Electro Chemical Machining (ECM)
Surface Characteristics

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The electro chemical machining (ECM) process is one that dissolves metal into a hydroxide form as metal is removed from a part. The resultant is a stress free etched surface. This presentation examines the characteristics of the surface left by the ECM process. It will examine the quality of the surface finish along with the metallurgical effects on the workpiece. Intergranular attack and fatigue effects will be discussed.

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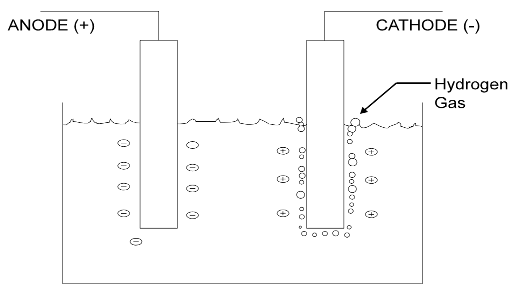
1.0 Basics of ECM

Electro Chemical Machining (ECM) is an electrochemical reaction caused by applying a DC potential between two electrodes, a cathode (Tool) and an anode (Workpiece). In the simple cell (Fig. 1.1) two electrodes are placed in a conductive salt solution such as sodium chloride. 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. 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 1.4 shown on the next page to keep the voltage the same. Figure 1.2 shows a simple cathode to form and embossment.

Figure 1.2 – Schematics of ECM process

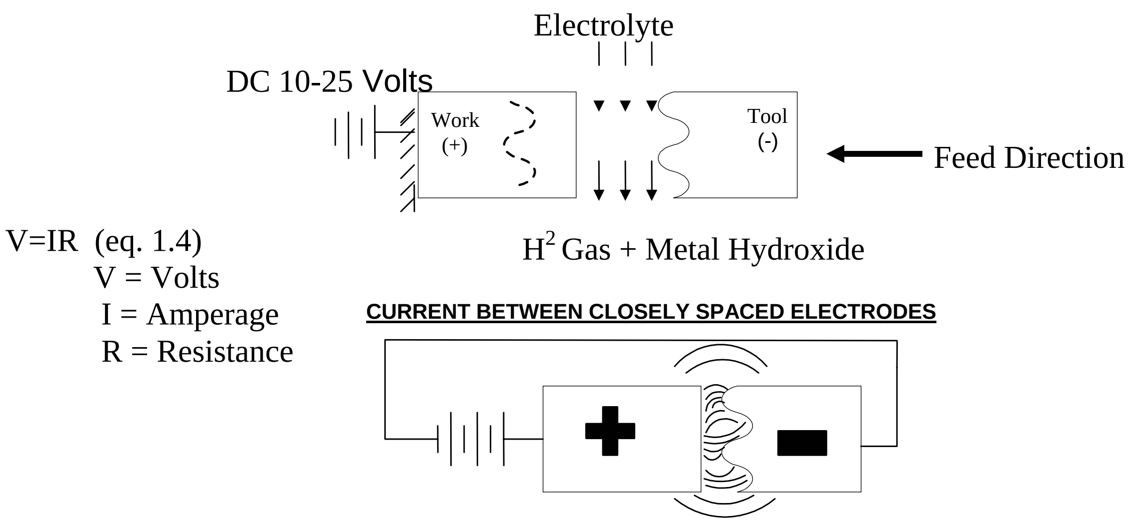
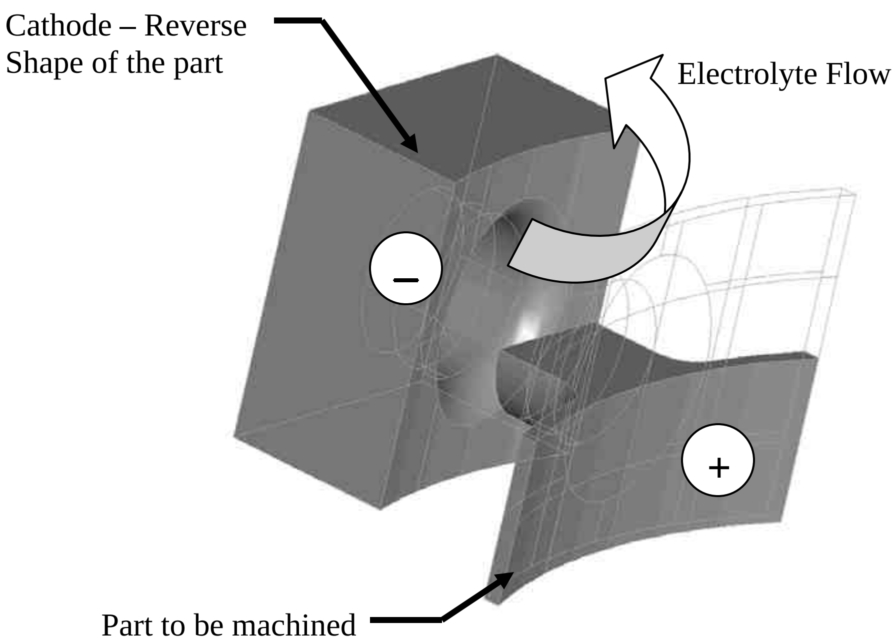


