Electro Chemical Machining (ECM)
What is It?

Terry Lievestro, Sermatech¨ Manufacturing Group, Cincinnati, OH

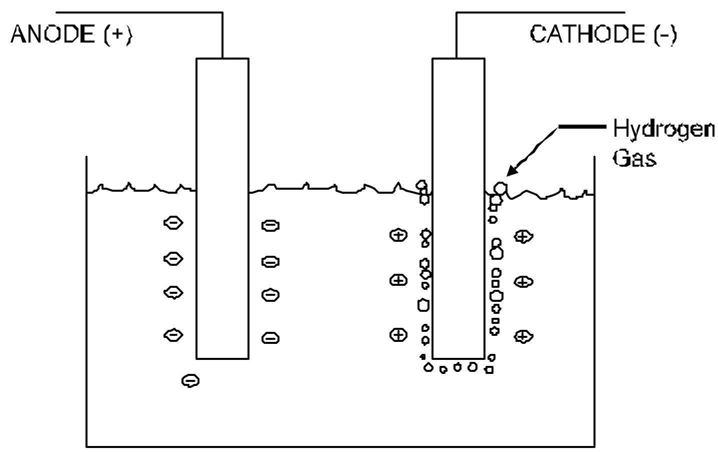
This presentation will be primarily a visual one with examples of tools and parts currently made using ECM. There will be a few slides to explain how the ECM process works with comparisons to other processes. The presentation will show a variety of types of parts made by ECM.

For more information, contact:
Terry Lievestro
Sermatech Mfg. Group
11230 Deerfield Rd.
Cincinnati, OH 45242
Phone 513-605-8112
FAX 513-489-2409
tlievestro@sermatech-lehr.com

1.0 Simple Electrolytic Cell

Electro Chemical Machining (ECM) works on the principle of the simple electrolytic cell we all learned in high school chemistry. In the simple cell (Fig. 1.1) two electrodes are placed in a conductive solution. In the case of ECM, we use a saltwater solution such as everyday table salt (NaCl). A DC potential is applied between the electrodes. The positive electrode is referred to as the anode and the negative one as the cathode. Because there is an electrical potential between the electrodes, current will flow between them. Bubbles of hydrogen gas (H_2) can be seen bubbling up from the cathode. The anode will begin to "corrode" as the electrons flow from it toward the cathode. As equation 1.1 below shows, the water (H_2O) is broken down with the electron flow resulting in H_2 gas and hydroxide ions (OH-).

Figure 1.1 – Simple Electrolytic Cell



Ions = electrically charged groups of atoms.

(eq. 1.1) $2H_2O + 2_e- \Rightarrow H_2 + 2OH^-$
Transfer of electrons between ions and electrodes

(eq. 1.2) $Fe \Rightarrow Fe^{2+} + 2_e-$

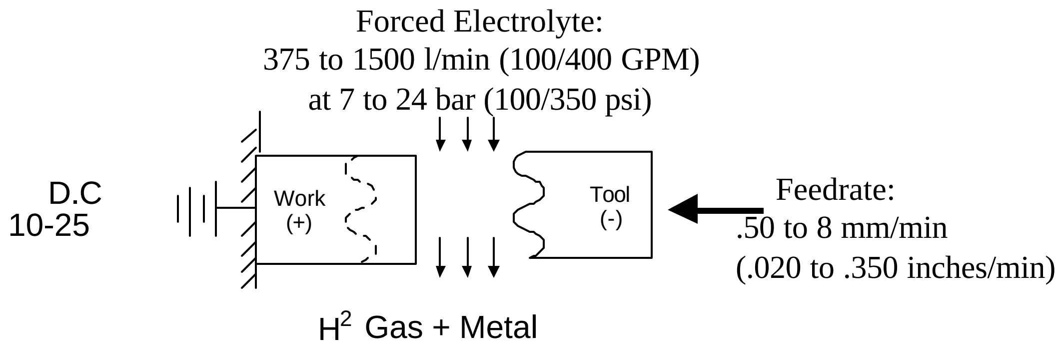
(eq. 1.3) $Fe^{2+} + 2_e- + 2H_2O \Rightarrow Fe(OH)_2 + H_2$
Metal Hydroxide + gas

As the electrons flow from the anode (in this case made from iron [Fe]), equation 1.2 shows the Fe^{2+} ions are released from the anode. When we put the reactions together in equation 1.3, we see the Fe^{2+} ions bonds with the OH- hydroxide ions. The result of this is the formation of iron hydroxide and hydrogen gas.

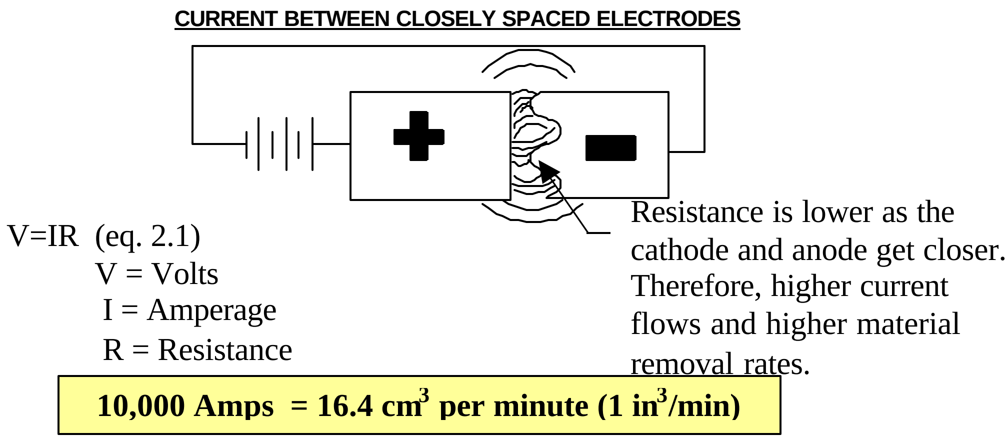
2.0 Fundamentals of ECM

In the practice of ECM, we bring the cathode (tool) and anode (part) close together to reduce the resistance between electrodes. We do this because of Faraday's Law that states: *The amount of and substance deposited or dissolved is proportional to the quantity of current passed.* ECM uses a fixed DC voltage usually between 10 and 25 volts. As we reduce the resistance, current flow increases as shown in equation 2.1 shown below in order to keep the voltage the same.

