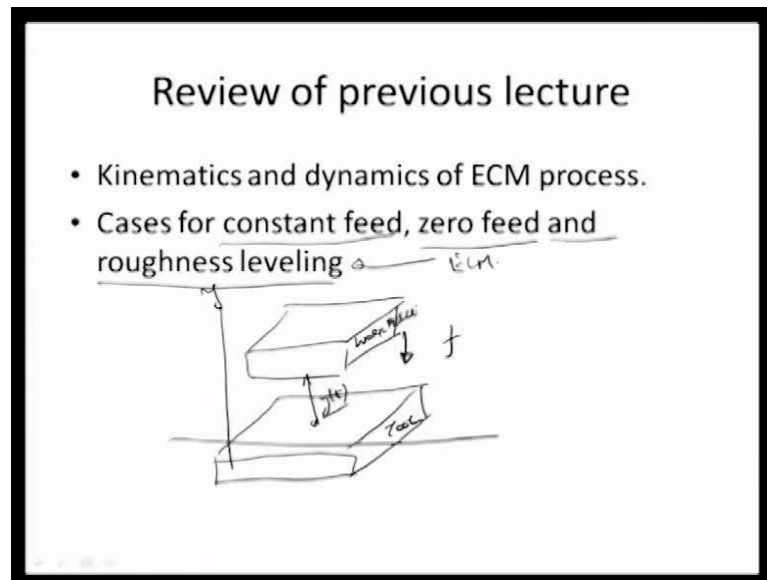


**Microsystem Fabrication with Advanced Manufacturing Techniques**  
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**Lecture – 15**

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Hello and welcome back to this fifteenth lecture on Microsystems fabrication by advanced manufacturing processes. Brief review of what we did last time, it is basically you started with looking at the kinematics and dynamics of the ECM process wherein, we assumed that there is a work piece. And this work piece actually moves towards a tool in the negative work negative y direction with the feed  $f$ . And then we tried finding out what the gap we do in the work piece and the tool would be as a function of time. So, what would this gap  $b$  we investigated the cases of 0 feed constant feed and then automatic surface leveling action that is done by the ECM process.

Today we would looking to a slightly different aspect of the ECM which is very critical for designing, particular electrochemical machining system for Microsystems design and fabrication. So, that is related itself to the electrolyte circulation or the electrolyte flow. So, basically there is a possibility that the electrolyte in a ECM process moves through a very small gap, because the equilibrium gap is of few 100 of microns.

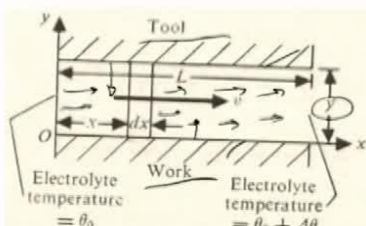
Then because of this continuous movement in a high value of current density there is always a possibility of the electrolyte being liquid to hit the boiling points some times. And the design guide lines should be such that the velocity of flow of this electrolyte between this gap the equilibrium gap should be in a manner that the boiling point of the electrolyte is never reached. So, you have to operate safely below the boiling temperature of a certain ECM process or of a of a electrolyte in ECM process.

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### Temperature and pressure rise during ECM

- So far as the machining forces are concerned, it may appear at the first glance that the forces acting on the tool and the work-piece are negligible since material removal takes place in the atomic level.
- But since the electrolyte has to be provided with an adequate rate of flow, normally the pressure is large.
- The hydrostatic forces acting on the tool and the work-piece are quite considerable in magnitude.
- The flow of electrolyte is necessary for the following reasons:
  - To avoid the ion concentration.
  - To avoid the deposition on the tool.
  - To remove the precipitation.
  - To avoid the overheating of the electrolyte.

The last one is very important and an estimate of the required flow rate of the electrolyte can be worked out on the basis of this.



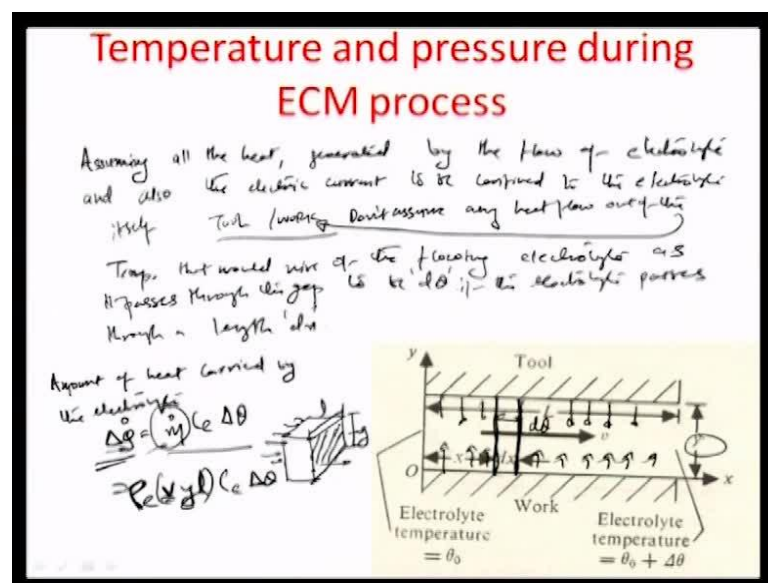
So, let us look at some of these parameters here in the slide temperature and pressure rise during the ECM process. And as we have already mentioned before that as far as machining forces are concerned, it may appear at first glance that the forces acting on the tool and work piece are negligible. Since material removal takes place in the atomic level; however, you can understand that because of the very small gap  $y$  here between the tool and the work pieces. You are seeing there is going to be enormous amount of concern about the pressure and the effective force on both the tool surfaces as well as the work piece surface because of the ECM, because of the electrolyte itself.

