COMPETITIVE METHODS FOR FINISH-FORM MACHINING OF LUGS AND TENONS IN TURBINE BLADE MANUFACTURING

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20 November 1980

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1. Summary

Three competitive methods ultrasonic machining, electrodischarge machining, and electrochemical machining - have been compared in order to investigate their potential use in the form-finishing of turbine blade profiles.

Of these processes electrochemical machining (ECM) is recommended because:

- There is no tool wear in ECM particularly important for complex (hence costly) tool shapes.
- There is no metallurgical damage to the surface of the component and hence fatigue life is good.
- The ECM process is readily automated thus eliminating the labor costs involved in the hand-grinding being used at present.

These are scientific criteria and this report has not considered the cost-effectiveness of ECM. Apart from equipment and tooling costs, ECM facilities should ideally be located in a separate part of the plant in order to isolate the potentially corrosive atmosphere associated with the process. In addition the 'sludge' resulting from the ECM process needs to be filtered and separated. This waste is not dangerous in any way but cannot be discharged without treatment, because of its quantity.

To summarize the technical aspects, there is a trade-off between the following factors:

<u>Production Advantages</u>

1. Automated Blade Finishing
2. No Tool Wear
3. High Quality Components from a Tolerance and Fatigue Life Viewpoint

Installation vantages

1. Cost of New Equipment
2. Cost of Isolating ECM plant
3. Cost and Floor Space of Waste Treatment

Further study is obviously needed to resolve this trade-off. This report considers the technical issues in more detail and identifies computer aided tool design as a potential area of research that could be carried out at Carnegie-Mellon University.

2. Introduction

2.1. The Problem

The lugs and tenons of a turbine blade usually have complex contours. Traditional cutting tools cannot "finish shape" the turbine blade due to geometrical limitations. Finishing is currently done by hand filing which is both time consuming and expensive. It is proposed that an automated, computer controlled process could significantly speed the operation, save money and increase the quality and uniformity of the turbine blades. Hand finishing cannot be tolerated if automated production is to be successful. Finish form machining must, therefore, be a major goal of an automated process.

2.2. The Rival Processes Considered in this Report

The three machining processes that have been investigated are

1. electrodischarge machining (EDM)
2. ultrasonic machining
3. and electrochemical machining (ECM).

All three methods are fairly new to industry and they all have features which make them suitable for automated production. Of the three, electrochemical machining appears to be the most promising method for the application to turbine blades.

3. Electrodischarge Machining (EDM)

Electrodischarge machining is a process where material is removed by repetitive, short-lived electric sparks between the tool and workpiece. It has found popular use in industry as a method for sinking complex shaped holes in hard and soft metals. The configuration of current EDM equipment for this purpose is illustrated in Figure 1.

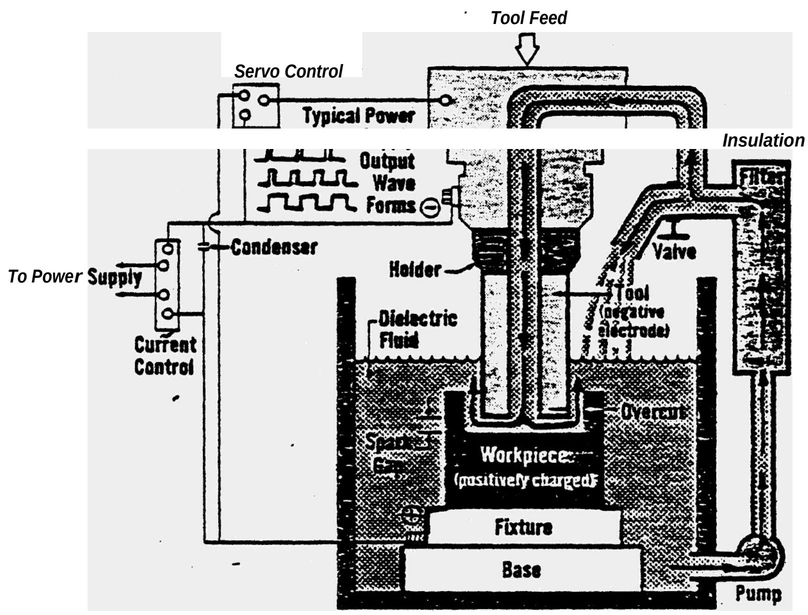


Figure 1. EDM Machining.