Figure 1.3 – Simple ECM Cathode



2.0 Surface Finish

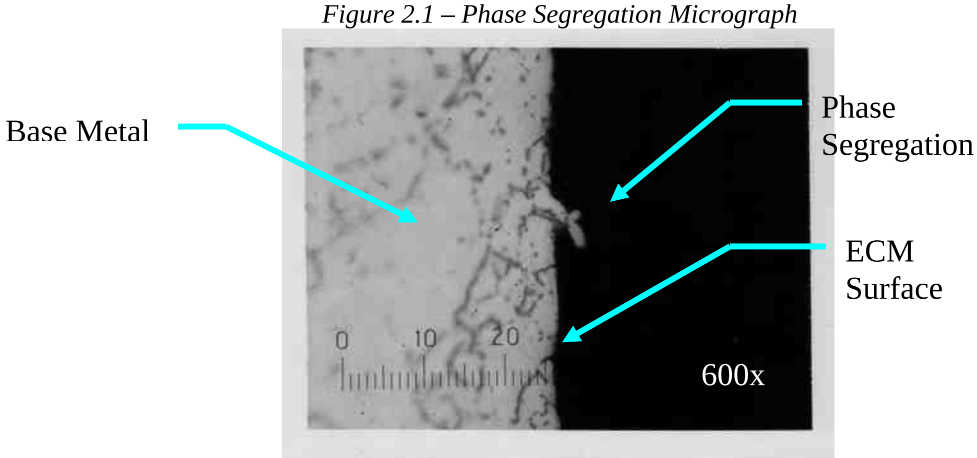
The resultant surface finish from ECM is dependent on a number of parameters. The type of workpiece material, heat treatment, and grain size are all parameters determined by the part design. The type, concentration, temperature, Ph, and flow of electrolyte all are parameters determined by the process needs. Power supply voltage and available amperage are the electrical parameters. Feed rate and cathode design determine the current density along with the maximum amperage.

The part material is determined by the design requirements. This is a given parameter usually out of the control of the ECM manufacturer. Higher temperature materials will have a better finish in general than lower temperature materials. Nickel, Cobalt, and Chrome materials all usually result in very good finishes. Wrought materials usually have a better finish than cast alloys. Highly alloyed titanium alloys usually have a rougher finish than less alloyed titanium alloys because of the varying breakdown voltage of the various metals. Materials such as titanium aluminide or carbon whisker reinforced materials all need special considerations in the ECM process because of the non-conductive particles.

In general the finer the grain size the better the surface finish. Because this is an "etching" process, the material tends to follow grain boundaries as the material is dissolved. Very fine grain material will usually give a very smooth finish. In some instances, a very large grain (i.e. ASTM 00) or single grain alloys, the grains are so large that the surface is does not follow the boundary resulting in very good finishes.

