

**Advanced Machining Processes**  
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**Week - 05**  
**Lecture - 11**  
**Electrochemical Machining-IV**

Hello and welcome back to this lecture on Microsystems Fabrication by Advanced Manufacturing Processes. A brief review of what we did last time it is basically we started with looking at the kinematics and dynamics of the ECM process wherein we assumed that there is a workpiece, and this workpiece 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 between the workpiece and the tool would be as a function of time. So, what would this gap be? We investigated the cases of zero feed, constant feed and then automatic surface levelling action that is done by the ECM process. Today we would look into a slightly different aspect of the ECM which is very-very critical for designing particularly electrochemical machining systems for microsystems design and fabrication and 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 hundred of microns and because of this continuous movement and high value of current density there is always a possibility of the electrolyte being liquid to hit the boiling point sometimes and the design guideline 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 electrolyte in an ECM process.


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 workpiece 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 workpiece as 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 workpiece 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 into 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 workpiece that is established and subsequent removal processes that is established at the workpiece can be taken care of you know in terms of the amount of heat stored within the electrolyte material as it flows.

So, it 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 preferred would be to avoid ion concentration, to avoid the deposition of the electrolyte material that is the electrode 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. And the last one is very important an estimate of the required flow rate. So, that the electrolyte can remain without boiling. So, these are principally the reasons why flow of the electrolyte is a preferred solution to address some of these requirements and problems.

And let us look into this a little more in a little more detail and the modelling 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 workpiece side. So, we do not assume any heat flow. In other words, we are neglecting the conduction and the heat conduction of the electrodes.

Temperature and pressure rise during ECM



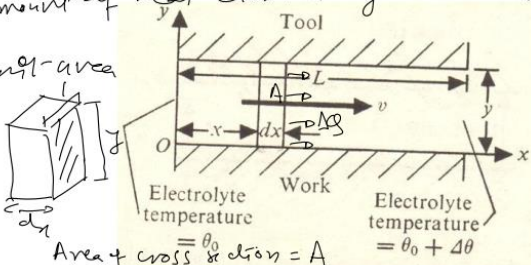
Assuming all the heat, generated by the flow of electric current, to remain in the electrolyte (i.e., neglecting conduction through the electrodes) the rise in temperature ( $d\theta$ ) on passing a length  $dx$  of the jet is given by the following -

$\Delta \dot{Q} = \dot{m} C_e \Delta \theta$  = Amount of heat carried by the electrolyte

heat released per unit area  
 $\Delta \dot{Q} = \dot{m} C_e \Delta \theta$

$= \rho_e v l A C_e \Delta \theta$

Let us assume width along z is unity  
 Area of cross section =  $A$




So, if we 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 instance in this case this is the gap  $dx$  through which the electrolyte is flowing and while passing from this phase right here to this phase there is an increase of  $d\theta$  and the temperature of the electrolyte. So, of course, the amount of heat carried by the electrolyte  $\Delta \dot{Q}$  is also given as the mass flow rate  $\dot{m}$  times of specific heat capacity  $C$  times of  $d\theta$  right  $Q$  equal to  $m C T$ .

$T$  is the temperature difference across which the heat flow is happening. So, just because it is the rate of heat rise it is 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 a total height  $y$  as given here which is also the equilibrium gap and we assume that the heat is flowing perpendicular to this shaded phase. 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 is 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 phase and this phase which would raise the

temperature of the electrolyte in turn by delta theta.

So, now we would somehow like to find out a relationship between the current density which is the main reason for the heat transfer from the tool or the workpiece onto the electrolyte. And if you look at that the electrical power due to the current density  $J$  which is dependent on the flow of the ions is equal to  $I^2 R$  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  $l$  mind you the current is coming perpendicular to this phase.

**Temperature and pressure rise during ECM**


The electrical power due to  $J^2 R$  heat dissipated per unit area

where  $I$  is the current  
 $R$  is the resistance of the medium

$$J^2 R$$

$$= J^2 (dx) \frac{1}{K} \frac{y}{dx} = \frac{J^2 dx y}{K}$$

$$\therefore \frac{J^2 dx y}{K} = \rho V \rho_e C_e \Delta \theta$$

$$\therefore \Delta \theta = \frac{J^2 dx}{K \rho_e C_e}$$

So, the length that it would face is  $y$  and the cross-sectional area that it would face is  $dx$  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 proportion, or which is actually perpendicular to this phase with area  $x dl$ . 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  $dx$  in 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 phase and this phase meaning thereby that there is a rise in the temperature because of the electrical heat or electrical power which is added 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 was also can be represented as  $dx ly C$  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 its function which is proportional to the square of the current density is inversely proportional to the thermal conductivity sorry electrical