So, you have to provide this electrolyte with adequate flow rate and that also because you know in to a small gap means that normally the pressure that is being met with is enormously high. And at that level the rate of flow should be such that the amount of heat, that is transferred because of the current density from the tool to the work piece that is established. And subsequent removal processes that is established at the work piece

can be taken care of you know in terms of the amount of heat stored within the electrolyte material as it flows.

So, you should just operate below the boiling point and the heat that is being dissipated by the current density because, of ion transport of the fluid flow should be just enough to operate the or to make the operating temperature of the electrolyte below the boiling point. And therefore, the flow of this electrolyte is definitely necessary for that. And some of the reasons why flow would be proffered would be to avoid ion concentration. To avoid the deposition of the electrolyte material that is the electro material that is removed on the tool to remove the precipitation of whatever goes in from the work into the electrolyte to avoid overheating of the electrolyte. The last one is very important an estimate of the required flow rate, so that the electrolyte can remain without boiling.

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So, these are principally the reasons why flow of the electrolyte is a preferred solution to address some of these requirements of problems. And let us look in to this little more in a little more details and the modeling aspects. So, assuming that all the heat generated by the flow of electrolyte and also the effective current that is pumped into the electrolyte to be confined to the electrolyte itself. So, we do not assume any heat flow, from the tool side or the work piece side. So, we do not assume any heat flow. In another words we are neglecting the conduction; the heat conduction of the electrodes.

So, if you assume that the temperature that would rise of the flowing electrolyte as it passes through the gap to be  $d\theta$ . If the electrolyte of course, passes through a length  $dx$  so the electrolyte is passing through length  $dx$ . Here for still in this case this is the gap  $dx$  through which the electrolyte is flowing and while passing from this face, right here to this face there is a increase of  $d\theta$  and the temperature of the electrolyte.

So, of course, the amount of heat carried by the electrolyte  $\dot{q}$  is also be when as the mass flow rate  $\dot{m}$  times of specific heat capacities  $c$  times of  $d\theta$  right,  $\dot{q}$  equal to  $\dot{m} c d\theta$ .  $T$  is the temperature difference across which the heat flow is happening. So, just because there is a rate of heat rise its proportional to the rate of mass flow.

So, in this particular case, if we assume that the electrode is of a depth within the plane of the paper  $l$  and the total height  $y$  as given here which is also the equilibrium gap. And we assume that, the heat is flowing perpendicular to this shaded face. So, we can easily say what  $\dot{m}$  would be by looking at the density and looking at the velocity with which it is flowing times of  $yl$ . As  $yl$  is the cross sectional area,  $v$  is the velocity of flow in this direction which meaning thereby velocity times area as the volume flow rate times of the density of the electrolyte  $\rho_e$  makes it mass flow rate times of  $c d\theta$ . So, that is the amount of heat flow which would happen between this face and this face; which would rise the temperature of the electrolyte in turn by  $d\theta$ .

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**Temperature and pressure during ECM process**


The electrical power due to current density ( $J$ ) =  $I^2 R$   
 where  $I$  is the current,  $R$  = resistance of the medium

$R = \frac{1}{k} \frac{y}{dx}$   
 $= \frac{y}{k(dx)}$

$\Rightarrow \int J^2 R = \int J^2 dx \frac{y}{k(dx)} = \frac{J^2 y dx}{k}$

$\Rightarrow \int \frac{J^2 y dx}{k} = Q = \dot{m} c \Delta\theta$

$\Rightarrow \Delta\theta = \frac{J^2 y}{k \rho_e c} \left( \frac{1}{2} \right) \quad \checkmark$



So, now we would somehow like to find out relationship between the current density which is the main reason for the heat transfer, from the tool or the work piece on to the electrolyte. And if you look at that the electrical power due to the current density which is dependent on the flow of the ions right is equal to  $j^2 i^2 r$ , where  $i$  is the current and  $r$  is the resistance of the medium.

So, the medium of course, was that small element  $dx$  as we suggested before. So, this width is  $dx$  the equilibrium gap is  $y$  and the depth into the plane of this board is  $l$ . So, therefore, the resistance here can be written down as  $1$  by  $k$  length  $l$ , remind you the current is coming perpendicular to this face right. So, the length that it would face is  $y$  and the cross sectional area that it would face  $dx$  times of  $l$ .

So, therefore, that is what the total resistance would be equal to  $y$  divided by  $k l dx$ . So, in other words  $i^2 r$  can be written down as of course, the current density which is proportional or which is actually perpendicular to this face with area  $dx l$ . So, I can write this as  $j$  times of  $dx$  times of  $l$  square. So, square of all of these times of  $r$  given by  $y$  by  $k l dx$ . In other words, it can be written down as,  $j^2 l dx y$  by  $k$ . So, that is what the total amount of electrical power is that is transmitted to this element here of thickness  $dx$  the equilibrium gap  $y$  with length  $l$  into the plane of the paper here, signifying it is a 3 dimensional volume.

So, the total amount of heat that is transmitted to this flowing electrolyte in this direction is really the total amount of heat that is transferred from between this face and this face meaning thereby, that there is a rise in the temperature because of the electrical heat or electrical power which is directed to the system. So, we can actually equate both of them. So,  $i^2 r$  here is nothing but, the rate at which heat energy is delivered which is power is  $q \dot{}$  which is  $m \dot{ } c_e \Delta \theta$ , as seen before which is also can be represented as  $dx l y c_e \Delta \theta$  times of  $\rho_e$ .