One of EDM's more attractive features is that it is capable of machining metal in its hardened state. The removal rate is not as dependent on material hardness as with conventional methods because the removal mechanism is independent of shear strength of the steel.

Unfortunately, the EDM dies do exhibit some wear during the machining process. There have been claims of zero tool wear but these have been documented solely *with* roughing operations. Tool wear is inevitable if finish machining is to be accomplished. Labor will have to be made available for periodic replacement of worn out tool dies. This *will* add to production costs and is considered a substantial drawback.

A phenomenon unique to EDM is a recast layer of *metal which* is established on the surface of the work. This layer is associated *with* some unfortunate characteristics. The recast layer is a region of higher carbon content and is ideal for the establishment of micro-cracks. This substantially lowers the fatigue limits of the blade. This condition is totally unacceptable. Therefore, if EDM were to be considered a method would have to be found to remove the recast layer. This would add expense to the overall production process. In the writer's opinion, the commercial processes that claim the ability to remove the layer, are not sufficiently well developed. Besides this the tool wear problem is a major drawback to EDM.

In sijmmari the problems of the recast layer and the tool wear that is. inevitable in finishing operations mean that EDM is not suitable for turbine blade manufacture.

4. Ultrasonic Machining

in ultrasonic machining, the workpiece material is chipped away by abrasive particles under a tool vibrating normal to the surface. The abrasive particles are held in a slurry and, due to the tools ultrasonic vibrations, impact the surface. The process has found acceptance in industry as a method for sinking holes in brittle metals and ceramics. Figure 2 illustrates the equipment used in the hole sinking process.

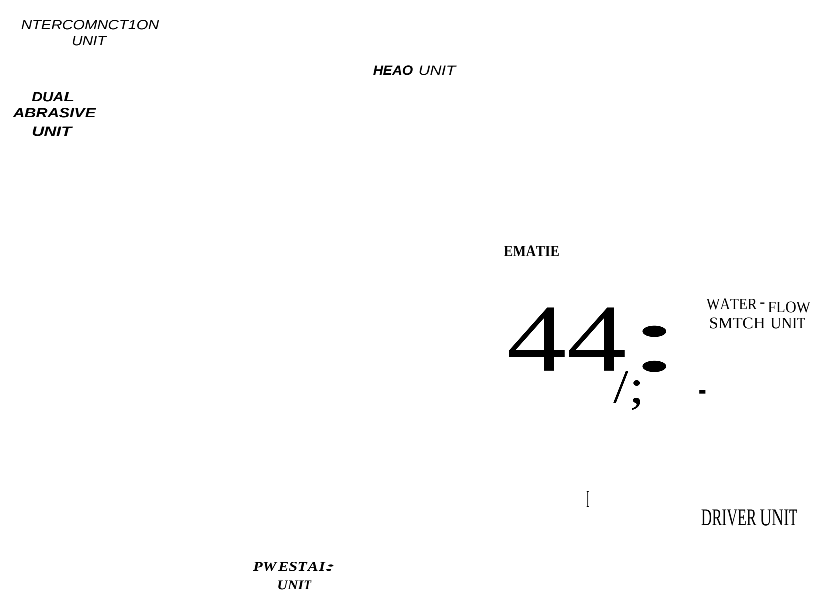


Figure 2. Ultrasonic Machining.

Ultrasonic machining has features which are desirable for automated machining and physical contact between work and tool isavoided by a force adaptive control system.

The finish of ultrasonically machined work is good. Finishing operations, performed with fine grit abrasives, commonly leave surfaces of 15 RMS finish. The workpiece characteristics are not altered in any way. There are no residual stresses present after machining. Fatigue properties are not adversely affected.

Ultrasonic machining does have shortcomings. The hammering action by which the work is chipped away also wears the tool itself. In the machining of hard alloys the tool wear rate can approach the rate at which the workpiece is being machined. The wear rates of the tool have not hindered the process development in industry, mainly because the tool is flat and thus will retain its shape as it wears. It is difficult to machine curved contours using the ultrasonic process. Areas of initial contact between tool and workpiece wear down quicker than the remaining areas resulting in tool deformation after a single pass.