The heat treat of a material will affect the way carbon "carbides" are dispersed. Many materials have a heat treat to form distinct carbide globules or other phase segregation to strengthen the material. This segregation (figure 2.1) has a different breakdown potential and may not dissolve under the same parameters as the base metal. This can result in particles being left on the surface or pits from where a particle was washed thereby degrading the finish.

Figure 2.1 – Phase Segregation Micrograph



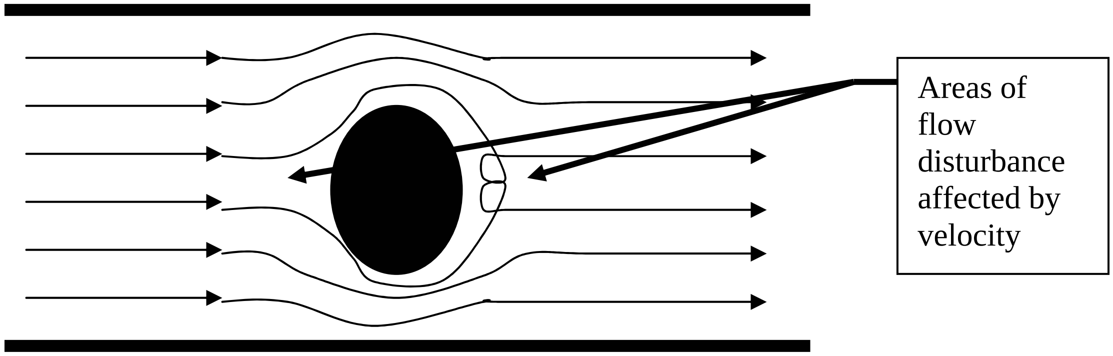
Given the material cannot be changed, the ECM manufacturer must look at parameters they can control. The first item usually considered is the electrolyte used. Different material types typically respond better to one type of electrolyte better than others. It is often possible to trade benefits of different types of electrolyte to get a better finish or higher material removal rate. If a part finish is not critical, then an aggressive electrolyte such as sodium chloride might be used. If finish is critical, then a more expensive electrolyte such as sodium nitrate might be required. Various other salts could be added to change the oxidation characteristics to protect adjoining surfaces. The type of electrolyte can also be used to minimize the effects multiple materials used in alloying. Often a mix of two electrolytes is used to gain benefits from each individual salt.

Some metals like a low concentration of salt in the electrolyte. This results in a lower conductivity for machining alloys such as aluminum that has a very low breakdown potential. Titanium alloys often work better with higher conductivity electrolyte because of the passive surface the results from the ECM process. The electrolyte must help the process break through a passivation layer that might otherwise stop the process resulting in a cathode shorting out on the workpiece causing a material meltdown locally. The temperature of the electrolyte may also be raised to increase the conductivity of the electrolyte. Titanium workpieces often are run with higher temperature electrolytes to keep the conductivity high enough to cut through the passive layer that usually builds on the surface during the ECM process. A lower temperature may be 29° C (84° F) whereas a higher temperature may be 49° C (120° F). If the temperature is raised too much, then the cooling effect of the electrolyte is reduced and local boiling in the cut may be a problem.

The Ph of the electrolyte has an effect on the passivation layer also. If the Ph gets too low, the hydroxide can build up in the flow passages of the cathode. Eventually, it can affect the flow volume or may break off as a solid causing a short circuit in the process thereby damaging the tool or workpiece. Most ECM applications will run for Ph 7 to Ph 11. This keeps the electrolyte neutral enough that the operators can handle it without the need of personal protection to protect from acid or basic burns or discomfort.

The flow of the electrolyte is probably one of the areas with the most impact on surface finish. With too little flow, the electrolyte heats up as it passes through the cut and may boil locally. This has the effect of an area with gasses present and no current flow through the gas. The process may continue but there is a shadow area on the part where there is an obvious breakdown of surface finish and contour control. Too much electrolyte may cause the velocity to be high enough to develop turbulent flow with eddies again causing gasses to be formed. The result is a surface with flow lines similar to that in sand behind and obstruction in flowing water as seem below.