So, therefore, the  $\Delta \theta$  comes out to be equal to square of  $j$  divided by  $k \rho_e c_e$  times of  $v$  where,  $v$  is the velocity of motion of the electrolyte. So, there does exist a relationship between the temperature rise of the electrolyte and its velocity. And it is a function which is proportional to the square of the current density; inversely proportional to the thermal conductivity, electrical conductivity of the electrolyte, and inversely also

proportional to the density of the electrolyte and the specific heat capacity of the electrolyte  $c_e n \rho_e$ .

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**Temperature and pressure during ECM process**

Conductivity as we all know varies with temp.  
 $\alpha = \text{Thermal coefficient of change}$

$$k = \frac{k_0 [1 + \alpha (\theta - \theta_0)]}{\rho_e c_e v}$$

$\int_{\theta_0}^{\theta} d\theta = \int_0^L \frac{j^2 dx}{k_0 [1 + \alpha (\theta - \theta_0)] \rho_e c_e v}$

Therefore, the conductivity again as we all know varies with temperature, just like any other resistivity or conductivity term. And this, let say is varying according to a thermal coefficient of change  $\alpha$  such that,  $k$  is  $k_0$  plus  $\alpha$   $\theta$  minus  $\theta_0$ .  $\theta_0$  is the baseline temperature,  $\theta$  is the increased temperature and  $k_0$  is the conductivity at  $\theta_0$ . So, this is the temperature dependency that the conductivity of the electrolyte would have. If we are able to somehow pluck this into the equation for  $\Delta\theta$  which is equal to square of  $j$  times of  $d$  x divided by  $k_0$  plus  $\alpha$   $\theta$  minus  $\theta_0$   $\rho_e c_e v$ .

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### Temperature and pressure during ECM process


The electrical power due to current density ( $\dot{Q}$ ) =  $I^2 R$   
 where  $I$  is the current,  $R$  = resistance of the medium

$R = \frac{1}{k} \frac{y}{dx}$   
 $= \frac{y}{k(dx)}$

$\Rightarrow \int R = \int \frac{y}{k(dx)} = \frac{1}{k} \int y dx$

$\Rightarrow \int \frac{y^2 dx}{k} = \dot{Q} = \dot{m} c \Delta \theta$   
 $\Rightarrow \Delta \theta = \frac{\int \frac{y^2 dx}{k}}{\dot{m} c}$

$\Rightarrow \Delta \theta = \frac{I^2 \rho_e l}{c \rho_e \rho_e l} \quad \checkmark$



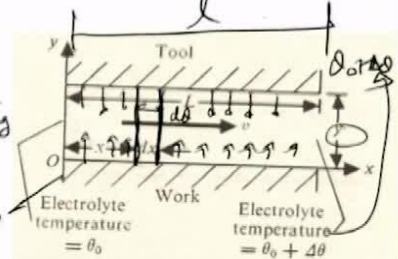
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### Temperature and pressure during ECM process

Assuming all the heat, generated by the flow of electrolyte and also the electric current is confined to the electrolyte itself. Tool heating. Don't assume any heat flow out of the tool.

Temp. that would rise of the flowing electrolyte as it passes through the gap is  $\Delta \theta$  if the electrolyte passes through a length  $l$ .

Amount of heat carried by the electrolyte  $\Delta \theta = \dot{m} c \Delta \theta$   
 $= \rho_e (y l) c \Delta \theta$



We are actually able to get a relationship between  $\theta_0$  on 1 hand and all these other terms  $j^2 \rho_e c \rho_e l$  and  $dx$  on the other hand. Of course, if you assume that the temperature has changed from let say 0 to some value  $\Delta \theta$ . So, we can integrate on the  $d\theta$  term as it moves along on the path 0 to 1. If you may remember this was illustrated here in the figure where the  $\theta_0$  is the temperature at 1 end and  $\theta_0 + \Delta \theta$  here is the temperature at other end; while the electrolyte translated by a distance  $l$ .



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**Temperature and pressure during ECM process**

Conductivity as we all know varies with temp.  
 $\alpha =$  Thermal coefficient of change

$$k = k_0 [1 + \alpha (\theta - \theta_0)]$$

$\theta_0$  = Initial temp.  $\theta$  = Temperature

$$\int_0^{\Delta\theta} \frac{d\theta}{k_0 [1 + \alpha (\theta - \theta_0)]} = \int_0^L \frac{j^2 dx}{\rho_e c v}$$

$$\int_0^{\Delta\theta} \frac{d\theta}{k_0 [1 + \alpha (\theta - \theta_0)]} = \int_0^L \frac{j^2 dx}{\rho_e c v}$$

$V = \frac{j^2 L}{k_0 (\Delta\theta + \frac{\alpha}{2} \Delta\theta^2)}$

So, we can write therefore, that the integration  $d\theta$  from 0 to  $\Delta\theta$  the change of temperature equal 0 to  $\int j^2 dx$  by  $k_0 [1 + \alpha (\theta - \theta_0)] \rho_e c v$ . And we can rearrange the terms in a manner that  $k_0 [1 + \alpha (\theta - \theta_0)] \rho_e c v$   $d\theta$  from 0 to  $\Delta\theta$  equals integral 0 to  $L$   $j^2 dx$  by  $\rho_e c v$ . Thereby, meaning that if you just do this integration here we are left with  $v$ , the velocity of the electrolyte which depends on square of  $j$  times  $L$  divided by  $k_0 \Delta\theta + \frac{\alpha}{2} \Delta\theta^2 \rho_e c v$ . And that is what the final velocity of design of the electrolyte is. So, we will have to just ensure that the  $\theta + \Delta\theta$  is below the boiling point of the electrolyte.