Figure 2.1 – Schematics of ECM process



FARADAY'S LAW: **The amount of any substance deposited or dissolved is proportional to the quantity of current passed.**



The result of increased current flow is an increase in the material removal rate. The part to be machined by ECM is made the anode. The tool to generate a shape is made the cathode. A near mirror image of the desired shape is cut into the cathode. As shown in the bottom of figure 2.1, the cathode has a variable distance between the part and the face of the cathode. This means a difference in the resistance and hence the current flow. The result is more material will be removed in areas where the cathode is closer than areas where the cathode is further. As the material is removed by the current flow, the cathode is advanced toward the part to keep the gap close.

To ensure the gap has the metal hydroxide and hydrogen gas removed, a high-pressure pump is used to force electrolyte between the cathode and the part. The by-products are carried away and fresh electrolyte is introduced with this flow of electrolyte. The gaps between the cathode and part are held relatively small with the advancing motion. This means the electrolyte requires pressures of 7 to 24 bar (100 to 350 psi) to force the electrolyte across the gap. Depending on the size of this cutting face and the gaps present, large flows typically in the range of 375 to1500 liters per minute are required. The flow will bypass the close gap and flow in larger areas where the cathode is still far away. The large flow rates will ensures a pressure drop across these open areas enough to force flow across the tighter gaps where the majority of the metal removal is taking place.

(eq. 2.2) $E = IV$

E = Watts

I = Amps

V = Volts

Because there is resistance across the gap and in the material of the cathode and the part, heat is generated (see equation 2.2). A second function of the electrolyte is to carry away the heat generated. Typically ECM used today can use between 1,000 and 40,000 amps for removing material (Cutting material). With voltages in the 10 to 25 volt ranges mean it is not uncommon for 1000 KW of power to be consumed. The heat from this amount of energy must be carried away or the electrolyte would boil and quit conducting current as it turns into a gas. The limiting factor on some parts is the amount of amperage used in which the heat can be carried away.

Different electrolyte salts are used for different applications. Sodium Chloride (NaCl) is the most common salt used. This is an inexpensive general-purpose electrolyte that is easy to store, handle and control. Sodium Nitrate ($NaNO^3$) is another common one. It is a more costly electrolyte that is also more of an oxidizer. This makes storage and handling more difficult. It has an advantage in use though in that it creates a passive layer in areas where the current density is lower. This creates a masking affect to protect areas from material removal in undesired locations. Other salts have other advantages for specific alloys that are beyond the scope of this paper. The thing to point out here, though, is most ECM applications use a water-based electrolyte. The PH levels are normally maintained in a neutral state so an operator can work with the electrolyte easily.

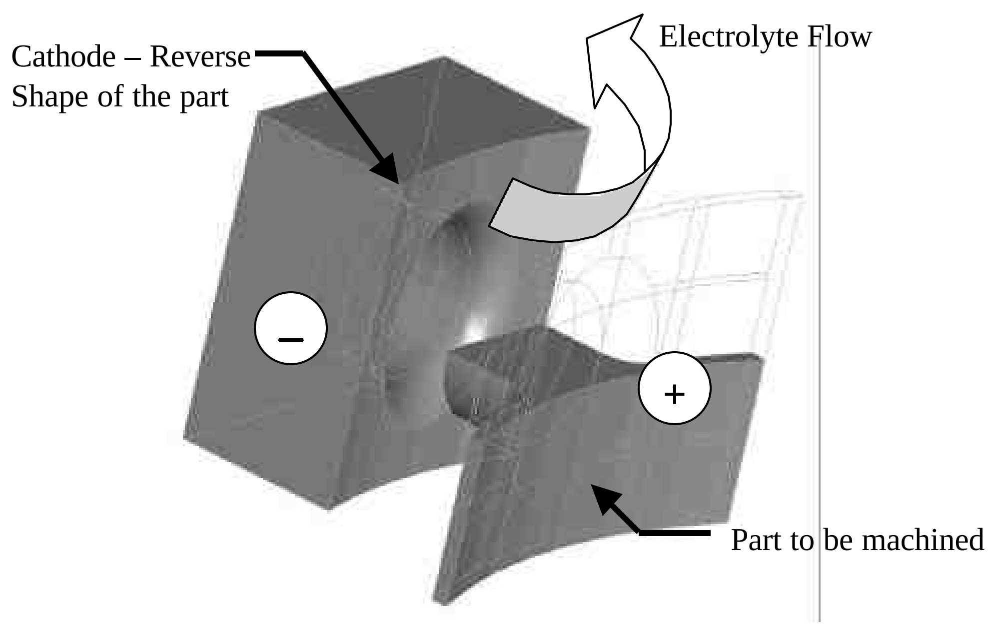
Forms of ECM do use an acid based electrolyte. These are usually used to generate small holes and the process is sometimes referred to as “Stem Drilling”. This paper does not include this sub category of ECM. Another category of ECM not covered here is one in which a reversing pulsed voltage field is used. This pulse ECM usually uses a water and salt-based electrolyte also. The reverse pulse field is used to passivate then depassivate a surface for other benefits. There are other papers that split this into an entire study and therefore are not covered here.

2.1 SUMMARY OF ECM FUNDAMENTALS

- The part or work piece is charged positive (+).
- The tool or cathode is charged negative (-). It is given a reverse of the shape to be formed.
- A water and salt-based electrolyte is circulated between the cathode and the part at pressures of 7 to 24 bar (100 to 350 psi).
- 10 to 25 volts DC are applied from a 5,000 to 40,000 amp DC rectifier.
- Positive ions of metal leave the part surface.
- Hydrogen gas forms on the cathode.
- Metal ions and hydroxide ions join to form metal hydroxide.
- Gas and metal hydroxides are washed from the gap and cutting continues.

16.4 cubic centimeters (1 cubic inch) can be removed in one minute when 10,000 amps of current are applied for most metals.

Figure 2.2 – Simple ECM Cathode



3.0 ECM Compared to other processes

First it must be understood there are the various types of ECM. This is a comparison of steady state DC ECM using a saltwater electrolyte. Reverse pulse, acid based, and some others fit different molds than are depicted here.

