AN ABSTRACT OF THE THESIS OF

Bruce C. Bingham for the degree of Master of Science in Mechanical Engineering presented on June 11, 2014.

Title: An Investigation into the Electrochemical Removal of Unwanted Residual Material Protrusions from Parts

Abstract approved:

______________________________________________________
John P. Parmigiani

Manuscript I: The removal of residual casting material from gating has traditionally been performed by abrasive grinding techniques. However, high amounts of belt wear can occur when working with high strength alloys, especially those typically seen in the aerospace industry. An alternative machining process called electrochemical machining (ECM) uses electrolysis to precisely remove material at high rates. ECM has many advantages over conventional grinding: no tool wear, no induced mechanical or thermal stresses, and high removal rates independent of material hardness or strength. The industrial application of ECM to residual casting material removal can potentially realize large cost savings and decreased component processing time by eliminating belt wear and increasing material removal rates. The approach taken in this work is the design and fabrication of a laboratory apparatus for the purpose of testing the ECM of casting material. Commercial ECM machines, while more powerful, can be excessively large and cost prohibitive when performing an initial feasibility study. Many times these commercial machines are calibrated to mass produce a specific part, and do not have the level of variability desired for laboratory experimentation. The test apparatus presented provides a robust and
relatively low cost method of investigating the applicability of ECM to this purpose. The device is comprised of an electrolyte filtration and delivery system, a stable machining enclosure, and a single axis computer controlled tool. The ECM variables that can be adjusted include electrolyte temperature, mass flow rate, applied voltage, tool feed rate, and electrode gap. Process data from these variables is collected via multiple sensors in the machine and provides real-time feedback to users. A universal tool connection and workpiece fixture allows for different experimental setups to be easily tested. From experimentation with this test apparatus, it will be possible to identify optimum methods for the ECM of these residual casting artifacts.

**Manuscript II:** Rapid tool wear can occur during the removal of residual protrusions from high strength alloy parts. In this work, a new method of using electrochemical machining (ECM) capsules to remove protrusions without any tool wear is presented. An ECM capsule is an electrochemical cell that is placed on a part over a protrusion, and removes material through electrolysis. These capsules are advantageous due to their low cost and simplicity compared to conventional ECM equipment. The use of these capsules is demonstrated in two ways. First, a parameter optimization was performed on the material removal rates of Inconel 718 and Titanium 6-4 bar stock using a $2^{8-4}$ fractional factorial design of experiments. Then, using the optimized values, torch-cut protrusions were machined off of manufactured Titanium 6-4 parts. Inherent variability in the geometry of the protrusions rendered it difficult to completely remove the protrusions without cutting into the part. Surface scans of the parts showed that the capsules were able to successfully remove between
63% and 80% of each protrusion. Properly integrated into a protrusion removal operation, these ECM capsules could offer significant cost savings due to their ability to machine protrusions with no incurred tool wear.
An Investigation into the Electrochemical Removal of Unwanted Residual Material Protrusions from Parts

by

Bruce C. Bingham

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APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial, and Manufacturing Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Bruce C. Bingham, Author
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Atanas (Nick) Atanasov assisted with the initial design of the electrochemical test apparatus. He was also involved in the writing of the manuscript that described the design and fabrication process.
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Chapter 1: General introduction

The aim of this work is to investigate the application of electrochemical machining (ECM) to the removal of unwanted protrusions from parts. This thesis is composed of two manuscripts: i) The Design and Fabrication of an Electrochemical Machining Test Apparatus, and ii) A New Method of Electrochemically Removing Large Residual Protrusions from Parts.

The first paper describes a laboratory ECM test apparatus that was designed and fabricated at Oregon State University. The ECM test apparatus has the advantages of being much lower cost than a commercial ECM machine, is sized for laboratory power, and can be easily modified for different experimental needs. The apparatus was extensively used to test different methods of ECM tooling for protrusion removal.

The second paper describes a new method that was developed of electrochemically machining protrusions using ECM capsules. An ECM capsule is an electrochemical cell that is placed over a protrusion to be removed, and removes material from the protrusion through electrolysis. These capsules are advantageous due to their simplicity, and the fact that multiple units can be used to machine different protrusions on a part simultaneously. The general design of the capsules, optimization of material removal rates, and the machining of protrusions on manufactured parts is discussed in this paper.
Chapter 2: The Design and Fabrication of an Electrochemical Machining Test Apparatus

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Abstract

The removal of residual casting material from gating has traditionally been performed by abrasive grinding techniques. However, high amounts of belt wear can occur when working with high strength alloys, especially those typically seen in the aerospace industry. An alternative machining process called electrochemical machining (ECM) uses electrolysis to precisely remove material at high rates. ECM has many advantages over conventional grinding: no tool wear, no induced mechanical or thermal stresses, and high removal rates independent of material hardness or strength. The industrial application of ECM to residual casting material removal can potentially realize large cost savings and decreased component processing time by eliminating belt wear and increasing material removal rates. The approach taken in this work is the design and fabrication of a laboratory apparatus for the purpose of testing the ECM of casting material. Commercial ECM machines, while more powerful, can be excessively large and cost prohibitive when performing an initial feasibility study. Many times these commercial machines are calibrated to mass produce a specific part, and do not have the level of variability desired for laboratory experimentation. The test apparatus presented provides a robust and relatively low cost method of investigating the applicability of ECM to this purpose. The device is comprised of an electrolyte filtration and delivery system, a stable machining enclosure, and a single axis computer controlled tool. The ECM variables that can be adjusted include electrolyte temperature, mass flow rate, applied voltage, tool feed rate, and electrode gap. Process data from these variables is collected via multiple sensors in the machine and provides real-time feedback to users.
tool connection and workpiece fixture allows for different experimental setups to be easily tested. From experimentation with this test apparatus, it will be possible to identify optimum methods for the ECM of these residual casting artifacts.

1. Introduction

The conventional milling, turning, and grinding of high strength alloys can pose challenges due to the large cutting forces required, fast tool wear, and low machining rates. High cutting forces can cause premature damage to tooling and induce excessive thermal and mechanical stresses into the workpiece. Alternatives to conventional machining methods exist and are being more critically considered as the market demand for stronger and harder materials increases.

Electrochemical machining (ECM) is a nonconventional machining process which offers numerous advantages when dealing with hard to machine materials and complex part geometries. The advantages of ECM are numerous: complex geometries can be easily machined into parts at rates independent of the part’s hardness or strength, no thermal or mechanical stresses are induced because the tool does not touch the workpiece, and high levels of surface finish can be obtained because material is incrementally removed at an atomic level. ECM can be thought of as highly accelerated and controlled corrosion. This process works on the principle of electrolysis; excess workpiece material is rapidly dissolved through electrochemical action [1].