Figure 2.2 – Simple flow pattern



In order to reduce the effects shown above, the flow can be captured down stream and the resultant backpressure can be controlled. By raising the backpressure, the vapor pressure of the electrolyte can be overcome and the gasses prevented from forming. The simplest and most inexpensive tool design lets the flow dump to atmosphere in an "open flow" tool. If the surface needs better control, then there are various types of tools to control the flow direction and backpressure. These are referred to "closed flow" tools. In the SURFIN 2003 proceedings, these tools have been described.

The electrical parameters are also controllable in the ECM process. The voltage is an input parameter to the process. The higher the voltage, the larger the cut gap between the cathode and the workpiece. It also results in higher power consumption and thus more heat generated from material resistance due to higher current flow. Material removal rates can be increased with higher voltages because the process is working further from the minimum material breakdown voltage. In general the surface finish is better with a tighter machining gap on most materials. It appears to be related to the thickness of the anodic layer. As a high point of material protrudes beyond the anodic layer, the potential required to breakdown the material is reduced therefore the peak is removed faster than the rest of the surface. Therefore, the process speed must be balanced with the heat generated and the finish required for the workpiece.

One predicable outcome of surface finish can be related to current density. If the current density is higher, then in general, the finish is better. Again there is a diminishing return to raising the current density for reasons mentioned above with overheating of the electrolyte. The size of power supply available is often a limiting factor for current density. If a machine has a 10,000 amp power supply, then a 161 square centimeter (25 sq. in.) cathode can only have a current density of 62 amps per square centimeter (400A/sq. in.). If the supply is 20,000 amps, then the same cathode can have a current density of 124 amps per square centimeter (800A/sq.in.). Normal cutting conditions usually are in a range of 23 to 124A/sq. cm (150 to 800A/sq. in.). Below 23A/sq. cm (150A/sq. in.) result in lower quality surface finishes.

The current density brings up another area of concern in ECM. Areas surrounding an ECM cut have a very low current density resulting in possible detrimental machining. If the current density gets too low, it is considered abusive machining. The result can be Intergranular attach and or pitting (see figure 2.3) from selective attack. For this reason, adjacent areas are either masked in some manner or have stock left on to be machined later. In a pocket condition where it is desired to have perpendicular walls, insulation is added to the side of the cathode. This drops the current density enough to nearly stop the ECM process after the exposed conductive portion of the cathode pass by (see figure 2.4). The surface finish in the bottom of the pocket in the high current density area will be best. The sidewall areas in the medium current density area will be somewhat rougher, and surfaces in the lower current density areas need to be masked or machined after ECM in many cases. Figure 2.5 shows the finish at the bottom of a pocket and figure 2.6 shows the sidewall finish.

