High volume, low cost, micromachining processes are emerging as enabling technologies for many new products. Electrolytic micromachining is one of those technologies. Electrolytic machining has been used for many years to machine airfoil surfaces in turbine engine applications and critical features in fuel system components for aerospace and automotive markets. Advances in this technology have led to a variety of new applications ranging from critical surface finishing to machining of micron tolerance features.

Electrolytic material removal is a process of high rate anodic dissolution driven by direct current in the presence of a salt based electrolyte. This paper will concentrate on electrolytic micromachining as characterized by the highly focused anodic material removal mechanism to produce features from microns to hundreds of microns in metallic components.

Initially, a process requiring one or more layers of masking was developed that has been termed through-mask electrolytic micromachining. Direct current pulsing techniques have enabled the electrolytic technology to produce micro features in components without the use of workpiece masking. Pulsing parameters along with characteristics of the machining cathodes govern the removal geometry in electrolytic micromachining. This paper describes how these aspects of the process effect material removal and influence predictable results.

A number of electrolyte related process parameters influence the machining result. The significance of the parameters with major influence on results is reviewed. There are additional factors that influence the micromachining process and these are described in this paper including specific examples of the capabilities and limitations. Typical control strategies used with this micromachining process that have proven successful are described along with an example of an electrolytic micromachining production system.

An insight into the typical development process for production applications is provided since most applications of high production electrolytic micromachining have unique characteristics. Examples will be used to emphasize the robust nature of the process from existing and future production applications.

Electrolytic machining is controlled metal removal via electrolytic dissolution which usually requires a shaped conductive tool to form a small gap between the tool surface and the workpiece; flowing conductive electrolyte in the gap; and allowing a DC current to flow between the two adjacent surfaces.
conductivity of the electrolyte solution allows electric current from a 5 to 30 volt DC power source to flow between the tool and workpiece. A typical electrolyte used in this process is a conductive salt solution such as sodium chloride (table salt) and water. The resulting electrical conduction within the solution is possible because dissolution in water breaks down the molecular restraining forces, so that the ions, called cations (Na+) and anions (Cl-), are free to move through the electrolytic solution. Application of an electric field causes migration of one ion species with respect to the other. Since each ion carries a charge, this movement constitutes an electric current.

Electrolytic current flow will cause atoms to be removed from targeted areas on the workpiece only and enter the electrolyte solution. The metal ions quickly form neutral metal hydroxides that are filtered from the recirculating electrolyte stream. Material removal rate for ECM is essentially independent of material hardness but can be affected by alloy composition and grain size of the material. The theoretical removal rate (MR) can be calculated based on Faraday's law.

For the reaction \( \text{M} \rightarrow \text{M}^{n+} + n\text{e}^- \)

\[
\text{MR} = \eta \frac{AI}{nF}
\]

Where
- \( \eta \) = current efficiency
- \( A \) = atomic weight
- \( i \) = current density
- \( K \) = electrochemical equivalent of the metal
- \( N \) = valence number
- \( F \) = Faraday constant

If a metal to be electrochemically machined is an alloy composed of \( e \) elements and each element represents a fraction \( f_e \) of the total, then the removal rate is

\[
\text{MR} = i \eta \left( F \sum \left( f_e \frac{n_e}{A_e} \right) \right)
\]

(assuming uniform removal of each element).

Most metals have similar electrochemical removal rates. For example nickel, chrome, iron and aluminum fall in the range of 2.2 to 3.1 cm\(^3\) per 1,000 amps per minute.

It has been established that pulsed direct current exhibits significant machining advantages over continuous current ECM. Pulse current will lower the overall material removal rate by virtue of the “off time” between pulses, however, there
are significant benefits from the pulse technique (surface finish and accuracy) and the relative high removal rates (when compared to other processes). The quality of the electrochemically machined surface depends on material chemical composition and micro structure, the electrolyte properties, and density of the material removal current. Pulsed current results in higher current densities when compared to constant DC. Higher current density results from the effect of the pause or “off time” between current pulses. When material removal current flows between tool (cathode) and workpiece (anode), the gap conditions change as a result of process by-products accumulating. Process heat, metal ions becoming metal hydroxide and hydrogen gas bubbles, all increase as the current flows. As these by-products increase, so does the ohmic resistance which limits the magnitude of current. Also, variation in local density of these by-products will result in variation in current from one area to another in the gap causing different localized dissolution rates. As current “on times” are shortened and pause or “off times” are lengthened, achievable current density is increased and process quality improved.

Typical pulse parameters are 0.1 to 10 millisecond “on time” with 1.0 to 50 millisecond “off time”. The ratio of “on time” to “off time” varies with application and values of the other parameters.

The microECM process can produce internal features a few microns deep by 10’s to 100’s of microns wide or external features as small as few microns in some applications. In general, the process is limited by the ability to produce the cathode tool required to machine the desired features.

An example of microECM is machining of grooves for fluid dynamic bearings (FDB’s). The typical requirement for FDB performance is a pattern of grooves on internal stator surfaces and thrust bearings. These grooves or channels are approximately 10 micron deep and less than 100 micron wide. Using fixed position cathodes, the groove depth is determined by gap, current, and time.

Fixturing of the microECM cathodes and workpiece are critical to obtaining good results. A narrow gap between tool and workpiece surface, minimizes “overmachining”.

Among the advantages to be realized from this process are reduced work-in-process, improved component strength, increased production and fewer rejects. The benefits of electrolytic deburring can be summarized as:

- Reduced costs compared with alternate methods
- Very low consumable costs
- Capable of machining multiple features simultaneously
- Unskilled labor can be used
- Tooling has long life - it is not consumed in the process
• ECM is a stress-free process
• Consistent results from part to part and batch to batch

The ability of the process to meet requirement for full form high volume machining, with non-consumed tooling, is very attractive to manufacturing. These microECM production systems have demonstrated unique capabilities with respect to micro machining.