Electrolysis is the initiation of a chemical reaction by the passing of direct current through electrodes submerged in an electrolyte solution. A potential is applied to two
electrodes that are separated by an electrolyte. The ions in the electrolyte carry electrons from the negatively charged cathode (tool) to the anode (workpiece). In order to sustain the electron flow, electrons are stripped from the anode and pass through the external circuit. The now positively charged molecules on the surface of the anode release and dissolve into the electrolyte. Figure 1-1 below outlines the action of the electrolytic cell [2].

Despite the previously mentioned advantages of this process, ECM is typically only used in industry for specialized applications. Nonconventional machining processes account for about 1% of total production, while ECM specifically holds about 0.15% [2]. The high initial equipment and tooling costs can be an intimidating barrier when considering the application of ECM to specific parts or applications. A large operator knowledge base is also needed in order to troubleshoot issues that will
arise. Common industry applications include the profiling of turbine blades, die sinking, and the cutting of the precise spiral groves on the interior of rifle barrels. ECM is a good fit for these applications due to the complex 3D geometry requirements, and hard materials used in the parts. The main economic advantages of this process are realized when mass production of a part with complex geometries is required [1].

Academic research has been conducted worldwide to further aid the understanding of this process [3-11]. One of the first analytical models was generated by Bhattacharyya et al. in 1973. Three electrochemical machining (ECM) constraints, electrolyte boiling, flow instability, and workpiece passivation, were assumed to be limitations on the maximum achievable material removal rate (MRR). Input variables were chosen to be tool feed rate and electrolyte flow velocity, and a single objective optimization result was obtained using graphical solutions [3]. These experiments provided much of the foundation for the work that followed. Further attempts have been made to derive analytical models of the process [3-6]. These models are useful for getting approximate ranges for machining parameters; however, most of these models were generated assuming a planar tool and workpiece [4,5,7,8]. Hence, these models are generally not valid for parts with different geometry or size. Multi-objective optimization techniques have also been commonly used to balance desired process responses: material removal rate, surface finish, overcut. Most recently, the vast increases in computing power has led to the use of evolutionary algorithms as viable optimization techniques [9-12]. A common subset of these are genetic algorithms which try to mimic environmental and animalistic behaviors to “evolve”
an initial design set into an optimal solution. These techniques are useful for generating Pareto optimal conditions, or solutions that are non-dominated. This allows users to essentially trade off one response for another that is better suited to the particular circumstance. However, these methods do require previous experimental information to determine relationships.

Calibration is almost always required for tooling geometry other than simple planar surfaces. For instance, consider the ECM variable electrolyte mass flow rate. Rough ranges of this parameter are provided as, “10 to 30 gal/min per 1000-A of electrolyzing current [4].” However, depending on the tool geometry and electrode gap size, the mass flow rate must be adjusted appropriately. Too high of a flow rate can lead to poorly machined areas due to cavitation [2]. On the other hand, too low of a flow rate can cause problems with inadequate flushing of dissolved material and gaseous by-products. These constraints create upper and lower bounds on the mass flow rate. Difficulty in determining appropriate ranges of these machining variables leads to extensive testing to properly calibrate the system for a specific part. This can be expensive and time consuming when performed on a full scale machine. A small and robust research unit that provides the ability to easily test ECM machining parameters would be greatly beneficial and could potentially save both time and money during the calibration phase.

This paper presents the design and fabrication of an ECM test apparatus. The independent input parameters are the electrolyte type, concentration, temperature, mass flow rate, tool feed rate, applied voltage, gap size, and workpiece type and material. The dependent outputs are surface roughness, material removal rate, and
machining overcut. This device allows users to conduct experiments to determine optimal ECM parameters and methods. The low cost of the device compared to that of a commercial machine makes it favorable for conducting initial feasibility studies and determining acceptable ranges of key machining variables. Specifically, this device will be used to research the ECM of residual casting material; however, it can also be generalized to test most general ECM experimental setups. Sections of castings will be placed in the machining chamber and process responses will be studied. Currently, the tooling is designed for planar samples; however, it is possible to fabricate new tools to test different geometries and curvatures.

2. Device design

The purpose of the device, as shown below in Figure 1-2, is to provide a simple and cost-effective method for testing different electrochemical machining setups and parameters.
There are six major sub-systems in this design:

1) Structure, Machining Cell, and Workpiece Fixture
2) Electrolyte System
3) Motor and Supporting Fixture
4) Tooling Design
5) Control and Feedback System
6) Safety Systems

A sample is tested by placing it in-between two brass clamps located in the machining chamber. The tool is located on a vertical carriage assembly above the workpiece, and has a programmable feed rate. The electrolyte is delivered to the workpiece through a tapered flow slot in the tool. A stainless steel basin underneath
the workpiece assembly collects the displaced electrolyte and funnels it back into the storage tank. The entire machine is fabricated from corrosion resistant material: stainless steel, aluminum, brass, rubber, and PVC plastic. An emergency stop button installed on the front of the machine is wired to instantly cut power to the motor, power supply, pump, and electrolyte heaters should any problems arise. Figure 1-3 shows a picture of the fabricated apparatus.

![Fabricated ECM test apparatus](image)

**Figure 1-3**: Fabricated ECM test apparatus

2.1. *Structure, machining cell, and workpiece fixture*

The structure of the ECM machine serves as the main support for all of the ECM components. While machining, the ECM tool resides within .005 to .02in of the
workpiece and therefore adequate structural support should be provided as to limit excessive deflections [17]. The frame should not only limit vibrations from the rest of the system, but it should also protect against movement induced by outside sources e.g., operators and other machinery. The system is shown below in Figure 1-4.

![Figure 1-4: Machining chamber, workpiece vice, electrolyte collection basin](image)

The overall structural system for the device is constructed from rigid steel members welded together to make a stiff frame. The structure is 32.75in long, 25in wide, and 33.5in tall. The frame rests on casters to facilitate movement of the machine. The machine cell, a protective machining chamber, is bolted on top of the main structural frame; the cell is the compartment within which the workpiece clamp, tool, and motor fixture are contained. The machine cell features 1.18in extruded aluminum channel for the outside frame and 0.24in, clear, acrylic panels for all the walls. The machining cell has a 0.024in thick, 316 stainless steel electrolyte
collection basin fastened to the bottom, which serves as a means of collecting the expended electrolyte. The cell features a lockable door in order to provide access to the components within it. All of the acrylic panels are lined with rubber seals and any additional openings are sealed with silicon caulking. The cell contains the workpiece fixture which is used to secure the workpiece in place during machining. The workpiece fixture also provides an outlet for the electrical current that is passed through the workpiece from the tool. Without this outlet, a closed circuit would not exist and no machining would take place. The workpiece fixture consists of a machined 6061 aluminum base, an acetal homopolymer, DuPont-Delrin, insulation plate, and two brass jaws. The brass jaws are held secure to the base by acetal insulated bolts and can be slid outward to encompass up to an 8in wide workpiece. Course fixture adjustment can be made by shifting the brass jaws and the micro adjustment bolts can be used for finer adjustments.