Figure 2.3 – Selective attack on an ECM surface

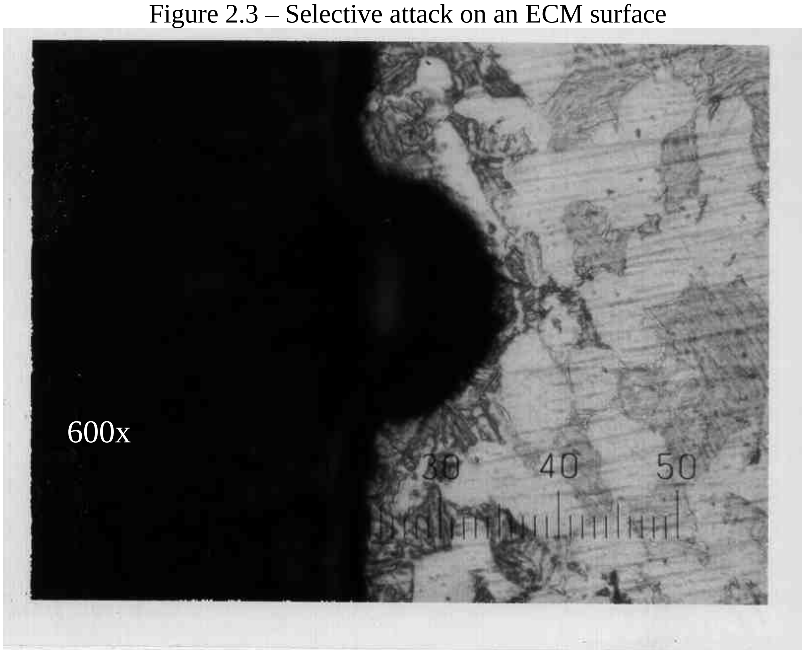


Figure 2.4 – Pocket cathode

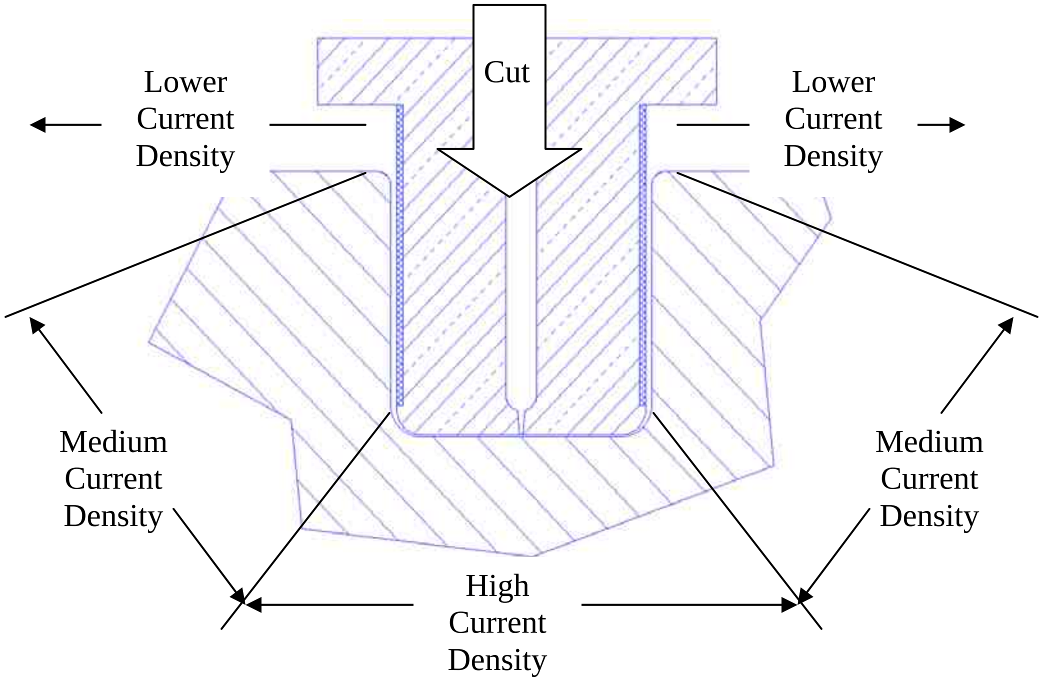


Figure 2.5 – Pocket bottom finish

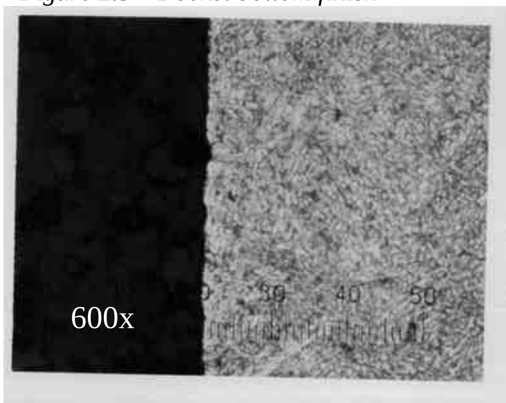


Figure 2.6 – Sidewall finish

There have been instances where ECM has found metallurgical problems not detected by other means in a workpiece. As mentioned above, the heat treat of a part affects the finish. The ECM process for a particular part had a normal surface finish of 0.55µm Ra (22 µ in. Ra). When a part was machined and a 0.12µm Ra (5 µ in. Ra) finish was seen by the machine operator, he called the engineer who ordered a metallurgic test of the part. The test showed a part with an “ASTM 00” (very large) grain size instead of an “ASTM 8” (very fine). This would be a major problem for the capability of the part. The tracing of the records showed an error in a heat treatment process that destroyed the properties of the part. Here ECM was an excellent tool for detecting changes in metallurgy.