ECM is often confused with Chemical Milling or Electrical Discharge Machining (EDM). Chemical Milling is a process in which a part is masked all over and then stripped in areas where metal removal is desired. The part is then immersed in an acid solution for a set time period. Metal is dissolved away with a chemical action only. EDM is a process where an electrode with a reverse shape is built and brought to the part. Then an electrical charge, AC or DC, is used in conjunction with a dielectric solution in order to "spark" the metal off the surface. This is a melting process that leaves a detrimental surface on the part. This surface effect is called recast. There is a micro surface cracking condition resulting from the melting of the surface during the spark removal of metal.

Chemical Milling is normally used very effectively for shallow pockets on large surface areas. The process is a slower process than ECM for a given spot on the surface. The fact that large surfaces can be machined at one time makes this an efficient process for shallow features. A draw back of Chemical Milling is if fillets are needed at the bottom of the cut. The method to get a fillet is to pull the part and re-mask it and strip a smaller opening to yield a stepped blend. The by-product is also much more difficult to handle because of the acid used.

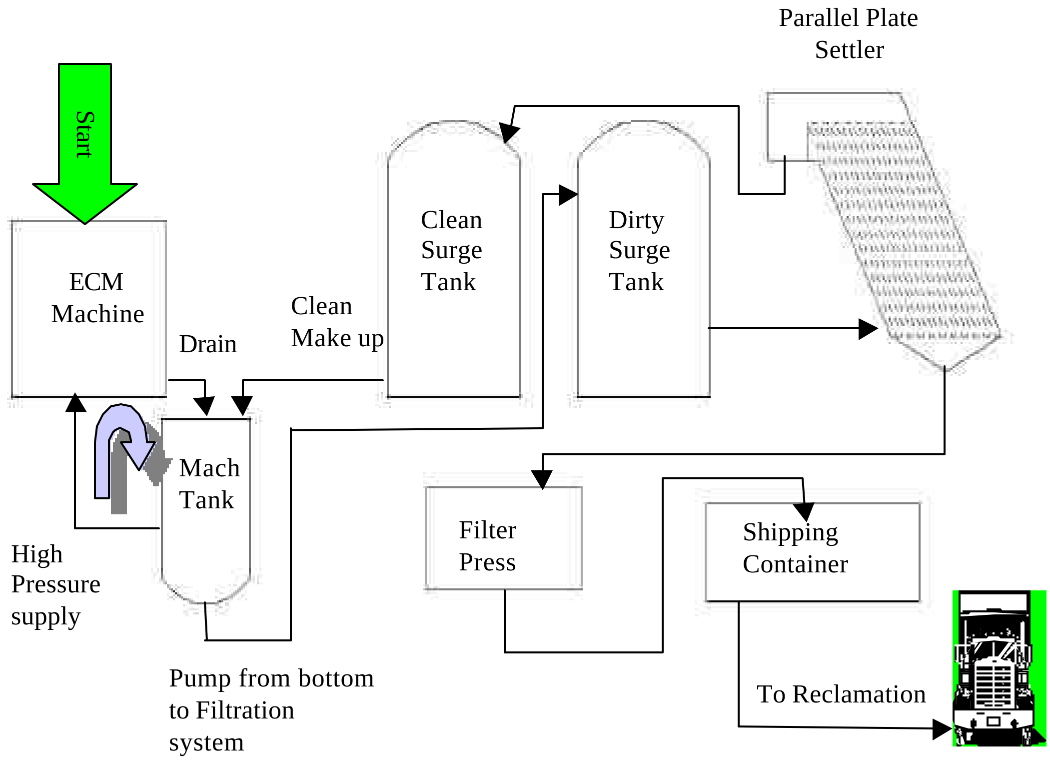
EDM is a relatively slow process relative to ECM. It is a good process to use for very small holes or complex shapes in hard materials. Again, the recast must be considered when using EDM. The process is able to give sharper corners than usually possible with ECM since there is no gap between the electrode and the part. There is still a by-product that must be handled just as in ECM or Chemical Milling.

ECM leaves the parent material untouched. There is no recast and only a very limited inter-granular attack in unusual conditions. ECM is the fastest removal method of these listed processes for any spot on a part. The metal is dissolved away with an ionic process with electricity being the driver. Steady state ECM is limited to a 3 mm (.118 in) diameter holes because there is a gap between the cathode and the part. The reversing pulse ECM can go much smaller.

3.0 What happens to the ECM metal hydroxide by-product?

ECM is a process used to remove a lot of material and it has a lot of metal hydroxide byproduct. Each ECM machine is hooked up to a filtration system for removal of the metal hydroxide. Figure 4.1 shows a typical system used for ECM. Different ECM filtration systems are used based on the type of parts being machined and the amount of metal removed. The one shown shows the basic parts used in all the systems.

Figure 4.1 – Typical electrolyte system components



Each machine has a high-pressure pump that is used to circulate the electrolyte through the tool. The drain returns the electrolyte with the metal hydroxide to the machine tank. A drain on the bottom of the machine tank is used to remove the dirty electrolyte to be sent to a filtration system. A float valve is used to maintain the level of the tank by filling clean electrolyte to the tank from the filtration system.

The dirty electrolyte from the machine tank is sent to a central surge tank that collects the electrolyte from all the individual machines. The dirty electrolyte is then sent through a parallel plate settler. Clean electrolyte from the top is sent to a central clean surge tank. The clean electrolyte is then sent back to the machines to make up for the dirty electrolyte removed to the filtration system.

A drain pulls a thickened dirty electrolyte from the bottom of the settler and sends it to a filter press. The settler reduces the volume to the filter press to about 10% of the initial volume. 90% is sent to the clean tank. The 10% off the bottom that was sent to the filter press has more liquid removed until a clay like by-product is produced as a cake. The liquid from the filter press is sent back into the settler to remove any hydroxide that may have escaped through the filter press.

The filter press cake is then conveyed to a sealed shipping container (see figure 4.2) where it can then be picked up by a truck. The cake is 75% water by weight which is about as dry as practical with a mechanical system. Salt makes up approximately 15% by weight and metal makes up the remaining 10% of the weight. This means eight to ten kilograms of by-product are produced for every kilogram of metal removed.

Figure 4.2 – "Ore" shipping containers with metal Hydroxide

This by-product is then sold as a high-grade ore. The "ore" is transported to a mill where a thermal process is used to reclaim 100% of the metals. This system used is the same as that used for ore from the ground. This means no waste must be disposed of.

If materials containing Chrome are machined, there is some Hexavalent Chrome produced. For this reason, the buildings used for ECM must be built to contain any spills. All piping used to move electrolyte is also kept out of the ground and drains are all on top of a rubber liner under the building.