2.2. Electrolyte system

The electrolyte system consists of the electrolyte tank, piping system, fluid pump, filter, heaters, and all regulatory sensors. The electrolyte system is crucial in the ECM process as it must supply electrolyte to the tool at a constant rate, maintain the fluid at a constant temperature, and maximize the usable life of the solution. The components are shown below in Figure 1-5.
A 1.5 horsepower stainless steel centrifugal pump circulates the electrolyte from the electrolyte basin to the tool through polyvinyl chloride (PVC) schedule 40 piping. The PVC piping in the machine was selected in order to withstand the maximum pressure within the system, 150 psi, and maximum temperature, 60 degrees C. As electrochemical machining takes place, the electrolyte gradually loses its ions due to the formation of metallic by-products i.e., formation of sludge by the bonding of the machined metal atoms with the ions within the electrolyte. The loss of ions cannot be prevented, so the electrolyte needs to be replaced periodically; however, the sludge by-product can be removed from the electrolyte in order to provide for a purer electrolyte. If the sludge is not removed, it can impede flow through the tool opening and also create a short within the system (the sludge branches the tool and workpiece...
and forms a very low resistance connection). The sludge in the ECM machine is removed from the electrolyte by a wire-mesh, 74 micron, particulate filter. The electrolyte is forced through the filter by the induced pressure of the pump; thus, the filter requires occasional cleaning as to prevent flow restrictions. The electrolyte within the system is maintained at a constant temperature by two stainless steel, coiled heaters. The heaters are submerged in the electrolyte basin and are regulated through the data acquisition system (DAQ) and LabView. When the temperature is either too high or low, the control module in the DAQ system sends a signal to the heaters to turn off or on. A thermocouple within the PVC piping, close to the final exit point, provides constant feedback on the electrolyte temperature; hence, the entire temperature control system is automated. To monitor the flows within the PVC piping, a manual flow transducer was installed.

2.3. Motor and supporting fixture

The motor and supporting fixture provide for movement and stability of the tool, respectively. The 1.8 degree stepper motor rotates a lead screw, which translates rotational motion into linear motion, and moves the tool connection plate vertically either upward or downward. The stepper motor/lead screw assembly provides for 12 micrometer/step precision and was selected to have the torque necessary to overcome the hydrodynamic forces created by the pumped electrolyte. The motion of the lead screw moves the tool connection plate, which is stabilized by two stainless steel guiderails; the entire assembly is fastened to the backplate of the supporting fixture. The supporting fixture is comprised of two triangular, 11 inch tall aluminum supports. The tool connection plate consists of an aluminum L-bracket fastened to the tool at
one end and an acetal homopolymer, DuPont-Delrin, block on the other. The free end of the block is fastened to a plate on the guide screw. This configuration of the connection plate allows for complete insulation of the supporting structure from the plate, and a diagram is shown below in Figure 1-6.

![Motor assembly and tool mount](Image)

Figure 1-6: Motor assembly and tool mount

Complete insulation is important because a large amount of current flows through the tool and must be contained as to not energize the entire structure. This would cause a safety hazard and possible damage to other machine components. Limit switches, which stop motor movement if engaged, are installed on the top and bottom of the acetal block as to regulate the working range of the motor. The entire assembly is controlled by an Arduino microcontroller which is connected to a Geckodrive motor driver. The Arduino is coded using the C programming language and is
interfaced with the LabView software by National Instruments. This provides for consolidation between the controls for all the machine components.

2.4. Tooling Design

Proper tooling design is one of the most critical parts of an ECM system. Uneven electrolyte distribution across the workpiece can lead to differential rates of machining and even short circuits. A 1.30 mm wide diagonal flow slot supplies electrolyte through the tool to the workpiece. The tool consists of two brass halves that are bolted together and sealed with a rubber gasket. The electrolyte hose connects to a barbed fitting that is threaded into the top half of the tool, and an interior taper smoothly funnels the electrolyte to the diagonal slot. The slot and taper were machined on a CNC machine with a 0.762 mm precision endmill. The two halves of the tool can be seen in Figure 1-7.

UL certified 3/0 welding cable was selected for the power cables because of the greater flexibility compared to that of conventional cable. The positive end of the 3/0
power supply wire connects to a copper lug located on the side of the tool. The tool fixture is also insulated from the remainder of the system with a ¾” thick piece of Delrin between the z-axis carriage and tool. The experimental setup is shown in the Figure 1-8 below.

![Figure 1-8: Sample of experimental setup for machining gating on planar samples](image)

The DCR 20-250 unit was chosen as the main power supply because it only requires 208V power that is readily available in most laboratories. It has a variable voltage control for adjustment from 0 to 20 volts, and built in circuit breakers to protect against overcurrent. The DCR 20-250 can deliver up to a maximum of 250 amps. Even though the workpiece vice and machining cell can accommodate large workpieces, the actual machining area is constrained by current density limitations. The minimum current densities required for ECM are about 10 to 15 amps/cm² [4]. Below these values, inefficient machining and poor surface finishes occur. From these numbers, this apparatus has an idealized maximum machining area of approximately 25 cm², or 3.8 in². A larger power supply is necessary for machining areas greater than this under ECM conditions.
2.5. Control and Feedback System

Machining parameters are measured with various transducers and interfaced with a computer through a NI cRIO-9076 data acquisition unit. Electrolyte temperature is continuously measured with a digital temperature sensor. Two 2000 watt electrolyte heaters are controlled via contactors and are connected to Labview; the heater are programmed to automatically turn on and off in order to maintain an approximately constant electrolyte temperature at a user defined level. An inline flow meter, 0 to 10 gpm, allows for monitoring of the electrolyte mass flow rate. It is important to note this unit requires a visual reading from the operator; it is not integrated into the Labview controller and thus does not output continuous flow readings. A Hall Effect current transducer takes continuous measurements of DC current from 0 to 250 amps. This allow for accurate monitoring of the total amount of charge passed through a sample during an experiment. It is also possible to see the initial transient current responses as the oxide layers on the workpiece are broken down. A protection circuit was implemented to protect the machine from damage if a short circuit occurs. Voltage readings are taken on each side of the inter-electrode gap; if the differential value drops very close to zero this means there is little or no resistance across the electrolyte solution. If this is detected, a signal is sent to the tool to reverse the feed direction. The diagram is shown below in Figure 1-9.
Two NEMA #1 boxes house all the electrical components; the high and low voltage components are separated to reduce electromagnetic interference. Corrosion resistant conduit protects wires in the machining chamber from electrolyte splashes. Aluminum conduit protects all other exposed wires.