It may be possible thatcontoured shapes, such as lugs and tenons, could be machined in several steps. The blade would have to be repositioned slightly between every step of the operation. Blade protrusions with unusual shapes and tight radiused curves may be impossible to machine.

Even under ideal conditions the machining rates for ultrasonic machining are slow. Rates of .003 in3 per minute or less are typical of this operation. Although there has been much research aimed at increasing the rate of machining, substantial improvement does not appear likely, in the time frame useful to Westinghouse.

In summary the tool wear rates and the relatively low machining rates are such that ultrasonic machining is not recommended for turbine blade manufacture.

5. Electrochemical Machining (ECM)

5.1. Introduction

The electrochemical machining process offers much promise for use in an automated manufacturing plant. In ECM, the workpiece is made the a node of an electrolytic cell. The tool having the required configuration, is made the cathode and is maintained within close proximity to the workpiece. An electrolyte such as sodium chloride solution is pumped between the work anode and the tool cathode while a strong direct current is passed across them. The work material is thus removed by electrolytic dissolution of the anode workpiece. Figure 3 represents a simplified view of the major components of the cavity sinking process.

TOOL CATHODE
ADVANCED BY
CONSTANT SPEED
MOTOR DRIVE

ELECTROLYTE

1-20
0C

WORK ANODE

Figure 3. ECM Process.

The most appealing factor of the ECM process is that Q.gj wear j zero under oroerconditions This is important because the tools used in ECM are expensive and time consuming to manufacture. ECM is economically attractive primarily because of the theorectically infinite tool life.

The ECM process, when executed with correct controls on process variables gives the workpiece an excellent finish. This excellent finish eliminates hand finishing and its inherently high labor costs.

ECM is self regulating if the cathodic tool is not advanced to quickly. The machining rate corresponds exactly with the rate of tool feed as long as its limits are not reached. Sophisticated control systems are not needed to control the rate of tool advance. There is a need, however, for devices which can guard against several possibilities. Arcing across the gap can put a crater in the tool, that can quickly render it useless. This 'sparkover' can be caused by electrolyte vaporization or actual contact between the tool and the workpiece. There have been control systems developed which sense the arc and instantaneously shut off the power supply. Careful design must go into the clamping mechanism, and the machine base, work table, and tool fixtures. Pressure due to the electrolyte flow require that these components be made as sturdy as possible. Yet most rigid metals are easily affected by the corrosive environment of the electrolyte. For this reason it is best to use all plastic components where possible. The tool itself is commonly stainless steel or copper due to the high conductivity and non-corrosive nature of these metals.

5.2. Plant Facilities

If ECM is to become widespread throughout a manufacturing plant there will have to be facilities provided for disposal of the "mudlike" sludge that is unique to the process. Sludge develops as the metal precipitates in the electrolyte to form hydrated oxides. While this sludge may tend to improve the anode finish at higher concentrations, it will block the flow passages and can break the connections in the gap. Even with a filtration system capable of extracting reusable electrolyte there is still a large amount of unusable sludge produced. Approximately 75 percent of the sludge is electrolyte. Electrolyte cost should thus be kept to a minimum by precipitate removal.

Of the numerous methods of sludge treatments developed, most are variations of three basic techniques: settling, filtration, and centrifugal seperation. While a system of settling tanks would be cheapest to install and need little maintenance, it would be the least efficient and would occupy much valuable floor space. Alternatively, one or several filters strategically placed in the flow passage would be effective, but would require frequent replacement. (In this area, progress has been made with a vacuum precoat filtration device having long lasting filters.) And finally, a centrifuge may cost more initially, but would occupy a small space and require little maintenance.

In addition to the precipitate, generous amounts of hydrogen are produced by the ECM process. Extraction systems must be installed to remove this hydrogen. If left to accumulate within the working gap, hydrogen bubbles will break connections and cause imperfections in the workpiece finish.

One final consideration in choosing ECM as a machining process is the installation aspects. It is not wise to place an ECM plant in a general shop because the salt electrolyte will corrode surrounding machinery. The ideal ECM setup would be comprised of three levels:

1. the electrolyte system,
2. the machine itself,
3. the electrical equipment.