All water used to wash parts and all spills on the floors are all sent to the filtration area. In the filtration area, the Hexavalent Chrome is reduced to Trivalent Chrome and then sent to the filtration system to remove all hydroxides. When the "wash water" is ready to be discharged, the local sewer district is called so they can come test the water to be discharged. Most systems used to remove the heavy metals from ECM are capable to exceed the current regulations by as much as 15 times better to ensure no environmental problems result.

Air scrubbers are used on all ventilation systems used to evacuate the hydrogen gas from the machines and electrolyte tanks. This is to ensure no particles of water containing contaminates are released into the atmosphere. All activities of Sermatech Lehr and others practicing ECM must be approved by the Federal Environmental Protection Agency (EPA), State EPA, and the local sewer district.

4.0 History of ECM

ECM has a history that can be tracked back to 1800 with the Volta Battery. Faraday developed the Laws of Electrolysis between 1812 and 1833. The original patent was issued in

Russia to Guseff for ECM. Another form of ECM called Electro Chemical Grinding was started in 1954. Here, a conductive wheel is used to combine grinding with ECM.

A company out of Chicago named Anocut had major developments in ECM between 1958 and 1968. They developed the current technology of the basic process and commercialized it. Between 1960 and 1965, many ECM machines were sold and there were many patent battles between machine builders. Brown & Sharpe bought Anocut in 1968. In 1970, they abandoned their patents on ECM.

Figure 5.1 - Early ECM Machine

Figure 5.2 - Modern CNC controlled ECM Machine

Many of the companies who bought ECM machines were successful between 1965 and 1985 if they had a “Champion”. Many others who were not as committed to ECM failed during this time and machine builders started dropping out. Companies who were successful either built there own machines or had ones built to their specifications. It became apparent those who were most successful knew how the machines had to function. Many machines were customized to a particular process, much the same as in many conventional machines.

In 1980, CNC was introduced to the ECM machine. This significantly expanded the possibilities for ECM. The changes here were similar to those of the conventional machine market where multiple axis machines became commonplace. The controls have continued to develop to control the process parameters along with the machine motions. It became easier to build a special purpose machine configured for particular types of parts. Tooling costs have been reduced just as the auto industry now uses a lot of soft tools in place of transfer lines.

CAD CAM has recently been the greatest improvement in the ECM technology. Because ECM is so good for complex shapes, there is a high degree of use of modern CAD CAM. These changes have even been more dramatic than that experienced with CNC programming.

6.0 When should ECM be used?

ECM is a process good for hard to machine alloys where there is a high cutter cost. ECM does not care how hard a metal is. It only needs a conductive material to remove the material.

Because there is no need to rotate a tool as in milling, a shaped cathode can be used to access difficult locations. Areas where long cutters would be required are also good candidates. See figures 6.1 and 6.2 for examples of this limit imposed on milling where ECM works well.

Figure 6.1 – Square hole over 300 mm deep requiring a 5 mm diameter cutter

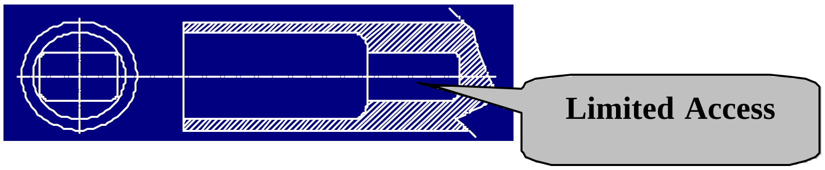
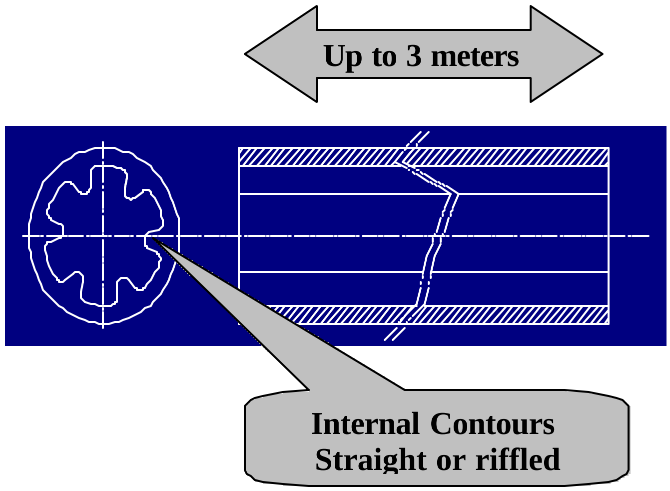
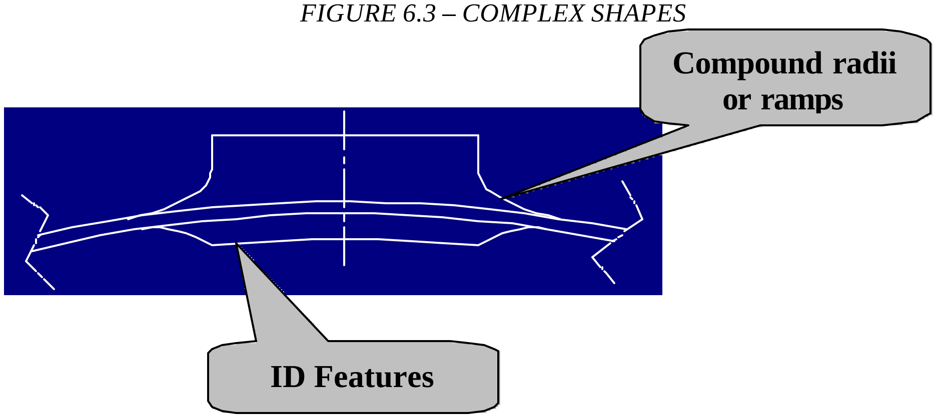


Figure 6.2 – Internal geometry in tubes. Soon to be capable of 7.6 meters



Complex shapes are the biggest portions of business for ECM. All the complexity is built into the cathode one time. The shapes are then transferred to the parts repeatedly just as easily as a simple shape. Features such as compound radii or elliptical radii are now an option for the designer. Ramps and other features can be added to a part to add local stiffness to a part. See figure 6.3 for an example.

