Advanced Machining Processes
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Week - 05
Lecture - 10
Electrochemical Machining-III

Hello, and welcome back to this lecture on Microsystems Fabrication by Advanced Manufacturing Processes. A quick recap of what we had done in the last lecture. So, basically, we were trying to study the various effects of ECM processes by looking at the kinematics and the dynamics of the process. So, what we really modelled or did is that we assumed that there is a workpiece as indicated here and then there is a tool surface indicated below and this workpiece is moved slowly towards the tool in minus y direction. This being the y-axis is a minus y direction. So, the workpiece is moved like this and then we assumed that there is a movement rate or feed of this particular workpiece towards the tool assumed to be f.

What we also tried to investigate is that while the ECM process would continue from this surface, there would be a slow dissolution of the surface indicated and this would result in a change in the total thickness of the workpiece. So, that would result or amount to the fact that there is a feed which is happening in the negative y direction as is indicated by this arrow here and then there is an upward movement of the surface because of the dissolution or a change in thickness of the workpiece which is happening in the exactly opposite direction. And so, we found out that we can actually represent this whole kinematics by looking at the rate of change of y, y is the distance between the workpiece and the tool surface and also y is a function of t as you know because there is a continuous dissolution and feed of the workpiece towards the tool. So, the dy by dt or the rate of change of this gap y between the workpiece and the tool was estimated as A times of J by rho Z F minus feed f here, where Z is the valency of the metal which you are dissolving, A is the atomic weight, J is the current density vector which is nothing but the current parent area, rho is the density and F of course, is 96500 coulomb.

So, therefore, that is what the dy by dt would amount to or look like, and then you know if you just substitute the formulation for the current density which is also represented as the conductivity of the solution minus the available voltage which is V minus delta V, delta V is the over-voltage potential which is has to be given in the design voltage. So, that the amount of machining that you are intending should take place divided by yt where y is the gap. So, this expression really amounts to dy by dt equals A times of the value for J divided by rho Z F y minus f, and then we assumed this whole term here to be some constant lambda which is dependent on the setups and the processes, and we can write this whole expression as lambda by y minus f. So, eventually that is what dy by dt or the rate of change of the gap between workpiece and tool would amount to. So, this is the component coming from the dissolution of the surface, this is the component coming from the feed of the tool or workpiece towards the tool.

So, now let us consider different cases in which various values of feed can be assumed and we try to eventually discuss or find out what is the net equation between y and these different parameters lambda f so on so forth for doing the surface analysis. So, the case 1 is a case where we assume the feed to be 0. So, therefore, the workpiece is a static with respect to the tool at time t equal to 0 and of course, as time progresses. So, at higher values of time t, the dissolution would lead to the movement of the front of the workpiece away from the tool. So, if you substitute this intended value in the equation dy by dt equals lambda minus f.

So, f is 0 here or y becomes equal to y dy times of lambda dt. Assuming that the gap was y0 to begin with and it goes to some value y and corresponding to time instances 0 to some value t. So, the y square becomes equal to y0 square plus twice lambda t. So, that is how this particular equation would be and if you plot the value of y with respect to t it would typically look like something like this here. This value is y0 and corresponds to the value of the gap between the tool and the workpiece at time t equal to 0.

And this is the extrapolated front which assumes that what would happen when y actually becomes negative at the y becomes 0 at negative point of time. So, typically this is like a parabolic equation, equation for a parabola as indicated by this y square equal to y0 square plus 2 lambda t here. And that is how the distance would behave with respect to time when the feed f is considered to be 0. Let us analyze another particular case in this particular you know process of constant feed. So, in this case, an ever-increasing gap being not desirable as was seen in the case 1.