So, in summary what we have really tried see is that there is an electrolyte which is flowing between a tool and a work piece. And there is a heat flow by virtue of the power the electrical power that is added onto the system, starting from 1 end of the equilibrium gap to the other end. And the velocity of flow is really dependent on a lot of parameters because, if you want to keep this constrain that the electrolyte does not boil off before it goes to the other end.

It should be able to transfer the power that is pumped in from the electrical system into the electrolyte, without changing the temperature state of the electrolyte so much that, it goes above the boiling point. Meaning thereby, that the electrolyte if the total amount of heat added to the electrolyte is given in terms of you know a flow, let's the mass flow



rate, the specific heat capacity and the temperature difference across which it is flowing. So, that heat flow rate should be exactly equal to the energy per unit time or power; the electrical power which is pumped in which is  $i$  square.

So, this is very simplistic model we are not assuming any heat conduction across the electrodes which may be a major problem because the conductivity of metals as such as very high. So, the model can be more complex when we try to accommodate for the conduction; the heat conduction across the electrode itself. So, it is no longer a 1 dimensional whatever comes in as electrical power goes out as in the electrolyte that kind of simplistic problem. So, this is just a simplistic model to make you aware that such things do exist in ECM process, which has to be very precisely control. So that, the velocity can come out depending on the you know amount of temperature difference that the system can sustain.

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**Temperature and pressure during ECM process**

If the gap between tool & workpiece is fixed

$$V_{elec} = \frac{j^2 L}{K(\Delta\theta + \frac{\alpha}{2} \Delta\theta^2) \rho_e c_e}$$

If the gap is 'y' and viscosity of the fluid is  $\eta$

$$P = \left[ \frac{0.3164 \eta V^2 L}{y^4 (Re)^{0.25}} + \frac{\rho_e V^2}{2} \right]$$

Pressure required to overcome the viscous friction & the 2nd term is the inertial term

So, let us finally, summarize there if the gap between tool and work pieces fixed the amount of electrolyte velocity can be calculated by square of  $j$ , the current density times of the total length of the electrode divided by conductivity  $k$  delta theta plus alpha by 2 delta theta square rho e c e. So, this is the total velocity of the electrolyte equation also, if the gap let us say is  $y$  and viscosity of the fluid the electrolyte is given by  $\eta$ . We do have a term given to us by fluid mechanics which indicates the amount of pressure that the electrolyte would have on the tool and the electrode.

So, this would definitely the pressure would definitely depend on an inertial component which is proportional to square of the velocity. The velocity is the designed velocity that you have already obtained in the previous step by imposing a condition that, the electrolyte will not boil as it crosses the machining zone. And also the sort of viscosity term, which comes out again proportional to the velocity square; so this is given to us by the fluid mechanics.

So, this pressure if we can somehow incorporate to find out whether this pressure is always lower to the ultimate yield stress of the material that we are machining like for example: iron or copper they have a definite flow stress or ultimate yield stress over which the material would seem to warp or plastically deform.

So, we have to somehow ensure that the velocity of course, is stringently maintained by the temperature guideline. But also, it should be maintained by the fact that it the pressure in that small gap should not be able to deform or warp that the electrodes as such because of plastic deformation. So, it should never touch the ultimate flow stress of the either the work material or the tool material. So, that pressure which is given by fluid mechanism. I am really not going into the details of how this pressure has been obtained. Is actually given by  $0.3164 \rho v^2 l$  divided by  $4 y r e$  to the power 0.25 plus  $\rho v^2$  by 2.

So, as I can realize of the first time, the first term is of the viscous term. So, this is the pressure required to overcome the viscous friction and the second term is the inertial term. So, as the gaps are very small sometimes, the first term becomes prominently important because, it is more a surface driven flow that we are talking about which is more you know which has more pronounced viscosity effects. So, the expression here Reynolds number of course, is containing the viscosity which is  $\rho v d$  by  $\mu$ . And because of this  $\mu$  term or because of the predominance that low Reynolds number scale of the surface  $x$ , this term is sometime is dominant and may be a very critical for investigating the pressure and that small gap region of an electrochemical machining process.

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**Temperature and Pressure rise  
during ECM**

The pressure acting on the tool face however is given by the first term.

**Numerical Problem**

During an ECM operation on an iron workpiece with a square face copper tool (using brine as the electrolyte), both having a flat surface, a feed rate of 2mm/min is used. The DC voltage used is 10 V and the total over voltage is 1.5V. The dimension of the tool face is 25.4mm X 25.4 mm. The boiling temperature of the electrolyte is 95 deg. C. Find out the total force acting on the tool.

Viscosity of the electrolyte =  $0.876 \times 10^{-3}$  kg/m-sec  
Density of the electrolyte =  $1.088$  g/cm<sup>3</sup>  
Specific heat of the electrolyte = 0.997, Conductivity of electrolyte =  $0.2 \Omega^{-1} \text{cm}^{-1}$

Ambient temperature = 35 deg. C

So, let us now try to solve numerical problem that, during an ECM operation on an iron work piece with a square face copper tool using of course, salt water solution or brine as a electrolyte. Both having a flat surface to begin with and a feed rate of about 2 millimeters per minute, the d c voltage that is used is about ten volts and the total over voltage is about 1.5 volts. The dimension of the tool face in this particular case is it is a square tool.