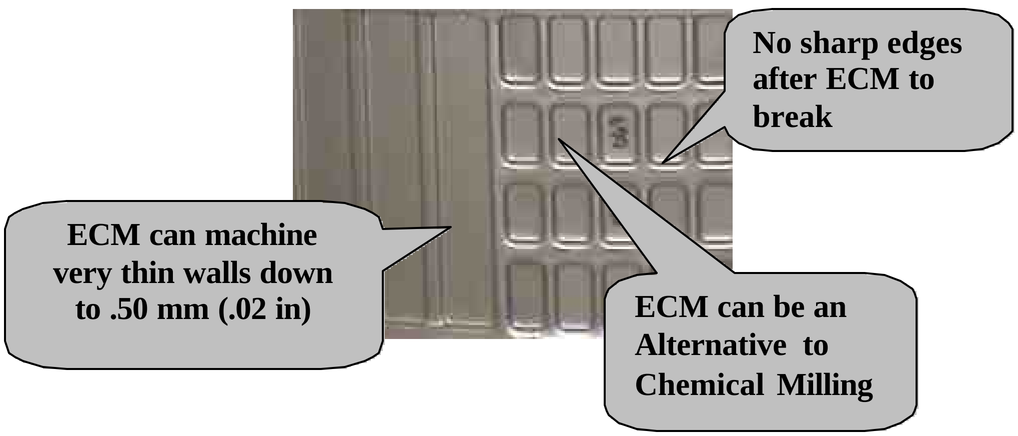
FIGURE 6.3 – COMPLEX SHAPES



Often parts are cast because of the complexity. The material properties of the casting may not be good enough. Weight is added and life is limited in order to keep the cost down by using a casting. ECM allows many of these parts to be made from a forging or bar stock. This gives better material properties that could result in lighter weights and longer lives. ECM yields the shapes often limited to a casting because of cost or inability to machine a shape.

Machining stresses often makes it difficult to machine thin walled structures. Because ECM does not have these cutting forces to contend with, thin walled parts are often machined with ECM. Figure 6.4 shows an example of a part with thin walls cut by ECM. It was used here as a replacement to Chemical Milling that left stepped fillets and sharp outside edges. ECM is currently used to machine walls down to .50 mm (.02 inches).

Figure 6.4 – Thin walled structure



Large contoured surfaces milled with small step overs are good ones for ECM. Shapes such as airfoils are machined into a cathode one time. Even if the part is delicate, a cathode can be used on two sides at one time to balance the hydraulic forces from the electrolyte. Concave features are limited quite often to the amount of horsepower that can be applied even with high-speed milling. Figure 6.5 shows an example of a Blisk (Bladed Disk) or IBR (Integrally Bladed Rotor) that had the airfoils machined with ECM. Figure 6.6 shows a blade that is an airfoil with platform on one end. Figure 6.7 shows a Vane that is an airfoil with a platform on both ends. All of these parts have been machined with ECM with no need for polishing after machining to remove cutter lines.

Figure 6.5 – Blisk or IBR

Figure 6.6 – Blade

Figure 6.7 – Vane

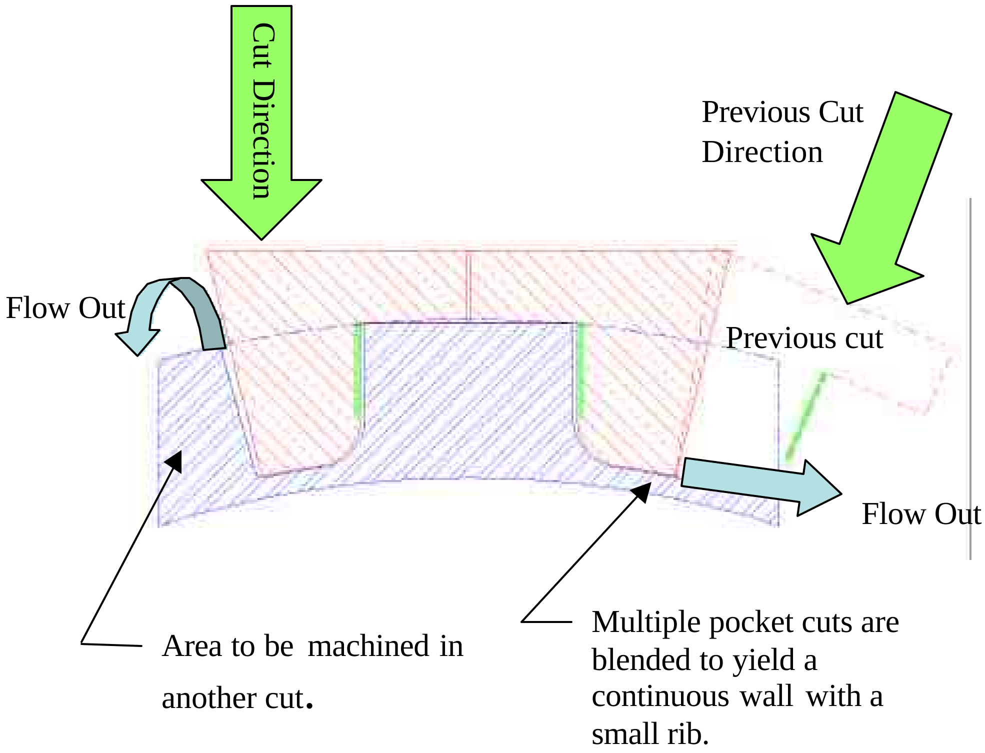
The Basics of ECM Tooling

The tooling for ECM consists of a part holding fixture and a cathode as a minimum. Gauges, multiple holding fixtures, cathodes, dams, material handling devices, or other items may be required. Part holding fixtures are usually made from a good conductor that will not rust such as a copper alloy. Structural components not required to carry current are often stainless steel or G-10 laminate.

Cathodes are usually made from a tough copper alloy such as bronze or copper tungsten. They are often made of multiple pieces to allow chambers to be fabricated to distribute the electrolyte to areas on the cathode face. A base usually has location features and a tip has the cutting geometry. It is possible to replace one or the other in the situation where one has been damaged. Because this is not a burning process such as EDM, the cathodes are reusable indefinitely. Handling damage, cleaning solutions, and water flow will eventually require the cathode face to be re-machined or replaced. However, one cathode could make thousands of cuts.