**3. Discussion**

A reasonably low cost device was needed to investigate the applicability of ECM to the removal of residual casting material. Commercial ECM units are powerful, but can be prohibitively expensive and often lack the adjustability needed for a preliminary research study. The device presented in this paper provides a viable solution to this problem. A few of the major benefits of this device compared to a commercial machine include:

i. Substantially lower cost

ii. Smaller electrolyte reservoir volume

iii. Large workpiece size accommodation

iv. Open access to all systems

v. User customization possible
As previously stated, this apparatus runs off of readily available 208V power, which eliminates the need for expensive electrical upgrades that become necessary for larger machines. Also, the system was fabricated from commercially available stock and components which are significantly cheaper than custom-made parts. The small electrolyte reservoir allows for easy testing of different solutions; filling industrial sized tanks with large amounts of electrolyte can be expensive if a user only needs to run a small number of tests. The unique workpiece vice can accommodate large sample sizes, which is essential when experimenting with the removal of gating material from sections of larger castings. Easy access is provided to all machine systems so users can modify components as needed for specific research needs.

Preliminary testing of system components has been performed. The electrolyte flow and collection system were tested with water, and leaks were noted around the corners of the machining cell. Silicone had been used to seal the gaps in-between the extruded aluminum supports; it is recommended that an O-ring cord gasket be used to provide a better seal. A batch of electrolyte containing dissolved particulate was used to test the filter. Out of a sample of ten particles from a drop of electrolyte in the reservoir, none were noted above a diameter of 74 microns. It has been recommended to remove particulates above this diameter to decrease probability of short circuits caused by material buildup in the inter-electrode gap [4]. The filter must be periodically cleaned during operation; hence, adding another filter unit in parallel would increase the capacity of the system. Cleansing of the filter can be performed in less than five minutes. While the motor and control system are operational, they need additional fine-tuning. Interference problems affect the waveform step signal sent to
the motor driver. Shielded cable should be used when possible for all control wiring, and proper grounding of all components is crucial. Fine motor control is necessary in ECM to maintain precise electrode gaps.

4. Conclusion

An ECM apparatus for testing different experimental setups and gathering machining process data has been presented. This device is a low cost, robust alternative to purchasing an industrial unit for an initial feasibility or research study. The design can be replicated, and improved, to provide a platform upon which ECM testing can be more widely conducted. Access to lower cost ECM equipment will allow more academic and industrial research to be performed, and ultimately allow for a deeper understanding of this process. This device will be used to conduct experiments on planer samples of castings containing residual gating material. Radial overcut, machining efficiency, surface roughness, and material removal rates will be studied. From the data gathered with this device, optimal methods for the electrochemical removal of this residual material will be identified.

5. Acknowledgements

Special thanks to Masashi Borges-Silva, Andrew Gabler, Felicia Glenn, Alexandria Gill, Patrick Sieg, Adlen Zouyed, Benjamin Carpenter, Robert Williams, and Luke Zollinger for their assistance in the design and fabrication of the device.
6. References


Chapter 3: A New Method of Electrochemically Removing Large Residual Protrusions from Parts

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Abstract

Rapid tool wear can occur during the removal of residual protrusions from high strength alloy parts. In this work, a new method of using electrochemical machining (ECM) capsules to remove protrusions without any tool wear is presented. An ECM capsule is an electrochemical cell that is placed on a part over a protrusion, and removes material through electrolysis. These capsules are advantageous due to their low cost and simplicity compared to conventional ECM equipment. The use of these capsules is demonstrated in two ways. First, a parameter optimization was performed on the material removal rates of Inconel 718 and Titanium 6-4 bar stock using a 28-4 fractional factorial design of experiments. Then, using the optimized values, torch-cut protrusions were machined off of manufactured Titanium 6-4 parts. Inherent variability in the geometry of the protrusions rendered it difficult to completely remove the protrusions without cutting into the part. Surface scans of the parts showed that the capsules were able to successfully remove between 63% and 80% of each protrusion. Properly integrated into a protrusion removal operation, these ECM capsules could offer significant cost savings due to their ability to machine protrusions with no incurred tool wear.

1. Introduction

Large unwanted residual protrusions commonly need to be removed from parts during manufacturing. Conventional machining methods, such as grinding and milling, are frequently used due to their simplicity and high material removal rate (MRR) capabilities. Generally, there is no need to consider more complicated processes. However, high amounts of tool wear can occur if the protrusions being
removed are made of high strength alloys, e.g. stainless steel, and nickel and
titanium-based alloys.

The difficulty in machining these high strength alloys is attributed to their
excellent mechanical and thermal properties [1]. Stainless steel and nickel-based
alloys have the tendency to work harden, which generates high heat concentrations at
the cutting edge of the tool [2]. Titanium has been considered difficult to machine
because of its propensity to weld itself to the tool due to its high chemical reactivity
[3]. These characteristics can lead to high rates of tool wear; the machinability of
these alloys has been well studied and many comprehensive reviews are available [4].

Due to these difficulties, nonconventional methods have often been used to
machine these types of alloys. One method, electrochemical machining (ECM),
removes material from a workpiece without any tool wear. ECM can be described as
reverse electroplating. A tool electrode and a workpiece electrode are held in close
proximity to each other. Then an electrolyte, or ionic substance, is pumped through
the electrode gap. An external voltage applied between the two electrodes induces
electrolysis, or machining of the workpiece.

ECM has a few distinct advantages over conventional machining methods.
Because material is removed through electrolysis, no tool wear is incurred. Also,
because ECM is a non-contact process, the workpiece surface does not exhibit any
thermally affected zones [5]. Finally, high MRR’s and precise surface finishes can be
obtained with even the hardest materials [6]. However, ECM is a complex process,
and is generally limited to specialty applications, including the profiling of turbine
blades [7], surfacing of medical implants [8], the machining of thin walled components [9], and deburring of parts [10].

The majority of the literature on electrochemical protrusion removal is focused on electrochemical deburring (ECD). ECD can be a quick method of removing burrs that are otherwise difficult to remove, such as burrs occurring at the intersection of two drilled holes. Some ECD apparatuses will position a tool close to the burr and machine for a set period of time [10]. Others will immerse an entire part in an electrolyte bath. The machining current then concentrates at the protruding burrs and preferentially removes them from the part [11]. However, these ECD operations are typically only used to remove small volumes of material, where the machining on adjacent surfaces of the part is minimized.

Limited information exists on the electrochemical removal of larger protrusions from parts. Westley et al. described their work developing slotted ECM tooling for the removal of a large residual casting gate protrusion from an interior pocket of a turbine blade [12]. The focus of their work was to study electrolyte flow and electrode tool design. General guidelines to use while designing ECM tool electrodes were provided. However, the MRR’s of the protrusions and the types of tolerances achieved through ECM were not discussed.

An effective method for removing large protrusions from parts through ECM still needs to be determined. Even with a full-scale ECM machine, it is not intuitive how to position a complex part inside the machine in order to machine off a large protrusion. Often these protrusions are located on interior part surfaces which can be
difficult to reach with a large machine. If a practical method of using ECM to machine these protrusions could be determined, the benefits of ECM could be realized (no tool wear and no thermally affected workpiece zones).

In this paper, a method of using small modular ECM capsules to remove large protrusions from parts is presented. An ECM capsule is a small electrochemical cell that is placed on a part over a protrusion to be machined, and removes material through electrolysis. The ECM capsules are relatively simple and have the advantage of being much smaller in comparison to a full-scale ECM machine. Also, once a part is electrified, multiple ECM capsules can be used to simultaneously machine multiple protrusions on different areas of the part.

