the current distribution, and therefore the metal removal rate and surface quality, is controlled by chemical mediation. High concentrations of acids and organic chemicals are used to provide either a uniform or localized current distribution, to polish a metal surface or remove edge burrs, respectively. Compared to manual methods of metal surface finishing, the electrochemical surface finishing process 1) provides easy control, 2) requires less labor, and 3) has a higher finishing rate and a better surface appearance, especially in difficult to access areas. However, several challenges are involved with low-current DC electrochemical finishing processes: 1) it is hard to remove surface defects if the defect depth is over 50 μm, *e.g.,* removal of an EDM surface damaged layer or rough machining lines, 2) harmful solutions (strong acid and alkali) can lead to environmental problems, and 3) the low applied current leads to a low process efficiency for manufacturing applications, *e.g.,* it takes 3-30 minutes to remove 5-50 μm from a damaged surface.[1] To overcome these problems, research on metal surface finishing has focused on the use of high current electrochemical machining (ECM) technologies.[2]

High current ECM processes have proven to be effective in machining difficult-to-cut materials because of: 1) very high metal removal rates (0.1 – 10 mm/min), 2) ability to finish complicated contours and profiles, 3) no tool wear, 4) no burrs, 5) no scratches left on the machined surface and 6) using non-hazardous solutions (NaCl and $NaNO_3$). Because of these benefits, ECM has application to industries such as aerospace, automotive, and electronics. However, both industrial and laboratory researchers have observed difficulties in the high current ECM processes that are controlled by direct current (DC): 1) dimensional accuracy is poor due to stray current, and non-uniform electrolyte hydrodynamic conditions in the inter-electrode gap, caused by undesired products and heat, and 2) surface quality is poor due to cavitation resulting from gas bubbles and a high electrolyte flow rate. Hence, there is a limit to the metal surface finishing quality using the high current DC-ECM process.

The use of a pulsed electric field, *i.e.,* an anodic pulse followed by an off-time, can remove a damaged surface layer (around 50 μm to 200 μm depth) without creating additional damage to the surface of a tool steel part.[3] However, it is ineffective for hard, passive alloys, such as titanium, nickel-based superalloys, molybdenum, and stainless steels, since, in the presence of a sufficient amount of oxygen, the self-healing oxide film forms almost instantaneously during the off-time. As a result, a partial film breakdown often occurs during the next on-time period leaving the surface pitted and rough. Consequently, the surface quality of a hard, passive alloy after pulse ECM is unacceptable.

Faraday Technology, Inc. is developing an electrically mediated edge and surface finishing process for hard, passive alloys. Instead of environmentally harmful chemical mediation, the electric field is used to control the current distribution and improve the hydrodynamic conditions in the inter-electrode gap, to obtain the desired metal removal rate and surface finish quality. This electrically mediated electrochemical process can effectively remove the damaged surface layer and edge burrs from a variety of metals and achieve the desired surface finish quality. The process parameters, such as modulation frequency, peak current or voltage, cathodic and anodic on-time, and off-time can strongly influence the mass transport rate, diffusion layer thickness, current distribution, and inter-electrode gap hydrodynamic conditions in the electrochemical dissolution process. Therefore, by understand the mechanism of electrically mediated electrochemical finishing, the current distribution can be focused or made uniform to remove the edge burrs or polish a contoured surface, respectively.

Electrically Mediated Process Parameters

In the electrically mediated process, the electric field between the workpiece and tool is controlled by a non-steady state applied voltage. The voltage across the interelectrode gap influences the metal removal rate, dimensional accuracy, and surface quality because the mass transport, current distribution, and hydrodynamic conditions are changed in the interelectrode gap under different electrically mediated process parameters. As shown in Figure 1, the electrically mediated process consists of an anodic modulation voltage, V_a, an anodic on-time, t_a, a cathodic modulation voltage, V_c, a cathodic on-time, t_c, and an off-time, t_0. The sum of the anodic and cathodic on-times and the off-time is the period, T, of the waveform and the inverse of the period is the frequency, f, of the waveform. The anodic, γ_a, and cathodic, γ_c, duty cycles are the ratios of the respective on-times to the period. The average voltage, V_{ave}, is given by:

$$V_{ave} = V_a\gamma_a - V_c\gamma_c \qquad (1)$$

where:

$$\gamma_a + \gamma_c \leq 1 \qquad (2)$$

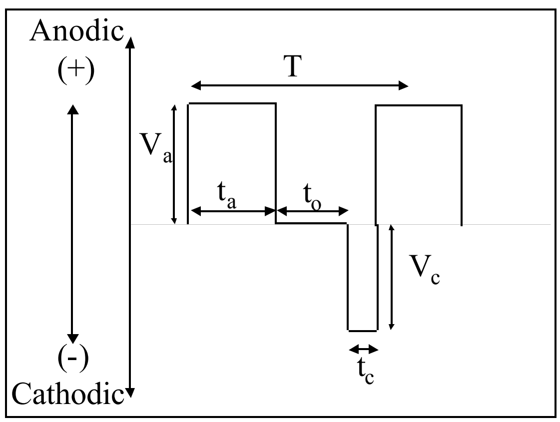

Figure 1 - Schematic of an electrically mediated process waveform.

It should be noted that the frequency, duty cycle and peak voltage or current, are additional parameters available to control the electrically mediated finishing process compared to conventional DC-ECM (constant voltage or current control processes). The unlimited combinations of these parameters can strongly influence the mass transport rates, current distribution, and hydrodynamic conditions, during the metal removal process.

Mass transport in electrically mediated electrolysis 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.[4,5,6] In steady state DC electrolysis, the diffusion layer thickness, δ, is a time-invariant quantity for a given electrode-geometry and solution hydrodynamics. However, in non-steady state electrolysis, δ varies from 0 at the beginning of the modulation to its steady state value when the Nernst diffusion layer is fully established. The corresponding diffusion limiting current density would then be equal to an infinite value at $t = 0$ and decreases to a steady state value equivalent to the DC limiting current density. In non-steady state electrolysis, the current can be interrupted before δ has a chance to reach its steady-state value. This allows the reacting ions to diffuse back to the electrode surface and replenish the surface concentration to its original value before the next current interruption. Therefore, the concentration of reacting species in the vicinity of the electrode pulsates with the frequency of the waveform.

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.[7] 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:

$$\delta_p = (CDt_c)^{1/2} \qquad (3)$$

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

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

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

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

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

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

Because $\delta_p << \delta$, a much higher limiting current density can be applied in the electrically mediated process, than under the steady state conditions (DC), to obtain a high metal removal rate.

During the electrically mediated finishing process, the current distribution consists of primary (geometrical), secondary (kinetic) and tertiary (mass transport) effects, all of which influence the metal removal rate, dimensional accuracy, and surface quality. Due to changes in both the mass transport and kinetics during the electrochemical reaction, the current distribution in electrically mediated finishing is quite different from conventional DC- ECM. For example, the current distribution in electrically mediated finishing can be changed by the addition of kinetic (secondary) and mass transport (tertiary) effects, by adjusting the 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, electrically mediated finishing process parameters can be designed to either provide a localized current distribution for deburring or a uniform current distribution for surface polishing.

In addition, the electrically mediated finishing process can achieve a hydrodynamic uniformity condition in the interelectrode gap between cathode (tool) and anode (workpiece). Compared to conventional DC-ECM, heat and undesired products generated by the high current can be swept away at slower flow velocities during the off time or reverse time. The nascent gas bubbles generated at the cathode during the forward pulse can be removed or anodically consumed during the off-time or reverse modulation. This minimizes the generation of gas bubbles in the electrolyte and the local high pH at the cathode (tool) surface via 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):

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

By consuming the nascent hydrogen in the interelectrode gap, the electrolyte density, thermal conductivity, and flow velocity will be more uniform. This hydrodynamic uniformity will eliminate the cavitation effects and improve the surface finish quality during the electrically mediated finishing process. The other advantage of the electrically mediated finishing process is minimization of the cathode tool size and shape changes, which will improve dimensional accuracy on the part, by adjustment of the pH near the cathode surface during the reverse modulation.