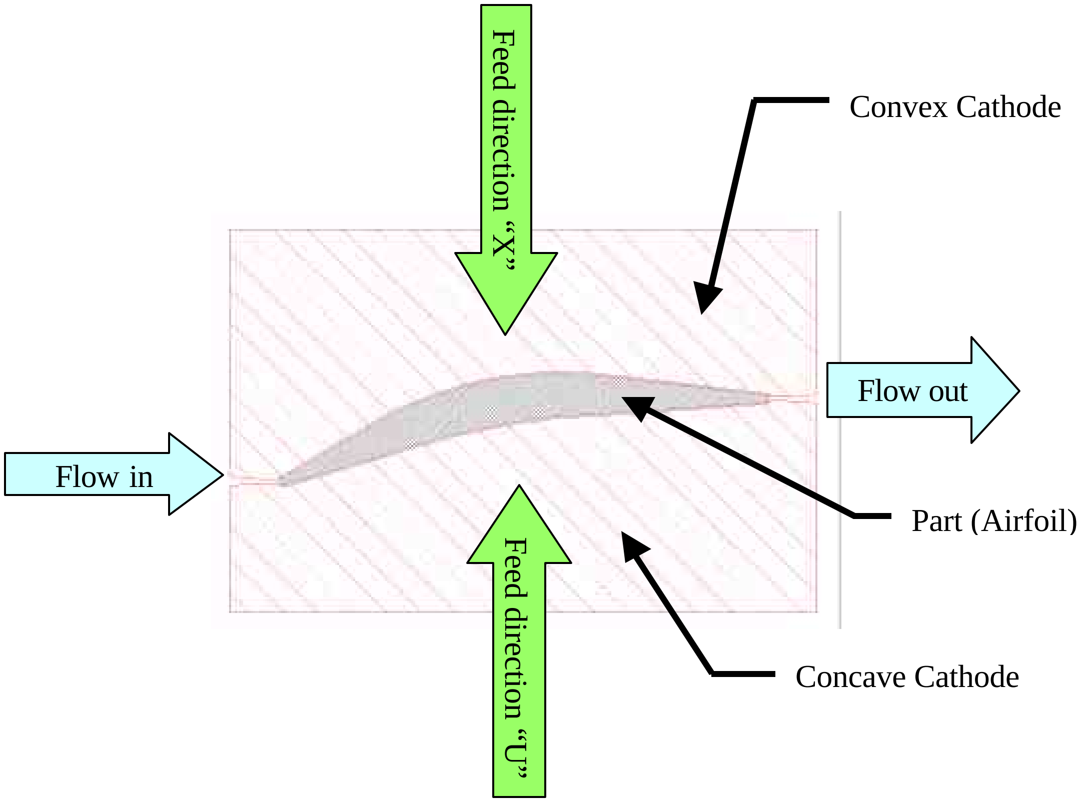
A cathode size is limited by geometry of the part or size of power supply available. A 15,000 Amp power supply usually is limited to 194 cm^2 (30 in^2) before running out of power. Standing features such as an embossment that is required to be perpendicular to a curved wall may require multiple cuts. Each embossment sidewall is parallel to the direction of cut. See figure 6.1 for an example of an embossment normal to a curved surface. The "previous cut" generated one embossment, and the cut shown is used to generate another. This figure also shows how adjoining cuts can generate a continuous wall with only a small rib between cuts.

Figure 6.1 – Schematic of adjoining ECM cuts



Some part features can be cut from two sides at the same time such as an airfoil. For this situation, multiple cathodes can be used in one cut as shown in figure 6.2. In this case flow is forced between the cathodes and the two cathodes are closed on two parallel axis "X" and "U".

Figure 6.2 – Skematic of Airfoil ECM cut



Cathodes use different types of flow. Each has it own special purpose and cost associated with it. The most cost effective type of flow is referred to as "open flow". Figures 6.3 and 6.4 show simple examples of this type of cathode. One is coated for parallel walls and one is left uncoated to save on cost. The coating is something that must be removed and replaced occasionally because the hydrogen in the cut will break down the bond to the copper alloy cathode.

For cuts that must make deep cuts relative to its' size, reverse flow is often used. Here, flow is forced down the outside of the cathode and out through the center of the cathode. Figure 6.5 below shows this type of cathode. A flow box called a "dam" is required for this type of cut. The dam drives up the cost of this tool along with having to incorporate flow in two directions. The sealed dam gives another advantage in being able to hold backpressure on the exit. This limits the ability of gas to form on the cathode that would stop the cutting action.