So, the tool face is about 25.4 millimeter times of 25.4 millimeters. And the boiling temperature of the electrolyte is about 95 degrees. So, if you really want to be safe you have to not really hit the boiling point, but stay a little bit lower than the boiling point. We will of course, calculate in this particular numerical problem assuming that we hit only 95 degrees and not beyond and then find out we will have to find out.

So, whether the total force that is acting on the tool is sufficient to cause a warpench, of either the copper tool or the iron or a work piece. Meaning thereby, that the pressure which is generated because of viscous effects as I told you the first term of the expression for pressure should be lower than, the ultimate yield stress or the low stress of either the tool or the work piece surface, in this particular case. Some of the parameters which are given are viscosity of the electrolyte density of the electrolyte, the ambient temperature, specific heat of the electrolyte and the conductivity of the electrolyte.

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**Solution**

The equilibrium gap  $y_e = \frac{\lambda}{f} = \frac{kA(V - \Delta V)}{\rho \sum F f}$

*over-voltage potential*

*2mm/min*

$= \frac{0.2 \times 55.85 \times [10 - 1.5] \times 60}{7.86 \times 2 \times 96500 \times 0.2} \text{ cm}$

$= 0.02 \text{ cm}$

Current density  $i = \frac{k(V - \Delta V)}{y_e} = \frac{0.2 \times 8.5}{0.02}$

$= 85 \text{ amp/cm}^2$

Allowable rate in ramp  $\Delta \theta = 60 = 950 - 350$

So, let us look at how we step by step solve such a design problem. So, the equilibrium gap  $y_e$  is of course, given by  $\lambda$  by  $f$  for the constant feed case as you may remember in the section on kinematics and dynamics of ECM. And this can further be represented as  $k$ , conductivity of the electrolyte times of atomic weight of the species that you are dissolving which in this case is pure iron.

The component machine times of  $v$  minus  $\Delta v$  where this  $v$  is the applied voltage and this is the overvoltage potential; times of or divided by  $\rho$  the density of the work material that you are removing in this case it is a density of iron times of the lowest valence state assuming that the lowest valence is being removed. So, iron can be removed mostly at plus 2. So, it is a Ferris state, that we are removing times of minus 6500 coulomb which is the unit for 1 farad for the farad constant  $f$  and times of feed, feed rate which is given to be 2 millimeters per minute.

So, if I am able to calculate the equilibrium gap this way just plucks the values: 55.85 is the atomic weight for iron and the overall voltage available is 10 1.5 volt is the over voltage which is available. Times of this are 2 millimeter per minute, meaning thereby, that you can convert it into centimeter per second by multiplying with 60 and dividing by 0.2. That is how the feed rate is 0.2 by 60 centimeter per second. Times of the density of iron which is 7.86 grams per centimeter cube; we are assuming the low is valence state and 96500-coulomb which is farad constant.

So, this must centimeter should be what the equilibrium gap is going to be. And this becomes equal to about 0.02 centimeters about 0.2 millimeters is about 200 microns. So, the current density with this gap is can be calculated. So, the current density as we know  $j$  is represented by the conductivity of the electrolyte times of voltage minus over voltage potential which is available, per unit the equilibrium gap. We assume that the  $y_e$  value here remains at equilibrium the  $y_e$  is kind of constant.

So, this is the current density is actually conductivity times of the field the total voltage which is available after taking care of all the different you know an audit over potential, over potential due to migration effect all those things together, as we illustrated before  $\Delta v$ . So, effectively available voltage between the 2 electrodes which can do machining is  $v$  minus  $\Delta v$ . So, the current density which is the ionic transport between the 2 electrodes is actually equal to the conductivity times of this available voltage per unit the equilibrium gap  $y_e$ , which is there between the tool and the electrode.

So, this becomes equal to 0.2 times of 8.5 by the new equilibrium gap which has been calculated from the previous step was 0.02 centimeter. And this you can represent as 85 ampere per centimeter square. So, the allowable rise in temperature  $\Delta \theta$  in this case is about 60 degrees. We assume that we operated 95 degree celsius and already mentioned in the numerical example is that, the room temperature or the temperature at which the baseline temperature for the experiments which all the processes start is about 35 degree celsius.

So, that is a difference above about 60. So, typically if you assume that tool and the work piece from 1 side to other the temperature should actually start from 35 degree celsius ambient and go up to 60 degrees more. This is  $\Delta \theta$ . So, as the electrolyte is flowing it should not go above 95 degree celsius to give the maximum you know minimum velocity advantage to the electrolyte.

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**Solution**

$$V = \frac{j^2 L}{k_0 \Delta \theta \rho_e c_e} \quad \text{with } \frac{dT}{dx} = 0$$

$L = 25.4 \text{ mm}$ ,  $j = 85 \text{ amp/cm}^2$   
 $\Delta \theta = 60^\circ$ ,  $\rho_e = 1.8 \text{ g/cm}^3$ ,  $c_e = 1 \text{ cal/cm}^3 \cdot ^\circ\text{C}$

$V = 1410 \text{ cm/sec}$   
 $Re = \frac{\rho_e V d_{eff}}{\mu} = \frac{1.8 \times 1410 \times 0.001}{0.01} = 253.8$

$d_{eff} = \frac{4A}{P} = \frac{4 \times 1 \times 1}{2(1+1)} = 1 \text{ cm}$

So, therefore, that now we can calculate the design velocity which is given by square of  $j$  times of  $L$  by  $k_0 \Delta \theta \rho_e c_e$ . And with the temperature coefficient of change in conductivity we assume here as 0 just to make things simpler. So, there is no change of  $k$  with temperature and we are actually taking the  $k$  at more or less the same ambient condition of 35 degree celsius here. So, by plugging in all these values the  $j$  square  $L$  by  $k_0 \Delta \theta \rho_e c_e$ , we get the total length to be spanned is 24 25.4 millimeters.