Compared to DC-ECM process, 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 off-time and reverse time; 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) minimize oxide film re-healing on the part surface, to allow polishing of passive alloys.

Prior Work

In previously reported work, we accomplished the following milestones:

- Electrically mediated polished of H-13 steel and Inconel® 718, to remove damage from EDM processing,[8,9]
- Electrically mediated deburring of cast aluminum alloy wheels.[8,10]
- Electrically mediated deburring and polishing of 316 stainless steel medical valves.[10]
- Electrically mediated polishing of titanium wire.[10]

Experimental Work Using Electrically Mediated Finishing Process for Metal Surface Finishing

Electrically Mediated Surface Finishing of Titanium Alloys

Faraday is developing an electrically mediated surface finishing process for titanium alloys, in salt-based electrolytes. A wedge shape tool and parallel flow cell was used to determine whether a NaCl electrolyte could provide an equivalent or better surface finish for titanium alloys, than the sodium perchlorate solution used in commercial practice. Electrically mediated waveforms and direct voltage (DC) waveforms were utilized in the finishing process for all electrolytes. Three titanium alloys were used: Ti-17, Ti-6Al-4V, and Ti-6Al-2Sn-4Zr-6Mo. The test coupons were 1″ x 2″ x 0.5″ and the initial surface roughness was 90-120 μin. Figure 2 illustrates the experimental setup, the finishing area and flow path on the test coupon surface. Figure 3 shows the surface finishing fixture. The experimental conditions and process parameters were: 1) DC and average voltage ~ 20-27 V, 2) frequency = DC or 50-400 Hz, 3) duty cycle = 75% to 83%, 4) 304 stainless steel wedge shape tool as cathode, 5) 2.5-3 L/min of flow rate (provide by air driven diaphragm pulsating pump), 6) initial gap size = 0.35 mm, 7) test duration = 13-15 sec, and 8) current density during the test period = 40-80 A/cm^2.

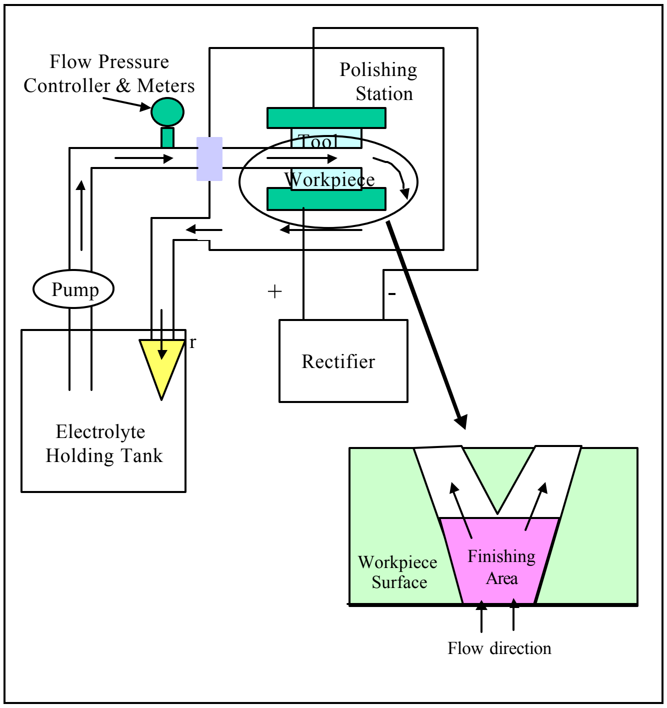

Figure 2. Schematic of Experimental Setup for Electrically Mediated Finishing and Electrolyte Flow Path on Workpiece Surface using Wedge Shape Tool.