The remainder of the paper is outlined as follows. In section 2, the general design of these ECM capsules is described. In section 3, a $2^{8-4}$ fractional factorial design of experiments with one replicate was conducted to optimize the MRR’s of two aerospace alloys: Titanium 6-4, and Inconel 718. Finally, in section 4, these capsules are tested on different torch-cut protrusions on Titanium 6-4 parts. Conclusions and recommendations for future work are given in section 5.

2. ECM capsule

This section i) describes the function and main components of an ECM capsule, iii) provides general guidelines when designing an ECM capsule for a specific application, and iii) shows an example of an ECM capsule.
2.1. ECM capsule description:

An ECM capsule is a small electrochemical cell that is placed on a part over a protrusion that is to be removed. The ECM capsule is then connected to an external pump and power supply, and machines the protrusion through electrolysis. The ECM capsule consists of four main components: a capsule housing, a tool electrode, a drive system, and an electrolyte connection. For the following discussion, refer to Figure 3-1 where a diagram of an ECM capsule is shown.

![Diagram of ECM capsule](image)

Figure 3-1: A diagram of an ECM capsule removing a protrusion from a part. There are four main components of an ECM capsule: the capsule housing, the tool electrode, the motor and drive system; and the electrolyte connection

The capsule housing is the main body of the ECM capsule, and functions as a platform to integrate the other components. The housing has a slot for the tool electrode, and has holes to mount the motor and drive system. The lower part of the housing contains the electrolyte connection, and the interior is shaped in order to
direct the electrolyte flow through the gap in-between the protrusion and the tool electrode.

The tool electrode is a piece of metal with the same size as the protrusion to be removed, and acts as the cathode needed for the electrolysis reaction to occur. The tool electrode sits in a slot in the center of the capsule housing directly above the protrusion. An attachment point in the tool allows the negative lead of an external power supply to be connected. The edges of the tool that interface with the electrolyte are radiused in order to help ensure smooth electrolyte flow. The interior of the tool is hollow, which allows the position of the tool to be controlled by the motor and drive system.

The motor and drive system consist of a motor connected to a precision lead screw by a shaft coupler. This system is used to control the position of the tool. As the protrusion is machined away, the motor feeds the tool electrode down towards the part by rotating the lead screw at a predefined rate. The lateral position of the lead screw is restrained by a radial bearing that is pressed into the capsule housing. The bearing helps to eliminates tool deflection that occurs from the high electrolyte flow velocities on the rear face of the tool.

The electrolyte connection is a coupling point located in the side of the ECM capsule. It functions to allow the capsule to be connected to an external electrolyte system, which provides pumping, filtration, and storage of the electrolyte. Electrolyte enters the capsule through this point, and then flows across the machining surface through the gap between the tool electrode and protrusion. The electrolyte flushes
away the dissolved material as the protrusion is machined. The electrolyte exits through the front of the capsule, at the opposite end from the electrolyte connection.

An ECM capsule has all of the same major components as a full-scale machine, but in a smaller size. Each ECM capsule is made up of four main parts: the capsule housing, which is the main body of the capsule; the tool electrode, which is the cathode in the electrolysis reaction; the drive system, which controls the position of the tool electrode; and the electrolyte connection, which allows electrolyte to be pumped into the capsule from an external system. The ECM capsules are a small, low cost alternative to a commercial ECM machine for machining protrusions on electrically-conductive parts.

2.2. General ECM capsule design guidelines

During testing and experimentation with different ECM capsules, several items were found to improve the machining performance of the capsules. While these guideline are specifically for ECM capsules, the principals behind them are general and can be applied to a variety of electrolyte side-flow tool electrode designs in ECM. The findings are summarized below:

1. Provide a radius on the edges of the tooling electrode that interface with the electrolyte. A 5mm (0.25”) radius has been recommended for electrolyte supplied at a 90 degree angle to the machining surface [12]. In this work, the electrolyte was supplied parallel to the machining surface; a smaller 0.05” radius was found to work well. These radiuses are shown in Figure 3-2 below.
Figure 3-2: Electrode edge radiuses; the side flow electrode used in this work (left), and the slotted electrode (right) used by Westley et. al

2. The electrolyte flow path should be as short as possible to minimize the length of time that the machining by-products are in the electrode gap. Whenever possible, design the ECM capsule to direct the electrolyte flow across the shorter side of the protrusion.

3. The width of the interior capsule geometry should be as small as possible, but still able to fit the largest anticipated protrusion. This will help minimize the undercutting occurring from high electrolyte velocities that diverge around the protrusion.

4. Ensure the tool electrode has sufficient travel to clear the tallest anticipated protrusion. Tall protrusions may require elongating the bottom half of the capsule, and raising the electrolyte connection point.

5. Use insulation. Insulation around the protrusion is necessary to prevent overcutting onto the adjacent surfaces of the part. Thin rubber sheets with cutouts that were placed around the protrusions were found to work well. Taping around the protrusion was also tested, but the tape had the tendency to pull up along the edges where it was subject to high electrolyte flow velocities.
6. The tool electrodes in this work have been designed to be the same size as the area where the protrusion interfaces with the part. More optimal electrode designs could exist, e.g. slightly oversized or undersized electrodes.

Clearly, many of these recommendations are general. However, by adherence to these design guidelines, most major problems can be avoided. Good engineering judgment should always be used in conjunction with these recommendations.

2.3. Example of an ECM capsule:

When designing an ECM capsule to machine a new type of protrusion, it is often helpful to reference pictures or models of successful existing designs. An example of an ECM capsule design is shown in this section.

The ECM capsule, shown in Figure 3-2, was designed to remove a $\frac{3}{4}'' \times \frac{3}{4}''$ square protrusion from a flat part. Initially, these $\frac{3}{4}''$ square protrusions were milled from blocks of aluminum for testing. Thus, these protrusions were virtually perfect: vertical walls, no radius into the part, and smooth top profiles. This allowed the bottom half of the capsule to be machined to near-perfect fit; a luxury not available if high variation is present in the protrusion. Note the simple electrolyte flow path. Electrolyte flows from the electrolyte hose connection, over the protrusion, and out the front of the capsule with minimal variation in flow path. Also, the top half of the tool electrode was widened in order to accommodate a tapped screw hole to connect the power lug to. This was done because the tool electrode was hollow; there was insufficient material to drill another hole to connect the power cable lug.
Figure 3-3: A CAD model of an ECM capsule removing a $\frac{3}{4}$" x $\frac{3}{4}$" protrusion off of a flat part

While identical protrusion geometries to the one shown will likely not exist, the general design principals are emphasized. Using the ideas presented, it should be possible for a designer to create an ECM capsule to meet their specific protrusion removal needs. In the next sections, the MRR and accuracy capabilities of these ECM capsules are tested and evaluated through experimentation.