Figure 6.3 – Open flow – coated cathode

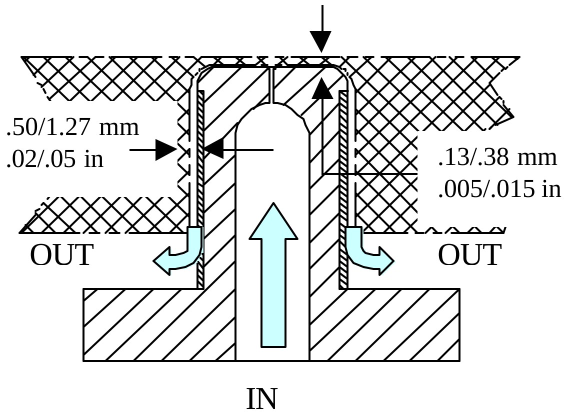


Figure 6.4 – Open floe – uncoated cathode

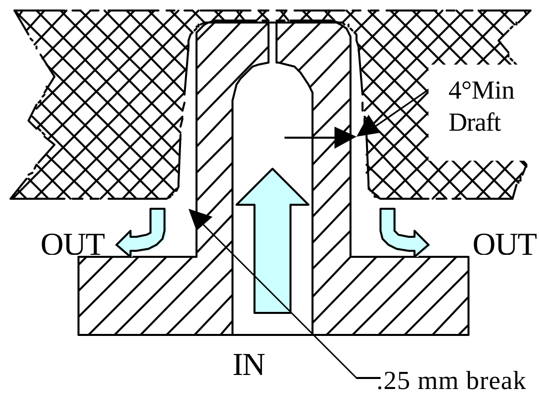


Figure 6.5-Closed flow – Reverse

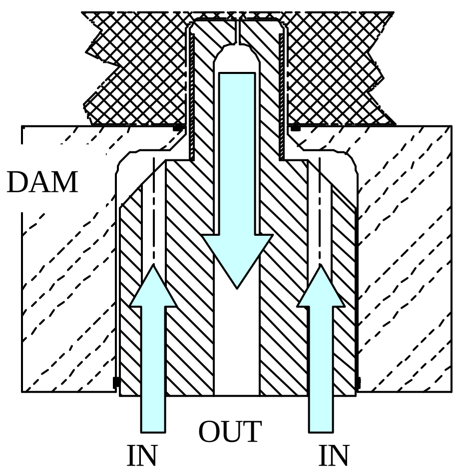
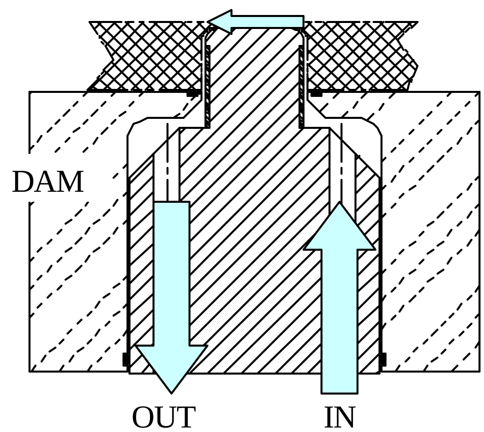


Figure 6.6 Closed flow – Cross flow



One last type is shown in Figure 6.6. This one is called “cross flow” because the electrolyte is forced in one side of the cut, across the face, and out the other side of the cut. The length of cut in the direction of flow limits this type. The electrolyte heats up and is picking up hydrogen and metal hydroxide as it passes through the tight gap. At some point, the electrolyte boils and lets gas pockets form. The current does not pass through these pockets of gas and the process stops. The conductivity of the electrolyte also changes and creates a taper that must be built into the cathode. This type of cut is used when a smooth surface is required without a flow rib.

7.0 What tolerances can ECM hold?

The tolerance an ECM cut can hold depends on many variables. The limits shown in this paper are typical one expected without any unusual efforts. The processes can usually be improved to give better tolerances than these but at a sometimes-higher cost. The method a surface is cut dictates how tight of a tolerance can be held. In figure 6.3 above, the magnitudes of the gaps between the part and the cathode are shown. In the “frontal” direction (in direction of travel), the gap is relatively small. Variations of 10 to 20% are usually negligible. On the side gap (where side of cathode generates shape), the gap is larger and a variation of 10 to 20% can have a significant effect. Thermal growth in a part from room temperature (21° C or 70°F) to a machining temperature (49° C or 120°F) can have an impact on bigger parts.

Figure 7.1 – Typical ECM pocket tolerances

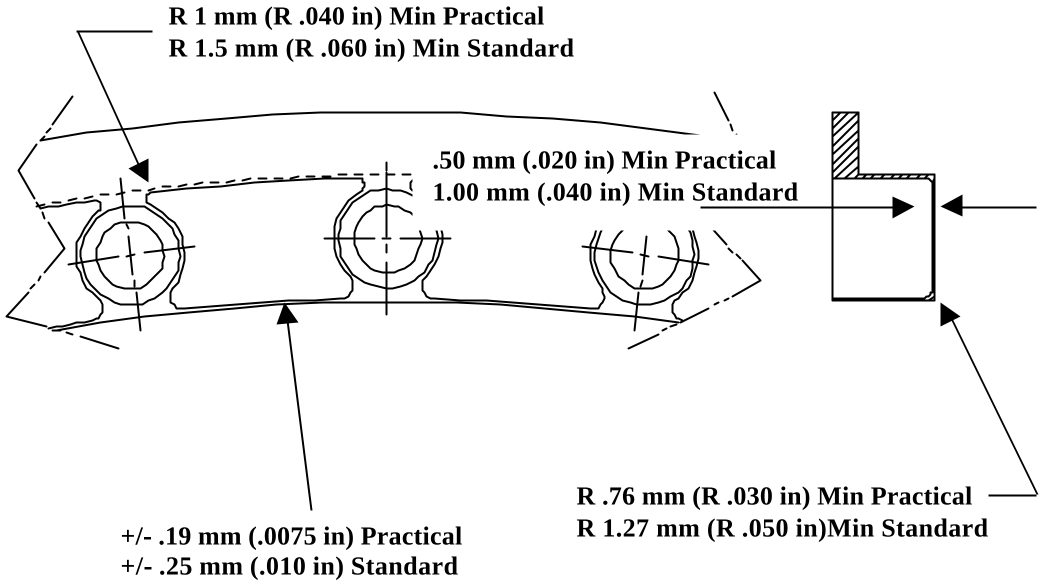


Figure 7.1 shows a pocket type of a cut. These tolerances are typical for about a 635 mm (25 in) diameter ring. The bottom wall thickness can be held +/- .13 mm (.005 in) as a standard. The radii are usually +/- .38 mm (.015 in). Sidewall surface finish is 3ìm (125 ìin) or better. The bottom wall and fillets are .8 ìm (32 ìin) or better. The material type and condition affects the finish and many alloys are significantly better than these.

For cases and other larger structural parts, part movement also affects tolerances as stresses are relieved. This same condition exists on milled parts also. Here typically, the size and location tolerances are tied together. Figure 7.2 shows a typical 760 mm (30 in) diameter case and the tolerances normally held. The wall thickness is dependent on the backside machining also. The tighter tolerances require a rough and finish cut. Each cut is inspected after rough and adjusted before finishing. The looser tolerance can be cut straight to depth. Just as in conventional machining, the tighter tolerance adds to the time to machine the part.

Figure 7.2 – Typical Case Tolerance

Blades, Vanes, Blisks (Bladed Disk), and IBR (Integrally Bladed Disk) airfoils all are machined to about the same tolerance. The size ands the material of the airfoil help determine the capability. These parts have extensive use of statistical process control used because of the volumes. These types of parts have simple functional gauges used on the machine by the operator. They also get a sampling inspection on a coordinate measuring machine (CMM) tied to a CAD/CAM system. The tolerances given in table 7.1 are the results of statistical data gathered across many different parts. Table 7.2 gives the same results in inches whereas table 7.1 is in millimeters.

Tube ID contours as shown in figures 7.3 and 7.4 can be held to a contour of .25/. 75 mm (.01/. 03in). This is dependent on the size and geometry to be machined.