Also needed is a washdown area where tools and fixtures can be cleaned and stored. The cost of installation and operation of this process is more than for conventional machining, but the rate of production for ECM is so much faster that these costs are regained several times over.

5.3. Surface Fatigue Properties

The surface left by ECM is in a stress free condition. Fatigue properties are not improved as in some processes where compressive residual stresses are left in the surface but the key feature is that the ECM process does not damage the surface in any way.

5.4. Elements of Cathode Tool Design

An interesting research area in the electrochemical machining process is the determination of the dimensions and contour of a cathode tool given the configuration of the desired finished product.

Consider the following tool arrangement composed of a frontal plane normal to the feed direction, a curved edge and a vertical uninsulated wall. Figure 4 illustrates this geometry.

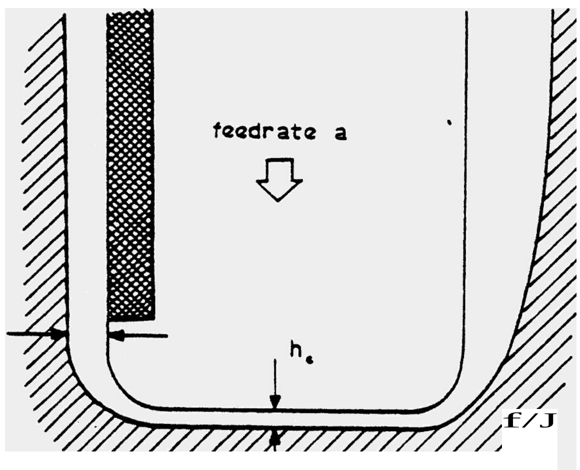


Figure 4. Simple ECM Tool Arrangement.

The gap at the face of the tool is the smallest and can be calculated by applying equation (19) (from the Appendix) for a constant feed rate. The form of the tool corresponding to the desired curve can be found by applying the cosine method.

The cosine method is a simple way to roughly calculate the tool contour for given workpiece dimensions. It entails the following. An equilibrium gap in the feed direction is first chosen (h_e) and at each point of the required workpiece a normal of length $h_e/\cos\theta$ is constructed. The required **surface of the** tool is then found by connecting the ends of the normals. The accuracy of this die design method has been found to decrease as the values of B become larger. Figure 5 illustrates this method.

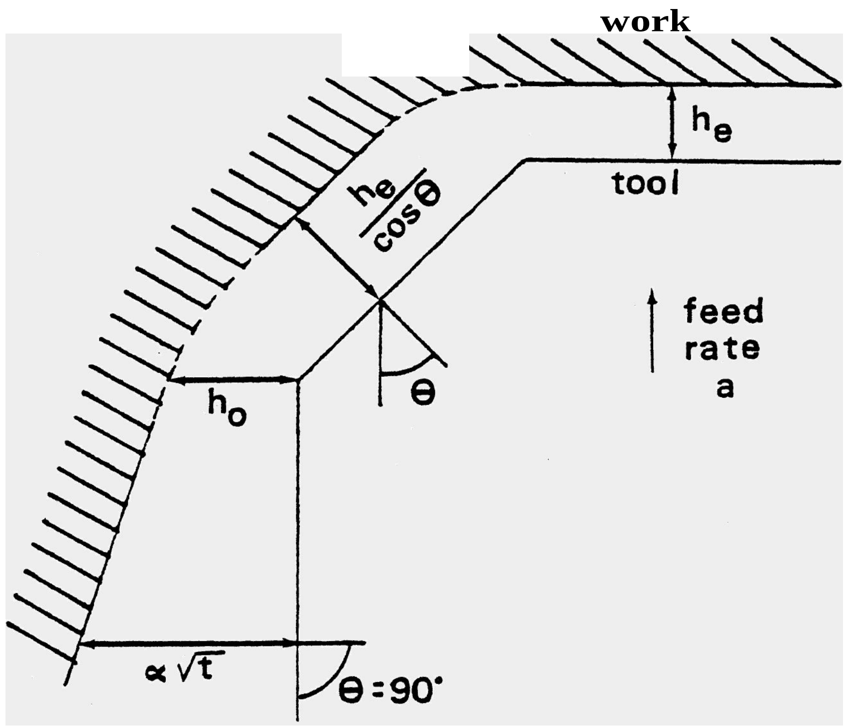


Figure 5. Cosine Method.