3.0 Intergranular Attack

Studies have shown ECM like many electrolytic or chemical processes can produce Intergranular Attack (IGA) in the workpiece. For this reason, most critical components that have an ECM surface are required to be tested for IGA. Parts such as rotating components for gas turbine engines are always checked for IGA on a process approval part. Here a test part is cut with the production part parameters and is then cut up for a full metallurgical evaluation. Figure 3.1 shows an acceptable evaluation for IGA for even a rotating part. Non-critical parts most often do not require such testing if the ECM process is operated in a “normal” range.

Figure 3.1 – Acceptable IGA

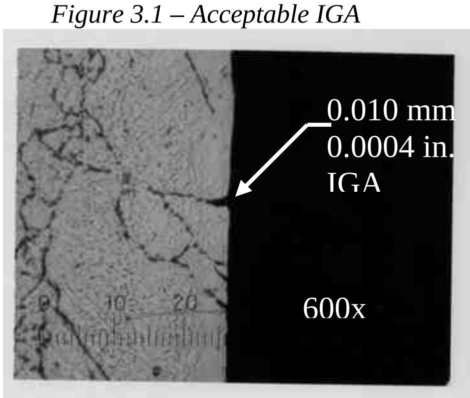


Figure 3.2 – Unacceptable IGA

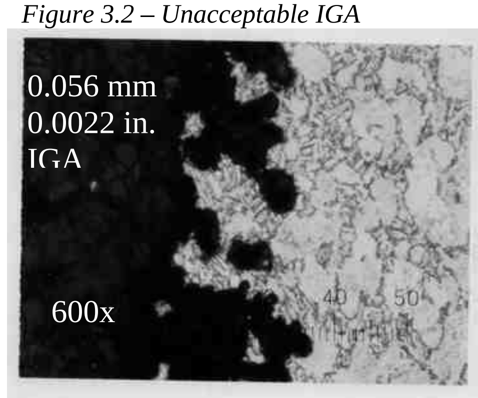
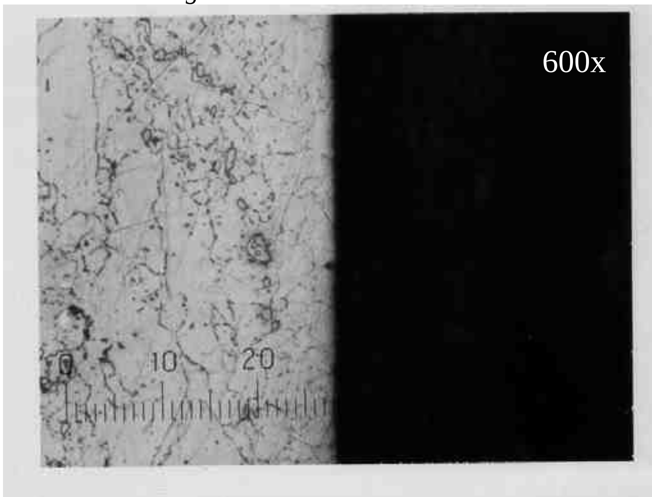


Figure 3.2 shows the result of a titanium surface exposed to a very low current density for an extended amount of time. An unacceptable IGA is present but a very rough surface is also present. For this particular test, the lab would not differentiate between surface irregularity, IGA or selective attack. This sample was machined under very abusive conditions and was visually obvious to be a failure.