3. Optimization of MRR

The goal of this section is to optimize the MRR of the ECM capsules. Optimization of a response can be done in different ways, but a common method is to use a statistically designed experiment (DoE) to identify the effects of various
parameters on a response of interest. Then, the key parameters can be run at levels which produce an optimal response. In this work, a $2^{8-4}$ resolution IV fraction factorial experimental design with one replicate was conducted on eight machine parameters in order to maximize MRR’s of the ECM capsules.

3.1. Equipment:

An ECM capsule which could machine square samples of bar stock was used for the DoE. Two set screws held the square samples in place. An electrified vise clamped onto the bottom of the samples to connect them to the positive lead of a power supply. Figure 3-3 shows a diagram of the capsule setup used.

The electrolyte system and power supply of a laboratory ECM test apparatus was used to supply electrolyte and current to the capsule. The electrolyte system consisted of a centrifugal pump, a flow rate sensor, and a gate valve to control the flow rate. The power supply was a Sorensen DCR 20-250A unit, with 300A welding cable used for the power leads. Additional information on the design of the laboratory ECM apparatus is available [13].
Figure 3-4: Experimental setup used in the DoE. Square samples were inserted into the bottom of the ECM capsule, and were held with set screws. An electrified vise was used to hold the samples in place and connect them to the power supply.

3.2. Materials:

Square 3/4” by 3/4” samples of Titanium 6-4 and Inconel 718 bar stock were used for experimentation. By using square bar stock for samples, the same sample geometry was preserved for every test in the DoE.

3.3. Method:

A 2^8-4 fractional factorial DoE with a single replicate was conducted to optimize the MRR response. A total of 32 tests were run, with one additional replicate which was blocked. The order of the experiments was randomized within each block, and the tests were run for two minutes each. The levels of each parameter used in the DoE
were determined from a preliminary study, and are shown in Table 3-1. Three parameter interactions and higher were ignored.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Titanium 6-4</td>
<td>Inconel 718</td>
</tr>
<tr>
<td>Flow (gpm)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Feed (mm/min)</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Concentration (% by weight)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Temperature (C)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>NaCl</td>
<td>NaNO₃</td>
</tr>
<tr>
<td>Gap (mm)</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3-1: Parameters with the corresponding low and high levels used in the $2^{8-4}$ fraction factorial DoE

The response measured during the DoE was the amount of material removed during each test. The amount removed was measured by weighing the sample before and after every test on a KERN PEJ 4200-2M precision balance, which is accurate to one hundredth of a gram.

3.4. Results:

The $2^{8-4}$ fractional factorial DoE revealed that the material type, flow rate, voltage, concentration, an interaction between material type and concentration, and gap size all had significant effects on the material removal rate at a significance level of 0.05. These results can be seen by the Pareto chart of standardized effects shown in Figure 3-4.
Because this was a fractional factorial DoE, the AE interaction was aliased with three other two-parameter interactions: AE = AE + BF + CH + DG. To determine which of these four interactions were actually significant, the original $2^{8-4}$ DoE was split by material type into two resolution III $2^{7-4}$ DoE’s. From analysis of the separate DoE’s for each material type, it was seen that concentration had a significant effect on the MRR of Inconel 718, but did not have a significant effect on the MRR of Titanium 6-4. Thus, it was concluded that the AE interaction was the significant interaction.

Using the effect estimates of the significant parameters from the DoE, a least squared linear regression model was fit with a $R^2$ value of 0.78. The coefficients in the regression model were the parameter effect estimates divide by two. The
individual regression equations were split by material type, and are shown in Table 3-2 below. These regression models predict the amount of material removed by the ECM capsules during a two minute machining period.

<table>
<thead>
<tr>
<th>Material</th>
<th>Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 718</td>
<td>$1.27 + 0.08B + 0.11C + 0.15E - 0.07H$</td>
</tr>
<tr>
<td>Titanium 6-4</td>
<td>$0.76 + 0.08B + 0.11C - 0.07H$</td>
</tr>
</tbody>
</table>

Table 3-2: Least squares regression fits from the significant DoE parameters. $R^2 = 0.78$. These regression equations predict the total amount of material removed in a two minute test.

To validate the regression model, five additional experiments were conducted for each alloy. The experiments were run using the levels of the significant parameters that maximized the amount of material removed. The results showed good agreement with the regression model predictions. The Inconel 718 prediction was 1.67 grams; the experimental results were 1.66 grams with a standard deviation of 0.19 grams. The Titanium 6-4 predictions were 1.02 grams; the experimental results were 1.05 grams with a standard deviation of 0.08 grams.

4. ECM of Titanium 6-4 protrusions

Using the optimal levels of the significant parameters from the DoE, the MRR and accuracy capabilities of the ECM capsules were tested on eight protrusions which had torch-cut surfaces from sections of Titanium 6-4 parts.

4.1. Equipment:

New ECM capsules were fabricated, one for each of the different protrusion geometries. The ECM capsules were designed and fabricated according to the design guidelines in Section 2.2. Welding clamps were used to connect the positive lead of the power supply to the part. The same electrolyte system and power supply as described in Section 3.1 was used.
4.2. Materials:

Eight protrusions on sections of Titanium 6-4 parts were used for tests. Each of the eight protrusions had one of three different geometries: four 2” by 0.77” approximately rectangular samples, two circular 1.15” diameter samples, and two 2.0” by 0.67” approximately rectangular samples. All of the protrusions exhibited torch cut surfaces, and their heights varied between 0.25 and 0.5 inches. Pictures of protrusion geometries #1, #2, and #3 are shown in Figure 3-5, Figure 3-6, and Figure 3-7 respectively.

Figure 3-6: Protrusion geometry #1, a 2” by 0.77” approximately rectangular sample. Four samples were tested

Figure 3-7: Protrusion geometry #2, a circular 1.15” diameter protrusion. Two samples were tested
4.3. Method:

The protrusions were machined using the optimal levels of the significant parameters as determined from the DoE. The only change made was that the flow rate of the electrolyte was normalized to the area of the protrusion being machined, e.g. a protrusion with twice the surface area of another would receive twice the flow rate. The amount of material removed was recorded at five or ten minute machining intervals for each group of protrusions, and machining was stopped before the capsules cut into the part. The MRR for each protrusion geometry was averaged over each machining time interval, and normalized to the surface area of the protrusion. This allowed an equivalent comparison to be made between the bar stock DoE results and the various protrusion geometries. Finally, coordinate measuring machine (CMM) scans were taken for some of the protrusions to investigate the machining accuracy of the ECM capsules.