In our present analysis the cosine law is applied systematically to the curved surface leading to increased gap width as the gradiant increases. The gap along the vertical portion will be time dependent and can be calculated using equation (17). The gap will gradually widen, as the tool feeds into the workpiece because the vertical walls generated initially will be exposed to the tool for relatively longer periods *of time. The time* dependence of the vertical gap leads to inaccuracy and is considered an undesirable feature. An insulation layer applied directly to the tool, has been found to be a particular method of minimizing stray machining.

The advantages of using an insulation layer on vertical tool walls are illustrated in Figure 4. The insulation on the left-hand side drastically reduces current flow and thus curtails undesired machining. The general requirements of an insulation layer are as follows:

1. **good adhesion**

2. **flexibility of use**

3. high electrical resistance

4. resistance to corrosion

Extra protection and care is given to the edge of the insulation in order to eliminate lifting and separation due to electrolyte flow.

Unwanted machining can also be reduced by electrical means. It has been found that a biased anode placed in close proximity to the cathode tool can deflect the path of damaging stray currents. The result is again curtailment of undesired machining. Figure 6 illustrates the use of both insulation and the biased anode methods.

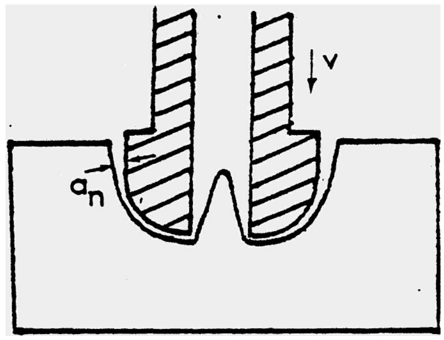
sleeve volts higher
than workpiece volts
workpice tool workpiacz tool insulation
feed feed
too tool
w
(positive) (Pos.tivc)
normal **machining** machining with boundary
control

Figure 6. Insulation and Biased Anode.

The anode is placed *on the* cathodic tool with a layer of insulation serving as an electrical barrier. Although effective, the method has disadvantages. The power supply must be increased in size and complexity due to the power needs of the subsidiary anode. The electrode must be manufactured from a noble metal to avoid electrochemical erosion.

One of the primary causes of uncertainty in cathode design is, in fact, the changing conductivity of the flowing electrolyte. The addition of hydroxides, hydrogen bubbles and other impurities as the electrolyte flows along the gap all serve to lower its conductivity.

While impurities which lower conductivity should be avoided, a controlled lower conductivity may serve to eliminate empirical corrections. When a passivating electrolyte such as $NaNO_3$ or $NaClO_3$ is used instead of NaCl, metal removal is restrained and overcut is greatly reduced (see Figure 7).



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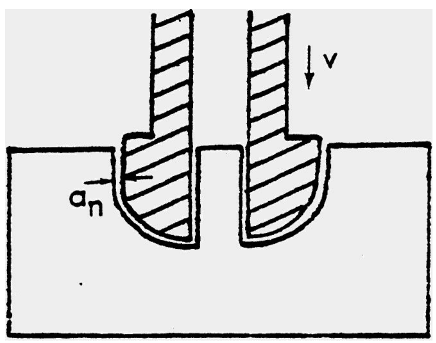


Nct40

Figure 7. Nonpassivating vs. Passivating Electrolyte.

With a passivating electrolyte, the tool can be made to the desired shape, making allowance for constant working gap only. The one drawback to this method, however, is the loss of energy due to low current efficiency. Its use is therefore uneconomical for large series machining.

Not only is the type of electrolyte important to tool design specifications, but also the direction in which it flows. The standard direction is from a recess in the tool to the outer edges of the workpiece (as was shown in Figure 3). It may be more advantageous, though, to use a convergent flow as shown here in Figure 8. The application to turbine blades appears to suit this type of reverse flow.