conductivity of the electrolyte and inversely also proportional to the density of the electrolyte and the specific heat capacity of the electrolyte  $\rho_e$  and  $C_e$ . Therefore, the conductivity again as we all know varies with temperature just like any other resistivity or conductivity term and this let us say is varying according to a thermal coefficient of change  $\alpha$  such that  $K$  is  $K_0 [1 + \alpha(\theta - \theta_0)]$  this is the baseline temperature this 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 plug this into the equation for  $\Delta\theta$  which is equal to square of  $J$  times of  $dx$  divided by  $K_0 [1 + \alpha(\theta - \theta_0)] \rho_e C_e v$ .

We are actually able to get a relationship between  $\theta$  on one hand and all these other terms  $J^2$  square  $\rho_e C_e v$  and  $dx$  on the other hand. So, of course, if you assume that the temperature has changed from let us say  $\theta_0$  to some value  $\Delta\theta$ . So, we can integrate the  $d\theta$  term as it moves along the path  $0$  to  $l$ . If you may remember this was illustrated here in the figure where the  $\theta_0$  is the temperature at one end and  $\theta_0 + \Delta\theta$  here is the temperature at other end while the electrolyte translated by a distance  $l$ . So, we can write therefore, that the integration  $d\theta$  from  $\theta_0$  to  $\theta_0 + \Delta\theta$  the change of temperature equals  $0$  to  $l$   $J^2 dx$  by  $K_0 [1 + \alpha(\theta - \theta_0)] \rho_e C_e v$ .

And we can rearrange the terms in a manner that  $K_0 [1 + \alpha(\theta - \theta_0)] d\theta$  from  $\theta_0$  to  $\theta_0 + \Delta\theta$  equals integral  $0$  to  $l$   $J^2 dx$  by  $\rho_e C_e v$ . Thereby meaning that if we 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  $K_0 \Delta\theta + \frac{\alpha}{2} \Delta\theta^2$  square  $\rho_e C_e v$  and that is what the final velocity of design of the electrolyte is. So, we will have to just ensure that the  $\theta_0 + \Delta\theta$  is below the boiling point of the electrolyte. So, in summary, what we have really tried to see is that there is an electrolyte which is flowing between a tool and a workpiece and there is a heat flow by virtue of the power the electrical power that is added onto the system starting from one end of the equilibrium gap to the other end. And the velocity of flow is really dependent on a lot of parameters because if we want to keep this constraint that the electrolyte does not boil off before it goes to the other end.

### Temperature and pressure rise during ECM



Conductivity  $K$  of the electrolyte depends on the temperature as

$$K = K_0 [1 + \alpha(\theta - \theta_0)]$$

$$\int_{\theta_0}^{\theta_0 + \Delta\theta} d\theta = \int_0^l \frac{J^2 dx}{K_0 [1 + \alpha(\theta - \theta_0)] \rho_e C_e v}$$


integrating on both sides

$$v = \frac{J^2 L}{K_0 (\Delta\theta + \frac{\alpha}{2} \Delta\theta^2) \rho_e C_e}$$

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 us say 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 electrical power which is pumped in which is  $I^2 R$ . 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 is very high. And so, the model can be more complex when we try to accommodate for the conduction the heat conduction across the electrodes itself.

So, it is no longer a 1 dimensional whatever comes in as electrical power goes out as in the electrolyte that kind of a 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 controlled. So, that the velocity can come out depending on the you know amount of temperature difference that the system can sustain. So, let us finally summarize that if the gap between tool and workpiece is fixed the amount of electrolyte velocity can be calculated by square of  $J$  the current density times of  $l$  the total length of the electrode divided by conductivity  $K$  delta theta plus alpha by 2 delta theta square rho e Ce. So, this is the total velocity of the electrolyte in question.

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 and the velocity is the design 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.