The same types of parameters that have an affect on surface finish are usually the same ones that affect IGA. It has been found that for most materials, the “normal” range of the ECM process, if there is a problem with the process and the operation went outside of these normal conditions, then the part geometry would have significant changes and like violations long before the IGA would become a problem. Normal parameters would be considered to be 8-25 Volts, 23 to 155A/sq. cm (150-1000A/sq. in), 0.29-0.87 kg/l (0.5-1.5 lbs/gal) NaCl or 0.58-1.74 kg/l (1.0-3.0 lbs/gal) NaNO3 electrolyte in a 7-11 Ph, and 29-52° C (85-125° F). Figure 3.3 shows a very typical evaluation certified as no detectable IGA at 600x.

Figure 3.3 – No detectable IGA



4.0 Arc Burns

An arc burn can cause intergranular attack or other damage. If a less than optimum electrical contact or a particle in the cut gap is present, the large amperages required by ECM, can result in a local arc burn. This occurs as a result of a path of least resistance and too much current passing through a local area. A local overheating will cause a meltdown of the workpiece or cathode as a result of the resistance heating. Many properties of the workpiece can be damaged from the arc. If an arc occurs, an acid etch is often specified to open any damaged area enough to highlight the damaged area or to show there was not a significant damage.

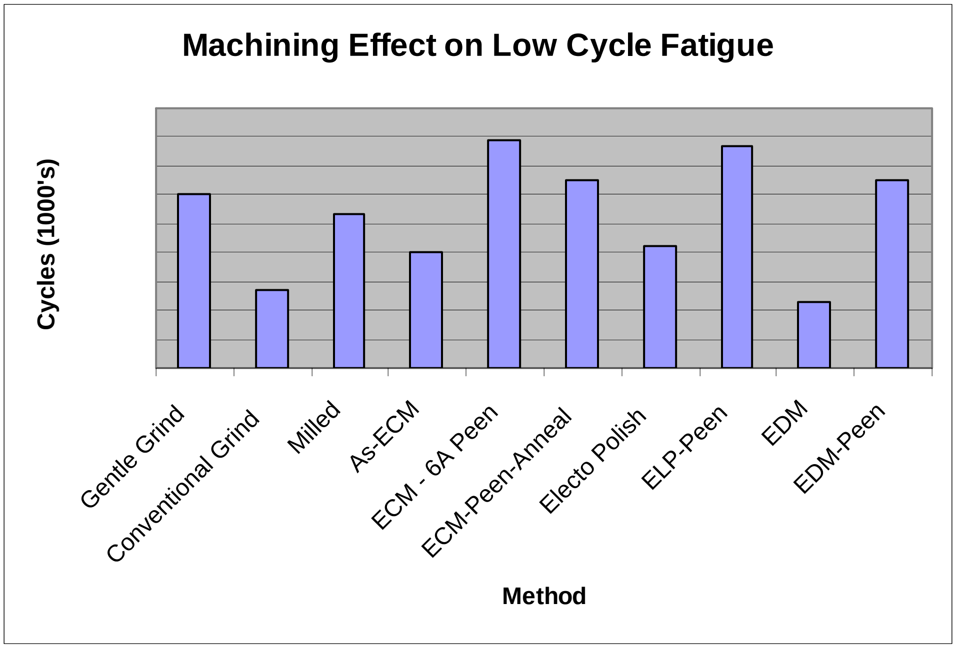
Most ECM power supplies are equipped with a “spark detect” and current dump circuit to minimize damage. It monitors for a rapid change in voltage or amperage that would occur milliseconds before an arc would occur. History has shown a sudden change will be detected in either or both of amperage or voltage just before an arc occurs. Therefore by doing an integration of the amperage and voltage, a sudden change can be detected. When detected, the process is shut down with the energy diverted to a “crow bar” (a big resistor) to dissipate the energy in the system.

5.0 Low Cycle Fatigue

ECM is often used in the gas turbine industry where difficult to machine alloys are common. These are also for parts subjected to low cycle fatigue. Flight engines in particular are scrutinized for the low cycle fatigue life of their components. The engines go from shut down to full power causing stresses on the parts to vary greatly. For these types of parts, ECM machined and other machined surfaces are analyzed for the effect that machining has on the life of the part.