Figure 7.3 ID Tube contour - Straight

Figure 7.3 ID Tube contour - Riffled

Table 7.1 – Airfoil tolerances (millimeters)

(All Dimensions in mm)	Small Ni or Steel	Medium Ni or Steel	Medium Titanium	Large titanium
General Airfoil Size				
Avg. Tip to Base Height	25.40	88.90	89.90	152.40
Avg. Chord Length	25.40	63.50	63.50	101.60
Airfoil Characteristics				
LE Thickness	+/- .076	+/- .089	+/- .102	+/- .114
Max Thickness	+/- .102	+/- .127	+/- .152	+/- .152
TE Thickness	+/- .102	+/- .127	+/- .152	+/- .152
Chord Length	+/- .254	+/- .305	+/- .381	+/- .457
Concave Contour	+/- .076	+/- .102	+/- .127	+/- .152
Convex Contour	+/- .076	+/- .102	+/- .127	+/- .152
Platform Contour	+/- .254	+/- .305	+/- .381	+/- .508
Inner Section Location				
X Shift	+/- .127	+/- .152	+/- .152	+/- .254
Y Shift	+/- .127	+/- .127	+/- .127	+/- .127
Rotation	+/- 0º15'	+/- 0º15'	+/- 0º15'	+/- 0º20'
Outer Section Location				
X Shift	+/- .203	+/- .254	+/- .254	+/- .356
Y Shift	+/- .203	+/- .254	+/- .254	+/- .356
Rotation	+/- 0º15'	+/- 0º20'	+/- 0º20'	+/- 0º20'

Table 7.2 – Airfoil tolerances (inches)

(All Dimensions in inches)	Small Ni or Steel	Medium Ni or Steel	Medium Titanium	Large titanium
General Airfoil Size				
Avg. Tip to Base Height	1.00	3.50	3.50	6.00
Avg. Chord Length	1.00	2.50	2.50	4.00
Airfoil Characteristics				
LE Thickness	+/- 0.003	+/- 0.0035	+/- 0.004	+/- 0.0045
Max Thickness	+/- 0.004	+/- 0.005	+/- 0.006	+/- 0.006
TE Thickness	+/- 0.004	+/- 0.005	+/- 0.006	+/- 0.006
Chord Length	+/- 0.010	+/- 0.012	+/- 0.015	+/- 0.018
Concave Contour	+/- 0.003	+/- 0.004	+/- 0.005	+/- 0.006
Convex Contour	+/- 0.003	+/- 0.004	+/- 0.005	+/- 0.006
Platform Contour	+/- 0.010	+/- 0.012	+/- 0.015	+/- 0.020
Inner Section Location				
X Shift	+/- 0.005	+/- 0.006	+/- 0.006	+/- 0.010
Y Shift	+/- 0.005	+/- 0.005	+/- 0.005	+/- 0.005
Rotation	+/- 0º15'	+/- 0º15'	+/- 0º15'	+/- 0º20'
Outer Section Location				
X Shift	+/- 0.008	+/- 0.010	+/- 0.010	+/- 0.014
Y Shift	+/- 0.008	+/- 0.010	+/- 0.010	+/- 0.014
Rotation	+/- 0º15'	+/- 0º20'	+/- 0º20'	+/- 0º20'

8.0 Examples of parts made by ECM

Figure 8.1 – Tube ECM Machine

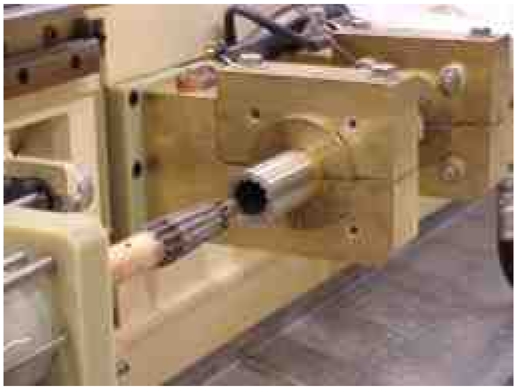


Figure 8.2 – Tube heat exchanger assembly

Figure 8.3 – Pre-ECM Blisk

Figure 8.4 – Rough ECM Blisk

Figure 8.5 – Blisk finished by ECM

Figure 8.6 – Driver Head

Figure 8.7 – OGV – vanes cut by ECM

Figure 8.8 – OGV – Close up

Figure 8.9 – ECM Blade from bar stock

Figure 8.10 ECM Vane from a forging

Figure 8.11 – Briquette Roll

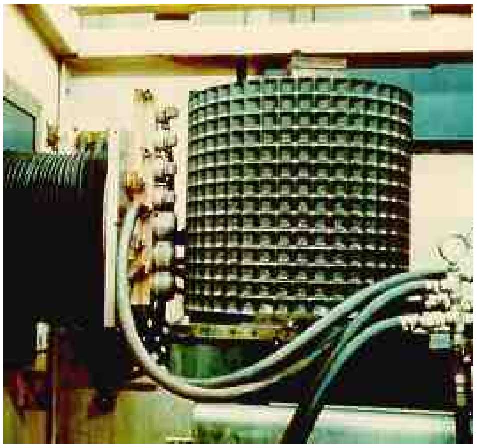


Figure 8.12 – Razor Screen

Figure 8.13 - ECM case machine

Figure 8.14 ECM case machine close up

Figure 8.15 Large ECM'd Case

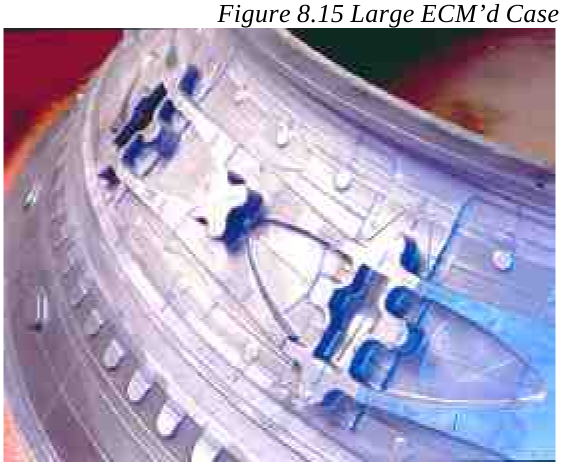


Figure 8.16 Finished Case

Figure 8.17 – Impeller in ECM Machine

Figure 8.18 – Disk embossments by ECM

For further information contact:

Terry Lievestro – Senior Applications Engineer
Sermatech Manufacturing Group
11230 Deerfield Road
Cincinnati, Ohio, USA 45242
Phone 513-489-9800 Fax 513-489-2409
ecm@sermatech.com