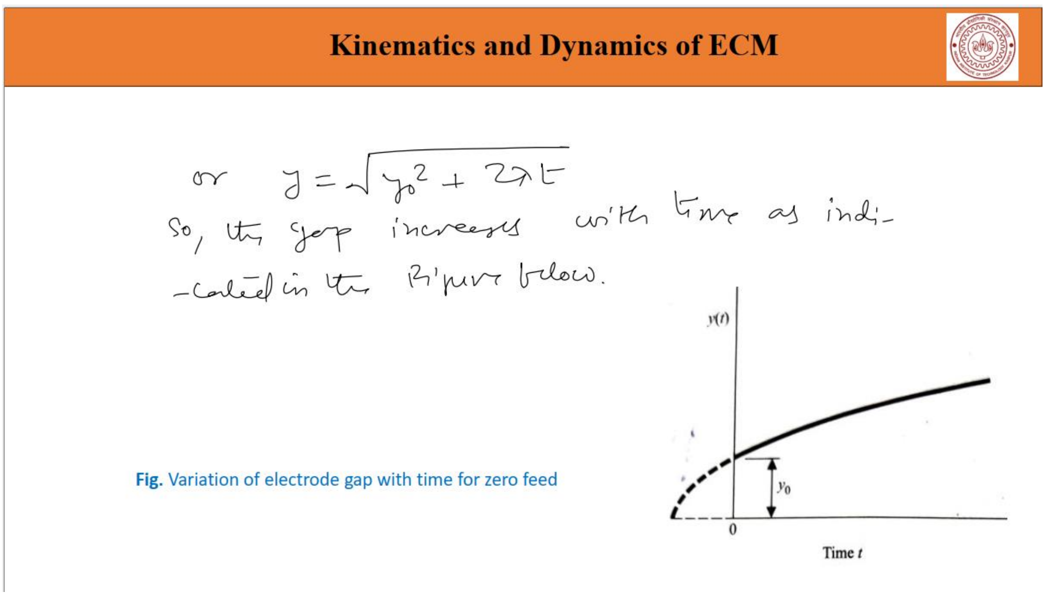
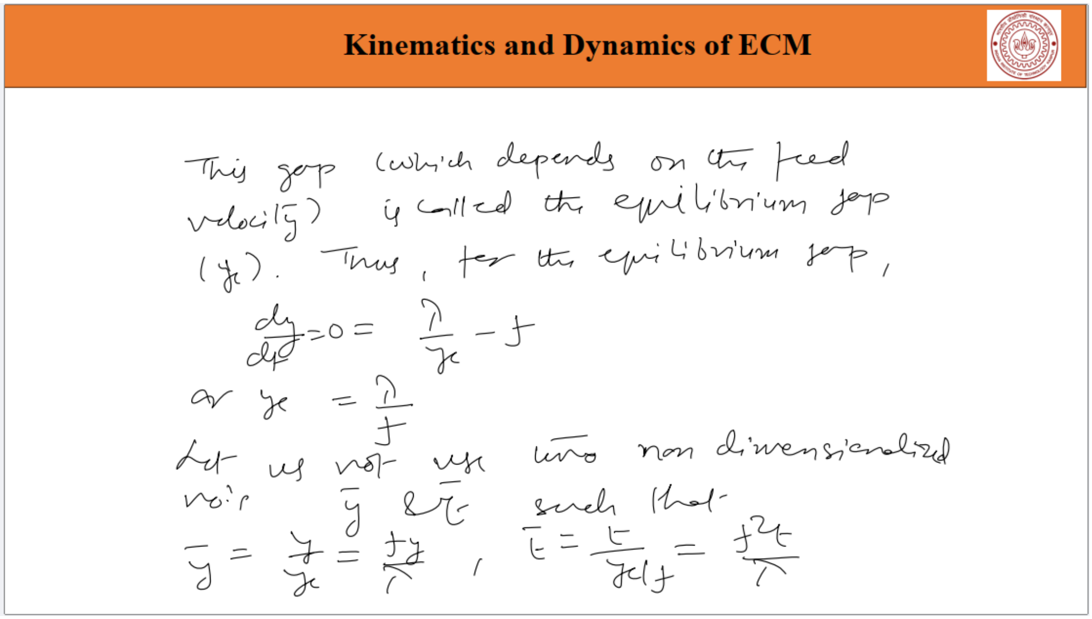


Fig. Variation of electrode gap with time for zero feed

In an ECM process, so the electrode is provided with the constant feed velocity of suitable So, obviously f equal to a constant. So, what eventually would happen is that there would be an illustration or there would be a case where the feed actually becomes equal to the rate of dissolution of the workpiece front. In other words, there is an equilibrating condition which would arise. So, this is the workpiece, and this is the tool surface, and this is the y value with respect to let us say the x y z coordinate system. And the illustration is that this workpiece starts moving towards the tool at a constant feed.

So, in the equilibrating condition, the amount of dissolution leading the surface workpiece surface away from this tool surface is exactly equal to the amount of feed of the workpiece surface. In other words, in that case the gap y is maintained as a constant equilibrium gap y eq. Why equilibrium? Because it is essentially the 2 processes of the surface moving away from the tool because of dissolution and the speed at which the whole workpiece is propagating towards the tool they are kind of an equilibrium with each other they are constant. So, dy by dt becomes equal to 0 in that particular illustration and that can be represented as lambda by ye where this ye or yeq is the equilibrium gap as already proposed before minus f. In other words, the equilibrium gap in such instance can be calculated by using lambda by f which again means because you know that there is a certain specific value of lambda that we are talking about.



So, it basically can be represented as K times A times v minus delta v the total amount of potential minus over potential times rho z coulombic the faraday constant times of f. So, that is how the equilibrium gap would look like between the tool and the workpiece surface and because of that reason, the condition of equilibrium would really come into picture. So, now let us just slightly change the paradigm, and because you know ECM itself as a process is to be applied to microsystems eventually. The whole kinematics or dynamics of the process should be scale-independent or should be made at least scale-independent. And for doing that we need to somehow non-dimensionalize the equation in a manner.

So, that irrespective of whatever be the scale, the scale is known by its length scale or time scale, or velocity scale. And then everything is a ratio metric in comparison to these scales established at any particular level of operation. So, if it is a meso scale or if it is a micro scale if it is a macro scale accordingly what is varying is the scaled quantities like the velocity scale may vary, the length scale may vary, the time scale may vary so on so forth. And then the equation can rhyme at every scale. So, it becomes completely independent of the scale.