4.4. Results:

The MRR of each protrusion geometry was plotted in Figure 3-8 along with the MRR of the regression model predictions from the DoE. Second order least squared trend lines were fit for each protrusion geometry type. Error bars were plotted as one standard deviation for each point.
At the onset of machining, the MRR of the protrusion geometries was lower than the DoE regression model predictions. This was expected because of the different surface characteristics; the DoE bar stock surface was smooth, while the protrusions exhibited initially rough surfaces. Interestingly, the exact reduction in MRR was also dependent on the specific protrusion geometry. Protrusion geometry #3 showed the highest MRR, possibly because the flow was supplied parallel to the torch-cut ridges. In contrast, the flow for geometries #1 and #2 crossed the torch-cut ridges, potentially resulting in high electrolyte turbulence. However, as the protrusions were machined down, the MRR increased towards the model predictions for all protrusion geometries. Geometry #3 completely converged; however, geometries #1 and #2 did not. It appears if machining were to be continued for geometries #1 and #2,
convergence would occur. However, continued machining was not possible without cutting into the part.

The ability of these ECM capsules to remove protrusions from parts was evaluated through CMM scans of the protrusion machining profiles. Figure 3-9 displays a typical CMM scan that was seen for one of the protrusion geometry #1 samples, and represents the typical machining behavior seen.

![CMM Scan](image)

**Figure 3-10:** A CMM scan of the initial and final profiles of one of the Titanium 6-4 protrusion samples. The scan shows the ability of the ECM capsules to remove the majority of the protrusion without cutting into the part.

It was observed that while the majority of the protrusions could be electrochemically removed, it was difficult to remove the entire protrusion without cutting into the part. If the ECM capsule was to continue machining the protrusion shown in Figure 3-9, the part surface would be cut into at $x \approx 2.4''$ before the entire protrusion was removed. While it is theoretically possible to design a tooling
electrode to exactly remove this protrusion, it would likely be impractical because the next protrusion would be probably be varied, e.g. different surface roughness or profile slope. However, even in the presence of highly variable protrusions, the ECM capsules showed the ability to remove the majority of the protrusion without affecting the part. From the measurements taken of the protrusions, it was calculated that between 67 and 80% of the protrusions were safely removed by the ECM capsules.

There are a few potential methods of increasing the amount of the protrusion removed while not cutting into the part. First, if variability in the initial protrusion geometry could be reduced, the amount of the protrusion removed could be increased. Second, if higher machining voltage gradients were used, areas near the tool would be machined at faster rates than the areas further from the tool. The resulting effect would be that the protrusion profile would flatten out more quickly, allowing more material to be removed. Higher voltage gradients could be obtained by reducing the electrode gap, increasing the voltage, or decreasing the electrolyte conductivity. Finally, a thinner or better fitting insulation surrounding the protrusion could help reduce the effect of the preferential cutting along the edges, which appears to be the first location that would cut into the part.

These ECM capsules show the ability to successfully remove the majority of a large protrusion from a part. Using these ECM capsules for an initial protrusion roughing operation could possibly be their most advantageous application. The remaining protrusion could then be removed using conventional methods, e.g. grinding or milling. Overall, the amount of conventional tool wear incurred would be greatly reduced, and the conventional surface finish and tolerancing capabilities
would be preserved. However, if an operation does not require tight tolerancing, or the protrusion variability could be minimized, these ECM capsules could be potentially used for the entire removal operation. Both scenarios offer significant cost savings potential through the reduction or elimination of tool wear.

5. Conclusions

A new method of using ECM capsules to remove large protrusions from parts has been presented. These ECM capsules are advantageous because of their ability to machine protrusions with no incurred tool wear. Also, their small size allows them to access difficult-to-reach areas on parts, e.g. protrusions on interior part surfaces.

The general design of these ECM capsules has been described, and good practices have been identified to use when designing a capsule for any protrusion geometry. From a $2^8-4$ statistical DoE using the ECM capsules, the key machining parameters and levels that had a significant effect on MRR were found. Next, tests on torch-cut protrusions on Titanium 6-4 parts showed that the MRR was initially lower than predicted, but tended towards predicted levels as the protrusions were machined down. However, due to the inherent variability in the protrusion surfaces, it was difficult to completely remove the protrusions without cutting into the part. CMM scans showed that between 67 and 80% of the protrusions were able to be removed without affecting the part. The removal percentage could be potentially increased by reducing the initial protrusion variability, machining with higher voltage gradients, or using a thinner type of insulation.
6. References


Chapter 4: General conclusions

In this work, the electrochemical removal of large protrusions from parts was investigated. Electrochemical machining (ECM) techniques have the advantages of no incurred tool wear and no imparted thermal or mechanical stresses onto the workpiece. First, an ECM laboratory apparatus was designed and fabricated. With this apparatus, different electrochemical protrusion removal tooling methods were designed and evaluated. Through this process, a new method of using ECM capsules to remove large protrusions from parts was developed. An ECM capsule is a small electrochemical cell that is set over a protrusion on a part. The capsule is plugged into an external electrolyte system and power supply, and contains a tooling electrode, a motor, and an electrolyte connection. Using these capsules, the material removal rate was optimized through a $2^84$ statistical design of experiments using samples of Titanium 6-4 and Inconel 718 bar stock. Next, these capsules were tested on torch-cut protrusions from Titanium 6-4 manufactured parts. The capsules showed the ability to remove the majority of the protrusions without cutting into the part. Properly used, these ECM capsules offer the potential for significant cost savings through elimination of tool wear during protrusion removal operations.
Chapter 5: Bibliography


Appendix A: Improvements to the ECM test apparatus

Various improvements were made to the ECM test apparatus after the first paper was written. The main upgrades include:

1. Redesign of electrolyte basin
2. Ventilation of machining chamber
3. Motor drive system redesign
4. Electrical wiring
5. Coating and assembly of the final ECM apparatus

A description of the upgrades performed is provided in the following sections.

I.1. Redesign of the electrolyte basin

The electrolyte basin was originally designed to fit under the ECM machining chamber. However, this made it difficult to access when mixing different electrolytes during testing. The electrolyte basin was removed from underneath the machining chamber and relocated to the side of the test apparatus. Two 500W Teflon heaters, along with a mixer, were installed on the lid of the electrolyte basin. This allowed the entire assembly to be removed if necessary. A stainless steel scale was added to allow simple measurements of electrolyte concentration. When mixing a batch of electrolyte, the correct weight of water is first added. Then, the scale can be zeroed, and the chemical weight can be added. The scale has a resolution of 0.1 pounds. Finally, in order to protect against accidental electrolyte spills, spill containment decks were placed under the entire machine.
Redesigned electrolyte basin. A mixer, two heaters, a scale, and a spill containment deck were added.

The electrolyte piping system was reconfigured to accommodate the electrolyte basin redesign. The additional piping length on the suction side of the pump helped ensure even flow.
I.2. Ventilation of machining chamber:

Gas, primarily hydrogen, is generated at the tool electrode during machining. In order to prevent dangerous gaseous buildups in the machining chamber during experimentation, ventilation was added. This was done by inserting vents in both sides of the machining chamber. The exhaust side of the chamber was vented to an approved disposal area inside the laboratory. The air machining chamber was flushed at 50 cubic feet per minute.