The  $j$  value of course, has been found in the earlier step as 85 amps per centimeter square. Delta theta is 66 degrees and  $\rho_e c_e$  the density of the electrolyte the specific heat capacity of the electrolyte etcetera have their own connotations and values which are given in the question, the velocity of design here can be found out to be 1410 centimeter per second. So, that is what would be the range typically of these velocities of electrolytes.

Let us now, calculate the equivalent diameter we do have a velocity term here. So, the Reynolds number here  $Re$  can be  $\rho_e v d$  times of effective diameter by  $\mu$ . This effective diameter can be calculated by looking at this cross section here or just like to draw your attention in the electrochemical machining process. So, this is  $y_e$  the equilibrium gap between the tool face and the work piece. And as we have already  $c$  sort of try to analyze this was a  $d \times$  length across, which the temperature was rising by  $d \theta$  and this length was assume to be  $L$  into the plane of the paper.

So, if you assume this  $l$  to be insignificant assuming  $l$  to be significantly higher than the equilibrium gap  $y_e$ . We can have 4 times area by perimeter as the effective diameter here. So, it is 4 times of  $y_e$  times  $l$  divided by twice  $y_e$  plus  $l$ , the perimeter of this whole area here right. And this can be effectively treated as twice  $y_e$  because,  $y_e$  plus  $l$  approximates  $l$ .  $l$  is very high in comparison to the equilibrium gap  $y_e$ .

So, here the  $r_e$  can be calculated by  $\rho v$  by  $\mu$  times twice  $y_e$  and gap has already been determined before as 0.02 centimeters. So, you kept the Reynolds number value for this particular problem as about 7000. So, for velocity of 1410 centimeter per second the Reynolds number that comes out in that small gap of 200 microns is about 7000. So, it is a huge Reynolds number.

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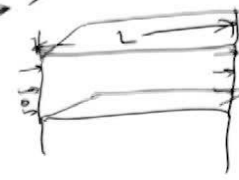
**Solution**

Effect of viscous forces

$$\tau = \frac{0.3164 \rho_e V_e^2 L}{4 y_e (Re)^{0.25}} = \frac{238 \text{ kN/m}^2}{8}$$

Area of the lost face =  $(25.4)^2 \text{ mm}^2$

$$F = \frac{1}{2} \tau A$$

$$F = 78 \text{ N}$$


So, now let us actually calculate the effect of viscous forces or the first term in the pressure equation, if you may remember. And the term that we are concerned with the pressure was 0.3164 times of  $\rho_e$  square of the electrolyte velocity times of length across which the electrolyte moves, divided by 4 equilibrium gap  $y_e$  times of  $r_e$  to the power of 0.25  $r_e$  here is about 7000. And we have different values for the density of the electrolyte the velocity of the electrolyte length across of the electrodes which it moves and of course, the equilibrium gap is 0.02 centimeters.

So, the pressure which comes out in this particular case because of viscous forces it about is about 238 kilo newton per meter square. So, it is a significant value and



therefore, if you look at the area of the face tool face is the area of the tool face is actually equal to 25.4 square millimeters square. And on such a tool face if such a large pressure of the electrolyte is imparted. The amount of force that the tool face would have is basically; at 1 side the when with the electrolyte has just about entered the 1 is 0. So, the pressure is 0 you can think about it as function of 1.

So, 1 is 0 here and the pressure here is 0 and it increases up to the full pressure value  $p$  when 1 is equal to the full length of traverse of the electrolyte. So, we can assume an average pressure value as pressure here plus pressure here by 2. So, the amount of force that is executes is half  $\rho$  tool times of  $a$  or pressure tool times of  $a$ . And the pressure values given to be about 238 kilo newton per meter square, a the value of the interfacial area as of the tool surface or the work piece surface is given by 24 25.4 square millimeter square. So, to force comes out to be about 79 Newton's in this manner.

So, that is about it. So, you will have to investigate what is the total force, sometimes you have to compare the pressure values with respect to the ultimate flow stress of the material. And then, you have to be very careful about 1 aspect that not only the velocity should be designed in a manner, so that the electrolyte does not reach the boiling point. But also the pressures that are thereby imparted because of whatever velocity level the electrolyte is flowing through should not be able to warp or damage the surfaces which are being machined or the tool surface.

So, these 2 are the design constraints for eventually determining, what is the optimal velocity with the temperature condition and the material condition of the tool as well as the work piece material. So, with this we are sort of finished with or done with the electrolyte velocity flow velocity design in a ECM process.

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### Effect of heat and Hydrogen Bubble generation

- In the whole mathematical analysis so far the different parameters and properties were assumed to be uniform throughout the face of the electrodes.
- A variation in these properties affects the machining process.
- Also, the electrolyte conductivity changes as the electrolyte passes along the gap owing to (i) increase in electrolyte temperature (ii) the evolution of hydrogen bubbles, and (iii) the formation of precipitates (this effect is of very small proportions).
- Because of the flow of electricity, the electrolyte temperature gradually increases and the conductivity changes, resulting in a non uniformity in the current density along the direction of electrolyte flow.
- Apart from this, the bubbles are formed as hydrogen is generated during the machining process itself.
- These bubbles are swept by the electrolyte, and the concentration of such bubbles tend to increase along the direction of electrolyte flow.
- As a result, the overall conductivity and the current density vary along the same direction.
- The resultant effect of these causes the equilibrium gap between the electrodes to vary.