**Temperature and pressure rise during ECM**


If the gap is ' $y$ ' and the viscosity of the fluid is  $\eta$ , the total pressure required (assuming a turbulent flow) to maintain a flow velocity  $v$  is given by

$$P = \left[ \frac{0.3164 Re v^2 l}{4y(Re)^{0.25}} + \frac{Re v l}{2} \right]$$

$Re$  being the characteristic flow Reynolds No. The first term is the pressure required to overcome the viscous friction & the 2nd term

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 as stringently maintained by the temperature guideline, but also it should be maintained by the fact that in the pressure in that small gap should not be able to deform or warp the electrodes as such because of plastic deformation. So, it should never touch the ultimate flow stress of either the work material or the tool material. So, that pressure which is given by fluid mechanics, and I am not really going into the details of how this pressure has been obtained is actually given by  $0.3164 \rho v^2 \left( \frac{l}{4 y Re} \right)^{0.25} + \rho v^2$ . So, as one can realize the first term is 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 at low Reynolds number scales of the surface effects this term is sometimes dominant and may be very critical for investigating the pressure in that small gap region of an electrochemical machining process. So, let us now try to solve a numerical problem that during an ECM operation on an iron workpiece with a square-face copper tool, you are using of course, saltwater solution or brine as electrolyte both having a flat surface to begin with and a feed rate of about 2 millimetres per minute.

The DC voltage that is used is about 10 volts and the total over voltage is about 1.5 volts and the dimension of the tool face in this particular case it is a square tool. So, the tool face is about 25.4 millimetre times of 25.4 millimetres 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 warpage of either the copper tool or the iron workpiece 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 flow stress of either the tool or the workpiece surface in this particular case. Some of the parameters which are given are viscosity of the electrolyte, density of the electrolyte, ambient temperature, specific heat of the electrolyte and the conductivity of the electrolyte. 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 to be machined times of  $V - \Delta V$  where this  $V$  is the applied voltage and this is the over-voltage potential times of or divided by  $\rho$  the density of the work material that you are removing in this case it is the density of iron times of the lowest valency state assuming that the lowest valency is being removed. So, iron can be removed mostly at plus 2. So, it is the ferrous state that we are removing times of 96500 coulomb which is the unit for the Faraday constant  $F$  and times of feed rate which is given to be 2 millimetres per minute.

So, if I am able to calculate the equilibrium gap this way just plug the values 55.85 is the atomic weight for iron and the overall voltage available is 101.5 volts is the over voltage which is available times of this is 2 millimetre per minute meaning thereby that you can convert it into centimetre per second by multiplying with 60 and dividing by 0.2 that is how the feed rate is 0.2 by 60 centimetre per second times of the density of iron which is 7.86 grams per centimetre cube we are assuming the lowest valency state and 96500 coulomb which is the Faraday constant. So, this much centimetre should be what the equilibrium gap is going to be and this becomes equal to about 0.02 centimetres about 0.2 millimetres 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  $y$  value here remains at equilibrium the  $y$  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 anodic over potential over potential due to migration effect all those things together as we illustrated before is  $\Delta V$ .

So, effectively available voltage between the 2 electrodes which can do machining is  $V$  minus  $\Delta V$  and 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  $y$  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 as 0.02 centimetre and this you can represent as 85 centimetre per centimetre square.

So, the allowable rise in temperature  $\Delta \theta$  in this case is about 60 degrees we assume that we operate at 95 degrees Celsius and already mentioned in the numerical example is that the room temperature or the temperature at which the baseline the temperature for the experiments at which all the processes are started is about 35 degrees Celsius. So, that is a difference of about 60. So, typically if you assume the tool and the workpiece from one 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 degrees Celsius to give the maximum velocity, I mean you know minimum velocity advantage to the electrolyte. 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  $J^2 L$  by  $K_0 \Delta \theta \rho_e C_e$  we get the total length to be spanned is 25.4 millimetres the  $J$  value of course, has been found in the earlier step as 85 amps per centimetre square  $\Delta \theta$  is 60 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 centimetre 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  $\rho v d$  times of the effective diameter by  $\mu$ . This effective diameter can be calculated by looking at this cross-section here I would just like to draw

your attention in the electrochemical machining process. So, this is the equilibrium gap between the tool face and the workpiece and as we already sort of tried to analyse this was a  $dx$  length across which the temperature was rising by  $d\theta$  and this length was assumed to be  $l$  into the plane of the paper. So, if we 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 the zone area here. 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  $Re$  can be calculated by  $\rho v$  by  $\mu$  times twice  $y_e$  and gap has already been determined before as 0.02 centimetres. So, you get the Reynolds number value for this particular problem as about 7000.