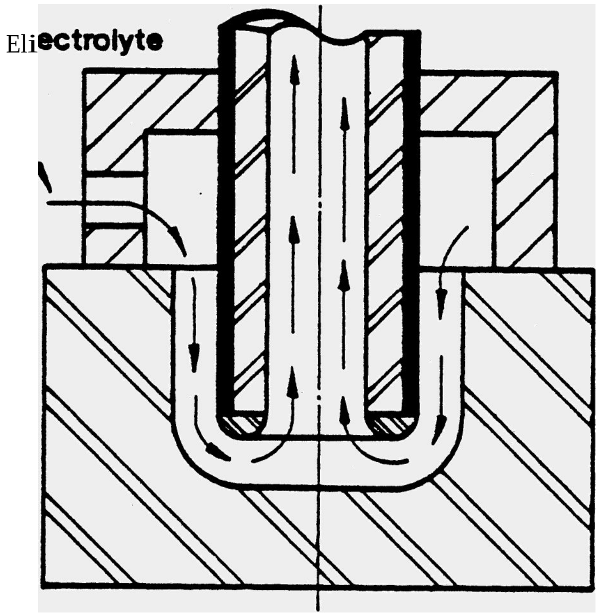
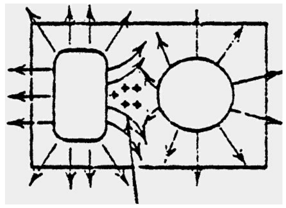


Figure 8· Convergent Electrolyte Flow.

Such a flow will produce a larger yet more constant and predictable overcut. Its uniformity promotes a better finish with less arcing and shorting. It should be noted, however, that this flow arrangement is complicated and initially expensive.

The main goal in tool and electrolyte flow design is uniformity. The more uniform the flow, the better the finish and the less the chance of breaks in the electrical current between tool and anode. To achieve such a flow, the tool should be built with porting through which the electrolyte may be admitted to the gap. At these points, ridges will be left on the workpiece to be machined later. To avoid as much additional machining as possible, the portings should be designed so as to take advantage of the natural features, *such as holes and* ridges, of the final anode configuration This techniique is demonstrated in Figure 9.



Passive area

(a)

Exhaust 4

Lth!:

Exhaust

Suppty

Section AA

Exhaust

(b)

Figure 9. Strategically Placed Portings.

Gap geometry and its corresponding empirical corre'ations have been studied by Konig and Pahi in a series of well planned eperiments. It was shown that the side gap increased with both the tool radius and the frontal gap. They established an empirical expression relating the side gap to these two variables. Later theoretical work by Konig and Degenhardt supported the earlier empirical studies. They determined the overcut for a variety of conditions including varying voltages feedrates and current densities. The conditions of the experiment, however, were selected such that no appreciable change in electrolyte conductivity developed along the gap.

A square, unradiused tool was the subject of analysis by PERA with the aim of determining the magnitude of the overcut and its relation to the frontal equilibrium gap. A relaxation analysis based on the application of one laplace equation to the potential difference between tool and workpiece, is used to determine the radial overcut oppositethe tool corner. Thus

2V + &2v = I
7

Determining the growth of the overcut until a stable overcut is reached represents the next stage in the analysis. The overcut is a function of the tool width W, the frontal gap h, and the radial overcut h0 such that

h0 = (2heW+(17he2)1"2

Using this simplified version of the cosine law a correlation between experimental and theoretical results has been obtained but more detailed curve fitting equations are still needed.

5.5. Computer Aided Design of ECM Tools

The cosine law can approximately predict the shape of the workpiece surface produced by a given tool form.

The practical issue is in fact the reverse of this: what is the tool geometry required to produce a predetermined workpiece contour? At present in the literative there is only an approximate analysis available and in addition this applies to small values of angle of attach <600. This is very inadeauate for designing tools suitable for turbine blade manufacture.

Further research in cathode tool design is needed and the analysis described below can be considerably improved by using CAD -

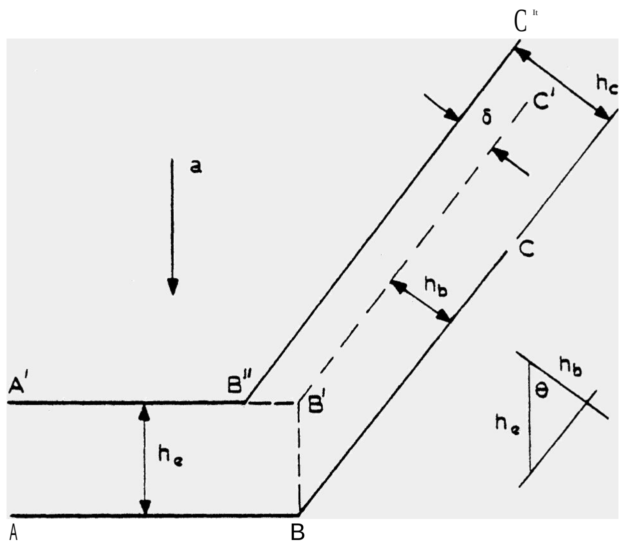


Figure 10. Correct Tool Geometry.