Let us look at some of the other important corollaries of an ECM process. There are several problems associated when particularly talk about electrolysis. So, the more important aspects of associated with the electrolysis are this: hydrogen bubble generation thereby changing of local conductivity or thereby registering a change in local conductivity and heating; non uniform heating of the electrolyte while passing through the equilibrium gap.

So; obviously, the electrolyte conductivity changes as a electrolyte passes along the gap. And of some of the reasons why this change would happen is because of course, the temperature  $k = k_0 [1 + \alpha(\theta - \theta_0)]$ . The evolution of bubbles of hydrogen particularly, when we are talking about machining iron and there is a exclusive possibility of generation of hydrogen because of the machining of iron. This hydrogen is not able to go anywhere because the gap is too small and it simply gets dissolved within the electrolyte.

So, this further changes the conductivity, it in fact decreases the conductivity because of dissolution of the hydrogen. And then of course, there is a formation of precipitates, precipitates because the process of the electrochemical machining concerns with the carrying out of the material and generating a compound which is not dissolvable anymore. So, it precipitates into the solution that is the prime of requirement of a ECM process.

So, this in fact, would have its own connotations because, it would impose change in local conductivity, because of circulation of the small debris so called as precipitate which is coming out into the ECM electrolyte. And although that precipitate effect is very small in terms of change of overall electrolyte, but you do have to consider particularly for microsystem design, this may be microsystem fabrication this may be a very important aspect. The changes of conductivity because of precipitate for all sort of materials.

So, also because of the flow of electricity as we have already seen electrolyte temperature gradually increases and because of the change in conductivity there is a non uniformity in the current density, along the direction of the electrolyte flow. So, as the temperature is higher the current density does not really remain same, it keeps on changing as the temperature of the electrolyte changes. High resistance would typically mean lower current.

So, current density would reduce as the conductivity of the electrolyte would reduce. So, with the change in temperature of course, the conductivity as we have seen goes up. So, if the conductivity goes up the resistance goes down and there would be an increase in the current. So, the gradual feeding of the electrolyte from 1 end of the gap to the other would mean, that more iron is transported towards the end you know and less iron is transported towards the beginning. So, that make a situation very non uniform in terms of the material removal across the work piece surface and this has to be accommodated for, when we are talking about ECM electrochemical machining.

So, apart from this the bubbles are formed, thus hydrogen is generated already talked about it during the machining process. And another big problem is that, you know let us say the hydrogen starts generating at the entry of the equilibrium gap. So, more amount of hydrogen would be packed on to the flowing electrolyte as you go towards the end. So, there is a gradient, even hydrogen. Hydrogen is generated to begin with or started to generate at the entry and this ... Where will this bubble go? It will go and flow along with the electrolyte.

So, the next instance when the electrolyte needs another fresh surface where it is doing some machining fresh part of the surface, more hydrogen is packed in and. So, the hydrogen concentration keeps on increasing as the velocity as the electrolyte flows

passed the gap. So, that gradient also is resulting in a differential change in the conductivity and differential change in the machining rate the material removal rate and certainly not good for the uniform nature or behavior of the ECM process.

So, the equilibrium gap really does not remain anymore the same value  $y_e$  as we have predicted before. It changes quite a bit going from entry side to the exit side of the electrolyte and that is a typically a problem in the ECM systems. And of huge consequence particularly for Microsystems fabrication, so these allowances have to be really taken into question when you design the Microsystems by using ECM.

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### Surface Finish

• In general, a very good surface finish is desired in the parts machined by ECM. study of the possibilities that may result in a bad finish is important.

• The surface finish is adversely affected by the

- (i) selective dissolution ✓
- (ii) Sporadic breakdown of the anodic film ✓
- (iii) Flow separation and formulation of eddies ✓
- (iv) Evolution of hydrogen gas ✓

Selective Dissolution:

• In alloys, the different constituents have varying electrode potentials. In pure metals too, the dissolution potential at the grain boundaries are different from those inside the grains. Let us consider the work surfaces (with 2 constituents A and B).

(a) Unevenness due to difference in dissolution potentials of different phases

(b) Reduction in unevenness with increase in anodic potential

The other aspect which is important in a ECM process is the surface finish and in general ECM does produce a good reasonably good surface finish. We have seen that, the process of a ECM really is a sort of self leveling process where, eventually the vias and the hills all leveled to a certain mean roughness or average roughness of the surface. So, if there is a local change of course, in the conductivity it may result sometimes in a different rate of removal of material, on specific areas or specific parts of the surface in question.