From studies, it has been shown that surfaces with lower compressive stress in the surface usually have a lower fatigue life. Conventional machining such as grinding, milling or turning induces a compressive layer on the surface of the part. Non-conventional processes like ECM and Electro Polishing do not induce compressive surfaces. Thermal processes such as EDM leave a recast that reduces the fatigue life. Gentle grind is often the baseline (see figure 5.1) other processes are compared against. You can even see a significant variation in grinding alone. When required, ECM surfaces often have a post treatment such as shot peening to add the compressive stress to the surface.

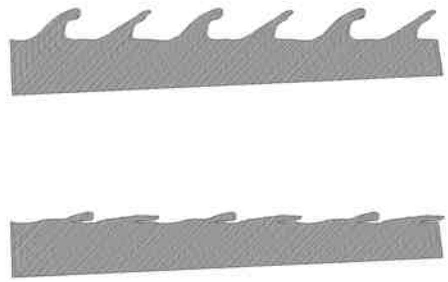
Figure 5.1 – Low cycle fatigue on a high temperature alloy



All machined surfaces that are subjected to a solution anneal after machining will usually have the compressive stress relieved somewhat during the heat treatment cycle. Often this heat treatment cycle is the first part of an aging or precipitation heat treatment cycle. For these parts, there is no lowering of fatigue life compared to conventional machining because ECM was chosen over the conventional machining process. If fatigue life is a concern for parts subjected to the annealing cycle, then they are usually subjected to a post treatment, regardless of the machining method, to put the beneficial compressive stress back into the part.

As seen in figure 5.1, ECM and electro polish both yield a higher fatigue life after peening. It is theorized to be the result of a clean surface free from the micro tears associated with conventional machining. When looking at a section of a conventionally machined surface at high magnification, it is possible to see how the surface is actually a torn or galled surface. When the surface is peened, the tears are folded down and smoothed. The fact is though, the cracks from the tear are still there as the sketch in figure 5.2 shows. Cracks eventually propagate from these micro cracks as the part is cycled through its stresses.

Figure 5.2 – Sketch of surface tears from Conventional Machining (highly magnified)



Therefore, if a part is machined and requires low cycle fatigue life to be maximized, it is recommended to impart some form of compressive stress. Shot peen is the most common method but other methods are available as well. A new method to impart compressive stress into a surface in a very controlled manner that does not deflect the part is to use a laser beam. This new method is often referred to as "shock peen". Surface treatments such as nitriding are other ways used for all surface types. Burnishing or other mechanical processes can also be used in some applications. Alternatively, the parts can be designed to lower the stresses in a part to minimize the low cycle fatigue concerns.

6.0 Hydrogen Embrittlement

Similar to electro polishing (EP), hydrogen is produced in the ECM process. Certain materials such as titanium are sensitive to hydrogen embrittlement. Unlike EP, ECM requires a high flow rate across the surface during the ECM process. This high flow is required to ensure no gasses are present on the surface to act as an electrical insulator as it carries away the hydroxide and heat. As a result, hydrogen embrittlement is not usually a problem with ECM. Critical applications do still require testing just to be certain. In the recent memory at Teleflex Aerospace - Cincinnati, the only failures from hydrogen embrittlement have been a result of material that failed the test throughout the part and not just in the ECM area.

7.0 Conclusion

ECM is a very good process for machining difficult metals with good surface finished right out of the process. Surface finishes of less than 63 Ra (inch) are usual for most metal types. Chrome bearing alloys are common to have finishes less than 16 Ra, especially if in a solution annealed heat treat condition.

Post processing is often required for parts that are sensitive to low cycle fatigue just as with many other processes. The post treatment usually results in a part with superior life to most other manufacturing processes.

Metallurgical testing is often specified for parts used in life threatening applications such as rotating jet engine parts. These tests may be for Intergranular attack, surface irregularities, selective attack, or for arc burns. In most situations though, a dimensional or change in surface finish will be apparent if there is a problem that would cause metallurgical damage.

References:

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