The workpiece surface to be produced above is ABC and the toot is being fed down normal to AB. As a result the normal to the surface BC is inclined at an angle 0 to the feed direction. If he S the frontal gap and the tool is advanced the inclined face gap will be hb = he cos 9, obviously less than he* Thus the current densities across the faces A'S to AB and B'C' to BC will be different unless the tool is "corrected" in dimension to be given the form AB"C". By retracting the face B'C' to B"C" by the amount 5 where 6 = he(sec 0 cos 0) the new tool shape produces the desired shape ABC.

The situation in the corner position B is the difficult one and it is here where shape matching on the computer could be carried out to great advantage. In the program it would be readily possible to include the equations for rate of metal removal based on the chemical attack of the turbine blade stainless steel and then use a similar analysis to that above to compute *the optimum tool shape for the given lug or tenon geometry. The analysis above applies to two* simple inclined planes rather than sculptured surfaces. It is the design of optimum tool shapes for such surfaces that would be a fruitful research area and one which would have potential use in Westinghouse.

6. Conclusions

The absence of tool wear and quality of surface finish make the ECM process the obvious choice for form finishing turbine blades. However, these are scientific criteria only and the production personnel considering the installation of ECM are assembling information on the costs of plant and waste disposal units. The cost effectiveness of ECM has not been addressed in this report and remains to be debated by the Westinghouse group. Computer Aided Tool design is a challenging research area in ECM and could be carried out at Carnegie-Mellon University and results transferred to production engineers.

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8. Acknowledgements

S. Kondogianis and J. Lawton have provided valuable assistance in the preparation of this report.

9. Appendix I

The rate at which metal is removed during the ECM process is a function of the chemical composition of the workpiece material and is directly proportional to the current, assuming 100% current efficiency. The volume of metal removed in a unit of time (t) can be expressed, using Faraday's laws, by the following equation

M = I/F/atomic weight's / % valence) density (1)

where: I = current

F = Faraday in coulombs (approximately 96,500 coulombs)

Atomic Weight = Gram Atomic Weight

Density = gram/cm3

V = cm3 of metal removed per second

t in' seconds

The inital assumption of 100 per cent current efficiency is valid. Studies by Meleka on various workpiece materials reveal actual efficiencies approaching 100 per cent .

Debarr and Oliver have considered the electrochemistry of the typical ECM cell. They utilized an iron anode in a sodium chloride electrolyte. This arrangement is not uncommon to industry practice . The machining process can be broken down into three zones, which aids in the description of the chemical reactions. These zones are the cathode (tool) film, the anode (workpiece) film, and the body of the solution. The films are considered to be the portion of the electrolyte which is in direct contact with the cathode and anode.

The body of solution undergoes several possible reactions. The sodium solution is ionized such the

NaCl = Na + Cl (2)

The water undergoes a partial dissasociation.

riu=ri + + (3)

At the anode surface, electrons are removed by the current flow and the metallic bonds of the molecular structure of this surface are broken. This reaction is expressed by the following equation:

Fe =Fe+2e− (4)

These positive iron ions move through the electrolyte towards the cathode due to electrical attraction. Once released from the anode, however, the iron ions combine to form an insoluble precipitate and are consequently removed by the flowing electrolyte. There are additional reactions at the anode surface. There is an evolution of Oxygen gas during the discharge of the hydroxyl ions

40H− = 2H20+02 ~ 4e (5)