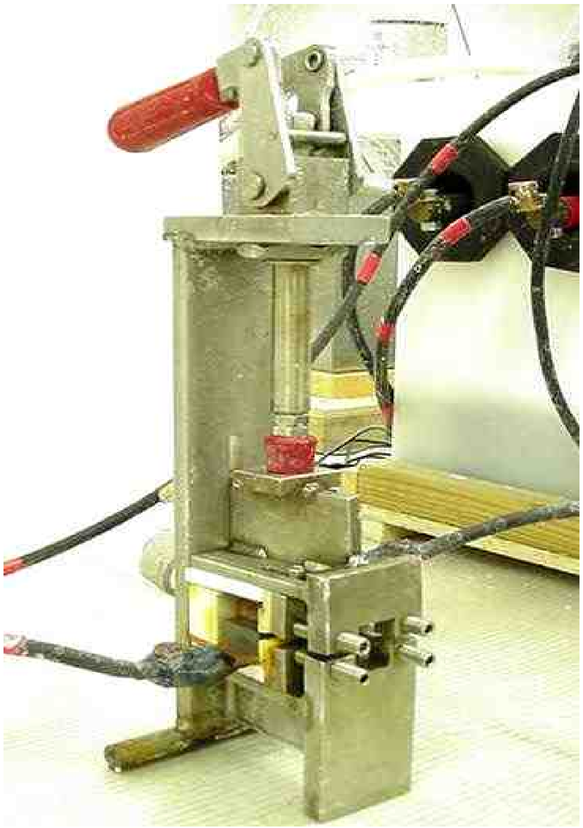

Figure 3. Fixture and tooling for Electrically Mediated Finishing and Electrolyte Flow Path on Workpiece Surface using Wedge Shape Tool

After each test, the metal removal rate (calculated from the change in thickness) and the test coupon surface roughness (R_a) were measured using a Mitutoyo depth measurer, Model ID-S1012E, and Mitutoyo Surftest profilometer, Model SV-400, respectively. Selected results for Ti-6Al-4V are given in Table 1.

Table 1. Experimental Results for Ti-6Al-4V

t_a/ ms	t_c/ ms	t_o/ ms	V_a/ V	V_c/ V	R_a/ µin	Removal Rate/ µm/s
Sodium Perchlorate Electrolyte						
DC	0	0	21	0	27	30
16	4	0	27	2.5	101.3	30
8	2	0	27	2.5	30.8	28
4	1	0	27	2.5	24.2	28.6
6.5	1.5	0	27	2.5	16	30
10	2	0	27	2.5	34	32
8	0	2	27	0	173.5	29.2
4	0	1	27	0	19.8	30.3
4	1	0	27	1.5	15.6	27
18.5% NaCl Electrolyte						
DC	0	0	21	0	34.0	24.5
8	2	0	27	3	17.3	25
8	2	0	26	2.3	21.3	25
6.5	1.5	0	26	2.3	17.8	23.7
7.5	2.5	0	26	2.3	25.0	20.5
8	2	0	26	2.3	23.8	23
8	2	0	26	2.3	24.0	21.1
8	2	0	26	2	22.8	20.9

The mean titanium removal rate was higher in the sodium perchlorate electrolyte and the mean surface roughness was lower in the NaCl electrolyte, for all three titanium alloys. Compared to DC electrochemical machining, the electrically mediated process significantly decreased the surface roughness and improved the removal rate in both sodium perchlorate and NaCl electrolytes.

The surface roughness R_a increased to a very high value in the NaCl electrolyte when the forward only electrically mediated parameters were used in the finishing process. The 18.5% NaCl electrolyte gave a low surface roughness and high removal rate for titanium alloys, compared to the other concentrations of NaCl electrolytes. Process parameters of 80% forward duty cycle and a 20% reverse duty cycle, with a frequency ~100-125 Hz, reduced the surface roughness value and gave a relatively high removal rate in both sodium perchlorate and NaCl electrolytes. Acceptable surface quality (R_a around 20 µin with a metal gray or shiny surface appearance) was observed on the Ti-6Al-4V and Ti17 coupon surfaces, but not on the Ti-6Al-2Sn-4Zr-6Mo coupons, in the NaCl electrolytes.

Effect of Electrically Mediated Surface Finishing on Fatigue Life

In ongoing work, Faraday is evaluating the effect of electrically mediated surface finishing on the fatigue life of specimens fabricated from a variety of alloys, such as Ti-6Al-4V, H-13 tool steel, 316 stainless steel, and Inconel® 718.