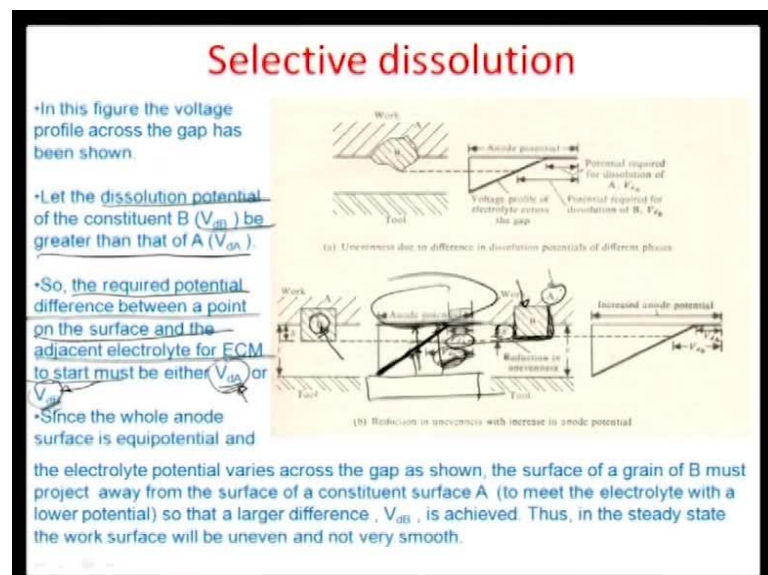
So, the for 2 reasons 1 the surface finish is adversely affected by these 3 or 4 processes associated with an ECM: 1 is a process if selective dissolution and other is the sporadic breakdown of anodic film. Of course, flow separation and formulation of eddies

particularly related to local precipitation of the material coming out at etcetera; an evolution of the hydrogen gas.

So, let us look at these different cases 1 by 1 and is to how the surface finish is changed adversely because of that. So, first the selective dissolution, so let us suppose we are machining an alloy with 2 different faces a and b as you can see here in this particular cartoon or schematic. So, the different constituents that we are using here a and b have also varying electrode potentials. So, a may have slightly higher dissolution potential than b or vice versa

In fact, if you go from alloy systems to pure metals also the dissolution potential at the grain boundary is quite different from those inside the grains. So, there is always a tendency of the boundaries of these different grains to be dissolved at a different potential level than the grains itself. So, these are like the grain boundaries a system. So, when you do ECM of this kind of a surface, these boundaries which generate there in may have a different potential altogether. So, in this particular case let us consider the anodic potential, dissolution potential which is available to a as  $V_d a$  and that which is available to b as  $V_d b$ .

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So, if we assume that the dissolution potential of b  $V_d b$  is greater than that of a  $V_d a$ . So, the required potential difference between a point on the surface and the adjacent electrolyte for ECM to start, for the face a must be  $V_d a$  or must be  $V_d b$  for the face b.

So, if only you know till and until this potential is reached of the surface the dissolution will not occur. Similarly, if for the d face this potential is not reached the dissolution will not occur.

What is interesting here is to see that because  $v_d a$  is lower than  $v_d b$   $v_d b$  is always you know, this is let us say they are not potential and this much amount is corresponding to the potential drop. So,  $v_d b$  the amount of available anode potential would be only at a certain distance away from the anode it cannot be near the anode.

So, this would result in an auto roughening because  $v_d b$  the face b would get dissolved away only when the voltage that it meets with this  $v_d b$ . And the as you have seen from this particular potential trend here, the effective anode potential is a smaller value  $v_d a$  available at the surface and this is a linear drop of course, because this is a ohmic drop.

So, therefore, the available potential nearer to the tool surface is more in comparison to that away from the tool surface right. So,  $v_d b$  will never get dissolved away in the tool in the in the in the anode surface of the work piece surface. So,  $v_d b$  will only get dissolved when the part b is projected outside and it is meeting this potential line or potential plane here, which will give the potential  $v_d b$  right.

So, it is auto roughening process. So, b does not get dissolved beyond this delta dash value and a starts dissolving whenever it reaches even if it reaches the anode it starts dissolving. So, if there is a close grain of b and a kept in unison as almost always happens in alloyed states. A would dissolve more to the surface towards the surface and b will only starts dissolving when it reaches that potential front.

So, there is a selective dissolution of a with respect to b unless and until b ensures that it projects into the solution at the potential front, where available  $v_d b$  would be able to dissolve away the b. So, it is an auto roughening effect which is happening in this process because of the differential or potential between the 2 faces.

So, it is a main reason it is main problem in all the ECM processes particularly with alloy is that, there is a roughening action. If you cannot choose the alloyed states to be having similar dissolution potential and life may not be that simple 2 substances may get alloyed; not depending on their electrochemical dissolution potentials. So, therefore, there is a possibility of a sort of mismatch between the dissolution potentials of 2 faces

which would create a self roughening effect, rather than a self leveling effect. So, ECM process which is known, well known for self leveling may actually be the other way around.

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### Selective dissolution

In this figure the voltage profile across the gap has been shown.

Let the dissolution potential of the constituent B ( $V_{dB}$ ) be greater than that of A ( $V_{dA}$ ).

So, the required potential difference between a point on the surface and the adjacent electrolyte for ECM to start must be either  $V_{dA}$  or  $V_{dB}$ .

Since the whole anode surface is equipotential and the electrolyte potential varies across the gap as shown, the surface of a grain of B must project away from the surface of a constituent surface A (to meet the electrolyte with a lower potential) so that a larger difference,  $V_{dA}$ , is achieved. Thus, in the steady state the work surface will be uneven and not very smooth.

(a) Unevenness due to difference in dissolution potentials of different phases

(b) Reduction in unevenness with increase in anode potential

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Selective Dissolution:

In alloys, the different constituents have varying electrode potentials. In pure metals too, the dissolution potential at the grain boundaries are different from those inside the grains. Let us consider the work surfaces (with 2 constituents A and B).

(a) Unevenness due to difference in dissolution potentials of different phases

(b) Reduction in unevenness with increase in anode potential

So, these are some of the typical problems associated with an ETCM. So, I think today we are at the end of our lecture. But, the other reasons, why surface finish may get adversely affected like: sporadic breakdown of anodic film, a flow separation, revolution of hydrogen gas we will try to finish in the next lecture.



Thank you.