I.3. Motor drive system redesign:

The redesigned motor drive system included new bearings, a larger mounting plate, liquid-tight conduit, limit switches, and a new lead screw. The bearings used were four pillow block style bearings, which eliminated the moment occurring when only two bearings were used. Also, ceramic coated aluminum rails were used which
eliminated corrosion concerns that occurred with the old rails (even though the old rails were stainless steel, pitting corrosion was still occurring). A larger mounting plate was added to accommodate larger geometries of tool electrodes. A limit switch was installed at the top limit of travel for the mounting plate. Finally, a new lead screw with a flanged ACME precision brass nut was added.

Redesigned ECM test apparatus ventilation at the top of the machining cell. The air was flushed at 50 cfm and removed to an approved ventilation area.

I.4. Electrical wiring:

Two 24” by 24” NEMA electrical boxes housed the electrical systems of the test apparatus. One electrical box housed the low voltage power supplies and data acquisition sensors. The second electrical box housed the high voltage relays, contactors, and emergency stop circuit.
The electrical box #1 housed the NI cRIO and motor drives used to control the ECM test apparatus. 5V and 24V supplies were used to power for various sensors and motor drives. All the terminal blocks used were touch safe.

The high power box used various relays and contactors to control the test apparatus functions including the pump, heaters, main power, and emergency-stop. The DC supply side of the 20V-250A power was routed through the box in order to measure machining current; the voltage drop over a high power precision resistor was recorded by a thermocouple module in the cRIO.
A high current contactor was later added to enable control of the machining power on the supply side from the control program.

1.5. Coating and assembly of final ECM apparatus:

The final version of the redesigned test apparatus is shown below. The entire apparatus was painted with a chemically resistant coating, and is shown below.
A workstation desk was fabricated out of 80-20 aluminum extrusions to hold the electrical boxes and the 20V-250A DC power supply which weighed 400 pounds. The functions of the machine were controlled by Labview 2012.
The entire experimental setup at Oregon State University in Graf hall senior design cage #6 (2013-2014)
Appendix B: CAD models of additional ECM capsules

While the design of the ECM capsules has been previously described, it is often helpful to reference additional designs when designing capsules to machine new protrusion geometries. The following pages show various ECM capsule designs that were designed to machining different protrusion geometries. The protrusions to be removed are shown in red.

ECM capsule for removing a protrusion off of a raised radius. Two screws were used as bus-bars to get machining current to the tool electrode. The electrolyte was supplied across the short side of the protrusion.
The interior flow chamber of the ECM capsule. The electrode was given a 0.05” radius. Also, the cell walls were designed to be as tight to the protrusion as was reasonable in order to minimize the effect of edge undercutting.

ECM test capsule in action. A welding clamp was used to supply power to the workpiece.
ECM test capsules for a circular protrusion. A welding clamp was used to supply power to the workpiece.

The interior flow chamber of a capsule used to remove a protrusion off of a raised ridge on a part.
A capsule removing a 1.15” square protrusion off of a curved part. It must be determined if it is worth the additional design and CNC machining time to design a curved tooling electrode. No doubt, a curved tooling electrode that matched the surface could remove much more material before cutting into the part than a flat tool electrode could.
Appendix C: Torch-cut bar stock: one off experiment

The surfaces of residual protrusions are thermally damaged during torch cutting. The torch cut surfaces normally exhibit large ridges and cavities which can negatively impact ECM parameters such as the electrolyte flow. The photos below show pictures of the surface of a ¾” by ¾” sample of Titanium 6-4 stock after being torch cut.

To determine the effect a torch cut surface had on the material removal rate in ECM, a one-off experiment was conducted. One sample with a torch cut surface and one sample with a ground surface were machined under identical ECM conditions. The ground surface was machined to a 15 degree angle to match the torch cut sample. Each sample was installed in the ECM capsule in the same orientation to ensure that the experimental results were not affected by the cut angle. The results of this experiment are shown below.
<table>
<thead>
<tr>
<th></th>
<th>Torch cut</th>
<th>Ground</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Charge (C)</td>
<td>18138</td>
<td>21783</td>
<td>16.7%</td>
</tr>
<tr>
<td>Delta Weight (g)</td>
<td>2.25</td>
<td>2.67</td>
<td>15.7%</td>
</tr>
<tr>
<td>Total Charge/Delta Weight</td>
<td>8061</td>
<td>8158</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

Results for one off experiment between torch cut and ground bar. Parameters: 20% NaCl, 0.75mm gap, 1 GPM, 20V, 20 degrees C, 10 minutes machining.

The machining current and material removal responses showed that the torch cut surface had a 15 to 17% decreased machining rate compared to a ground surface. However, the efficiency remained essentially constant between the two surface types indicating charge is directly proportional to material removal rate. The current passage during machining is plotted below.

![Pre-DoE: Machining current vs. time](image_url)

Results of torch cut vs. ground Titanium 6-4 bar stock. (20% NaCl, 0.75mm gap, 20V, 1 GPM, 20 degrees C., 10 minutes of machining)

At the start of the test, approximately a 50% difference in current passage occurs between the two surfaces. However, these curves begin to converge on each other towards the end of the experiment. The total charge difference for a desired time period can be calculated by taking the integral difference of the two curves.

\[ Q_{total} = \int_0^t I_{ground} \, dt - \int_0^t I_{torch} \, dt \]
Appendix D: Alternative ECM tooling methods

Many different types of tooling methods were tested. Some worked well and some did not. The tooling methods can be broken into three different categories depending on how the electrolyte is supplied to the machining surface: i) slotted tooling, ii) infinite hole tooling, and iii) side flow tooling.

i) Slotted electrode tools

Slotted tooling is commonly used for ECM. Electrolyte is supplied through a slot in the tool. The slotted electrodes generally do not require damming (see electrolyte containment in the capsules), but require flow slot ridges to be removed from the part after the ECM operation is complete. The tools are also difficult to fabricate, as the interior flow geometry can be complicated, and sharp corners requires blending or radiusing in order to ensure smooth electrolyte flow.
ii) *Infinite hole electrode tools*

An idea of using electrodes with “infinite holes” was tested. This tooling method did not work well. The electrolyte flow was severely restricted, even with larger holes. Also, because the electrodes were oversized compared to the protrusions, high current density concentrations occurred at the edges of the protrusions. This resulted in highly differential machining rates; not much of the protrusion could be removed before cutting into the part.

Different hole sizes and spacing’s were tested with the “infinite hole” electrode.

iii) *Side flow electrode tools*
The first version of the ECM capsule electrode. It consisted of a stationary tooling at the top of the cell, with the barstock friction fit in the interior. Electrolyte was supplied from the side of the capsule through the barbed hose fitting.

The interior of the first version ECM capsule. In later versions, the sharp changes in the electrolyte flow path was changed. In this design, the electrolyte undergoes two 90 degree turns as it goes from the barbed hose connection to the tool. Current designs attempt to have the barbed hose fitting in line with the machining surface, resulting in smoother electrolyte flow.