So, for a velocity of 1410 centimetre 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. 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  $Re$  to the power of 0.25.  $Re$  here is about 7000 and we have different values for the density of the electrolyte, the velocity of the electrolyte, the length across of the electrodes which it moves and of course, the equilibrium gap is 0.02 centimetres. So, the pressure which comes out in this particular case because of viscous forces about is about 238 kilo Newton per metre square. So, it is a significant value and therefore, if you look at the area of the face tool face this area of the tool face is actually equal to 25.4 square millimetre 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 one side the when the with the electrolyte has just about entered the  $l$  is 0. So, the pressure is 0 you can think about it as function of  $l$ . So,  $l$  is 0 here and the pressure here is 0 and it increases up to the full pressure value  $P$  when  $l$  is equal to the full length of traverse of the electrolyte. So, you can assume an average pressure value as pressure here plus pressure here by 2. So, the amount of force that is executed is half  $\rho$  tool times of  $A$  or pressure tool times of  $A$  and the pressure value is given to be about 238 kilo Newton per metre square  $A$  the value of the interfacial area is of the tool surface, or the workpiece surface is given by 25.4 square millimetre square. So, total 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 one aspect that not only the velocity should be designed in a manner. So, that if 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 workpiece material.

So, with this, we are sort of finished with or done with the electrolyte velocity, flow velocity design in an ECM process. Let us look at some of the other important corollaries of an ECM process. There are several problems associated when particularly you talk about electrolysis and . 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 the electrolyte passes along the gap and some of the reasons why this change would happen is because of course, of the temperature  $K$  equal to  $K_0 (1 + \alpha (\theta - \theta_0))$ .

And the evolution of bubbles of hydrogen particularly when we are talking about machining iron and there is an 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 and 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 prima facie 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 or microsystem fabrication this may be a very important aspect the changes of conductivity because of precipitates of 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 one end of the gap to the other would mean that more ion is transported towards the end and less ion is transported towards the beginning. So, that makes a situation very-very non-uniform in terms of the material removal across the workpiece surface, and this has to be accommodated for when we are talking about ECM or electrochemical machining.

So, apart from this, the bubbles are formed as 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 onto 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, at the next instance when the electrolyte meets 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 past 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 is certainly not good for

the uniform nature or behaviour of the ECM process. So, the equilibrium gap really does not remain any more the same value ye as we have predicted before. It changes quite a bit going from the entry side to the exit side of the electrolyte and that is 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 a microsystems by using ECM.

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-levelling process where eventually the vias and the hills are all levelled 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 one the surface finish is adversely affected by these 3 or 4 processes associated with an ECM one is the process of selective dissolution, another is the sporadic breakdown of anodic film.

Of course, floor separation and formulation of eddies particularly related to local precipitation of the material coming out etc. and evolution of the hydrogen gas. So, let us look at these different cases one by one as 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 phases 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 boundaries are 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 in a system and so, when you do ECM of this kind of a surface.

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- 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

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

(b) Reduction in unevenness with increase in anode potential

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,  $V_{dB}$ , is achieved. Thus, in the steady state the work surface will be uneven and not very smooth.

So, 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  $V_{dA}$  and that which is available to B as  $V_{dB}$ , So, if we assume that the dissolution potential of B,  $V_{dB}$  is 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 for the phase A must be  $V_{dA}$  or must be  $V_{dB}$  for the phase 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 B phase, this potential is not reached the dissolution will not occur. Now, what is interesting here is to see that because  $V_{dA}$  is lower than  $V_{dB}$ ,  $V_{dB}$  is always you know this is let us say the anode potential and this much amount is corresponding to the potential drop. So,  $V_{dB}$  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  $V_{dB}$  the phase B would get dissolved away only when the voltage that it meets with is  $V_{dB}$ .

And the as you see from this particular potential trend here the effective anode potential is a smaller value  $V_{dA}$  available at the surface and this is linear drop of course because this is a ohmic drop. And so, therefore, the available potential nearer to the tool surface is more in comparison to that away from the tool surface right. And so,  $V_{dB}$  will never get dissolved away in the anode surface or the work surface. So,  $V_{dB}$  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  $V_{dB}$  right.

So, it is a 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 start 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  $V_{dB}$  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 of potential between the 2 phases. So, it is a main reason, it is a 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 potentials 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 phases which would create a self-roughening effect rather than a self-levelling effect. So, ECM process which is known well-known for self-levelling may actually be the other way round. So, these are some of the typical problems associated with an ECM. 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.