There is also a further electrolysis of the water

$$2H_2O = O_2 \quad 4H \quad + 4e \qquad (6)$$

If the voltage difference is high enough, chlorine gas will also be evolved at the anode

$$2Cl = Cl_2 + 2e^- \qquad (7)$$

As these conditions are occuring at the anode other reactions are simultaneously occurring at the cathode. Positive hydrogen ions are attracted to the negatively charged surface of the cathode and are emitted at the surface to form hydrogen atoms which, in turn, combine to form hydrogen molecules. The following equations express these reactions

$$H + e = H \qquad (8)$$

$$H^O + H^\circ = H_2 \qquad (9)$$

The hydrogen molecules then escape the cathode film due to the low density and are swept away by the flowing electrolyte. The loss of hydrogen ions is the cause of another reaction at the cathode. Hydroxyl ion (OH) is the result. The reaction can be expressed in the following equation

$$2H_2O + 2e = 2\,(OH) + H_2 \qquad (10)$$

In a cell of suitable efficiency, with low chlorine levels and little overvoltage the overall cell reaction is

$$Fe^2 + 2OH = Fe(OH)_2 \qquad (11)$$

Where there is very high current densities it is common for overvoltage to be high enough such that both the oxygen and the chlorine reactions take place in addition to metal removal.

9.1. Dynamics of ECM

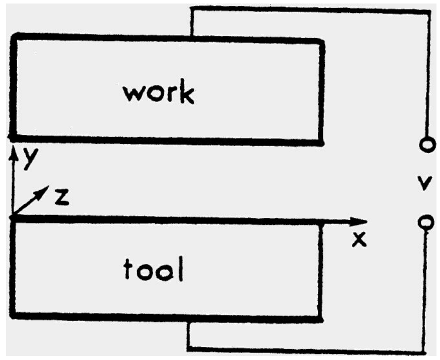
The main features of ECM dynamics can be determined from an analysis of simple shapes using mean values of parameters like temperature, electrolyte pressure, and electrolyte flowrate. This approach grately simplifies the ensuing mathematical analysis and allows useful conclusions to be made.

Consider a working gap with plane parallel surfaces and a constant difference in potential. Assume all electrolyte properties to be constant. Create a reference plane with $y = o$ at the tool surface and the workpiece surface representing the y component, always positive. The electrolyte will be assumed to flow at a velocity V with all properties independent in the x and z axis. Turbulence and variation of electrolyte properties due to entry-exit ports have been neglected. This configuration is illustrated in Figure 11.

I

O

O



Assuming 100 per cent current efficiency, the metal removal rate, using Faraday's Law, is equal to

(12)

where E = chemical eqivalent of workpiece material

J = current density (A cm2)

F= Faradays constant (-96,5OO coulombs)

pw = density of wortcpiece (g cm 3)

The rate of change of the workpiece surface relative to the tool surface is thus

$$\frac{dy}{dt} = E\ J\ \text{-(tool feed rate)} \qquad (13)$$

Tool feed rates are assumed positive in the direction of increasing y. If the voltage across the gap is constant then from ohms law we have

$$J = \frac{y.,}{Y} \qquad (14)$$

and writing EVK/FPW = C we have

$$\frac{dy}{dt} = \frac{c}{y} . a \qquad (15)$$

as the differential equation of the system with a representing the tool feed rate.

(a) Zero feed rate (static cathode)

O

The simpliest condition to analyze is that in which the tool is stationary:

$$\frac{dy}{dt} = \frac{C}{y} \tag{16}$$

Integrating, we have,

$$y = (y_0^2 + 2Ct)^{1/2} \tag{17}$$

where t is time and y_0 the machining gap at $t = 0$. When the tool is stationary, therefore, the gap increases at a rate proportional to the square root of time. Static cells have found many practical applications in industry among them, the finishing of turbine blade trailing edges.

(b) Constant feed rate

Constant feed systems are utilized in the majority of ECM plants. Equation (4) represents the constant feed condition. The steady state conditions exists when $dy/dt = 0$. This leads to the important principle of the equilibrium gap y_e represented by

$$y_e = \frac{C}{a} \tag{18}$$

Substituting the value of C we have,

$$y_e = \frac{EK \cdot V}{FP\,a} \tag{19}$$

This equation is of considerable practical importance. It shows that the equilibrium gap can be increased, in any machining opertion, by decreasing the applied voltage or the feed rate. Likewise, the gap can be decreased by increasing either or both. It is not unusual in industry to see initially large gaps reduced near the end of machining for purposes of accuracy.