Round fatigue test specimens, shown in Figures 4 and 5, have been fabricated at The Ohio State University. Half of the specimens will be polished using the electrically mediated process, and half will be polished using typical manual finishing processes. The fatigue life of the specimens will be tested at Wright-Patterson Air Force Base (Dayton, OH), under a Collaborative Technology Clusters (CTeC) program, administered by the Edison Materials Technology Center (Dayton, OH). The fatigue life of the specimens polished by the electrically mediated process will be compared with those finished using manual methods.

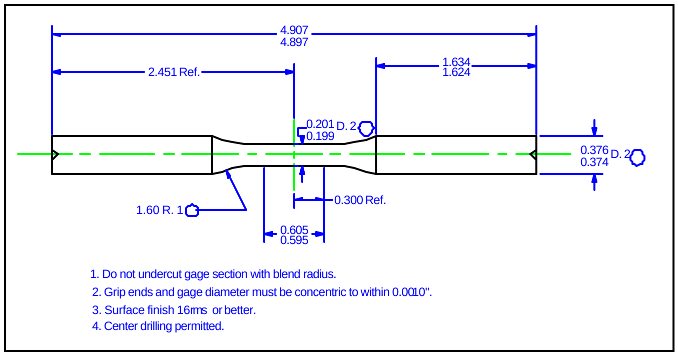

Figure 4: Schematic diagram of the round fatigue test specimens.

Figure 5: Photograph of the titanium fatigue test specimens.

A fixture for polishing the fatigue test specimens is currently being designed and fabricated by Faraday Technology Inc. The design of the polishing fixture will likely utilize a rotating apparatus, as shown in Figure 6. Results will be presented at the SURFIN/02 conference.

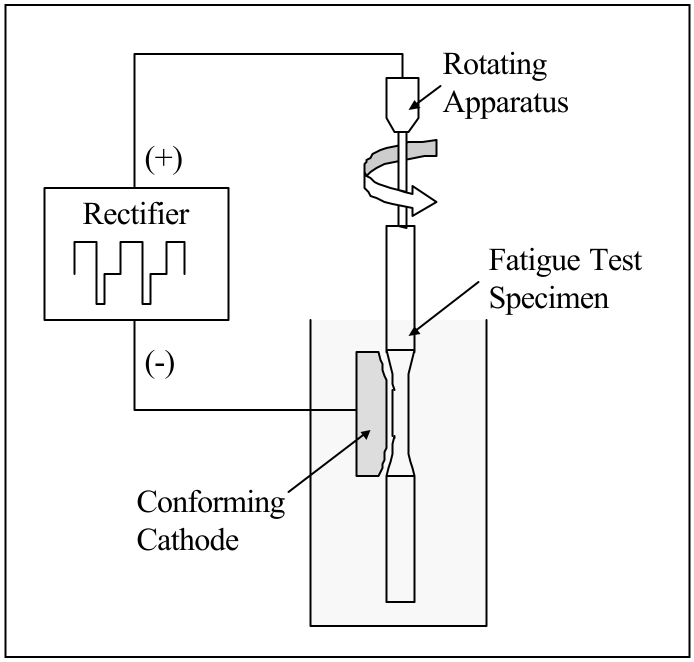

Figure 6: Possible design of a polishing fixture for the round fatigue test specimens.

Conclusions

Continuing work on the electrically mediated surface finishing process has concentrated on improving process control by using electrical mediation instead of chemical medition, specifically for polishing titanium alloys, using environmentally benign NaCl electrolytes. The results have shown an improved surface finish for titanium in NaCl electrolytes, compared to sodium peroxide electrolytes. Furthermore, the use of electrical mediation improved both surface finish and metal removal rates, compared to DC electrochemical processes.

Ongoing work is investigating the effect of electrically mediated surface finishing on the fatigue life of parts fabricated from titanium, and other passive alloys. Results will be presented at the SURFIN conference in June, 2002.

In summary, the electrically mediated finishing process is a robust process for surface finishing of 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 U.S. Air Force, the Edison Materials Technology Center, and the National Science Foundation.

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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