So, let us prepare a way or a method where we can non-dimensionalize this equation. And then we will see later on that how important this is in terms of things like roughnesses etcetera which can be predicted experimentally and otherwise using this non-dimensionalization approach. So, let us now introduce 2 non-dimensional numbers y dash and t dash such that the value of y dash is represented as the actual y divided by the equilibrium gap. In other words, this estimates or this gives an idea of how many times the equilibrium gap is actually the gap between the tool and the workpiece at a certain point of time at a certain instance of time. And also let us assume so, because y is already defined earlier in this particular case as lambda by f we can just substitute the value of y into this equation and write this down as f y by lambda.

So, let us call it 1. And for the time scale so, this is actually the we can say that y is the gap scale or equilibrium gap scale, or the length scale at any particular range of operation it is the scale which varies and the ratios kind of remain same and the final equation which will result will be in terms of ratios of to that to those scales. So, the other thing is the time ratio t dash which is represented by the actual time by the time that is needed to cover up this equilibrium gap assuming that the tool is moving at a feed rate of f with respect to the workpiece. So, the amount of time that the equilibrium gap would need to be covered up if f is the feed with which the workpiece is moving towards the tool the amount of time is ye by f. So, you basically ratio metrically comparing the time which is available to this parameter ye by f in a manner that again this can be substituted for the value of ye and made lambda by f square.

So, this comes out to be f square t by lambda. So, let us call it equation 2. So, you have now a time ratio and you have now a length ratio as y dash or t dash and y dash respectively and they have been somehow expressed as the scaled quantities by f y by lambda and f square t by lambda in both the cases. So, let us now see what dy dash by dt dash would really look like. So, dy dash by dt dash where these are all the ratios and we are trying to now build up an equation only based on the ratios would actually be equal to dy dash by dt times of dt by dt dash.

In other words, you can write this down as dy dash by dt divided by dt dash dt. So, just using the chain rule. So, here the dy dash by dt comes out to be equal to f by lambda dy by dt from 1 from this particular equation and the other dt dash by dt comes out to be equal to f square by lambda times of 1 dt by dt from 2. So, therefore, we can represent this in fact, as f 1 by f dy by dt and dy by dt as you all know is basically represented by lambda by y minus f from the previous equation where we talk about the how the equilibrium gap changes with respect to time assuming a certain lambda by lambda by y sorry not f this is y lambda by y minus f and so that is what the dy dash by dt dash would be in this particular case. And we can further modify it by taking this f inside the bracket and making it lambda by f divided by y minus 1 and as you know that lambda by f is actually 1 by y dash or y by y dash from this equation here and from equation 1 and so therefore, this becomes 1 by y dash minus 1.

In other words, dy dash by dt dash is equal to 1 by y dash minus 1 and this is the scaled version of the equation mind you these are all ratio metric quantities with respect to the length scale or the time scale dy dash is that with respect to the length scale dt dash with respect to the time scale so on so forth. And now what you very easily can observe is that this equation has gone independent of the feed because the feed is somehow buried inside the information for the time ratio t dash which is equal to equilibrium gap per unit feed ye by f. So, that is how you kind of have relationship between all ratios a non-dimensional relationship, and what I would be now interested to do is to somehow manipulate this in a manner by integrating with respect to time to see how y dash and t dash would vary as an equation. So, let us look at that part. So, you have dy dash by dt dash becomes equal to 1 by y dash minus 1 meaning thereby that y dash by 1 minus y dash dy dash becomes equal to dt dash and this can further be integrated with respect or between some quantities or limits and we can just simply look at both sides and try to solve what these values would be like.

In fact, the left side could be solved by considering a little bit you know partial fractions. So, this whole thing can be represented as 1 plus y dash minus 1 divided by 1 minus y dash times of dy dash and that is equal to integral of dt dash and further you can just split this up into 2 integrals. So, you have 1 integral 1 by 1 minus y dash dy dash plus or maybe it is a minus because the signs are different in both minus integral of just simply dy dash on 1 side and integral of dt dash on the other side. And in fact, if we solve this little further, we get that t dash as an indefinite integral t dash is actually equal to minus of y dash minus ln 1 minus y dash plus some value K. So, let us look at the boundaries and the limits to obtain this value of K.

So, we know that with initial conditions that we started with over that this y dash would be some y dash 0 at time t equal to 0. Meaning thereby as you already know y dash is nothing, but from the previous formulation it is basically y upon ye or f by lambda upon y and you can assume that at time t equal to 0 this y was actually equal to some value y0. So, y dash 0 can then be defined as just y0 by ye and that is what y0 is y dash 0 is at time instance t equal to 0. So, if you put this value here, and of course, as you know the other formulation t dash was calculated by looking at the actual time with respect to ye by f, or in other words it was calculated as f square t by some value lambda. So, we can assume that at time t equal to 0 when y was y0 and y dash 0 becomes equal to y dash the time t equal to 0 would also correspond to t dash equal to 0.

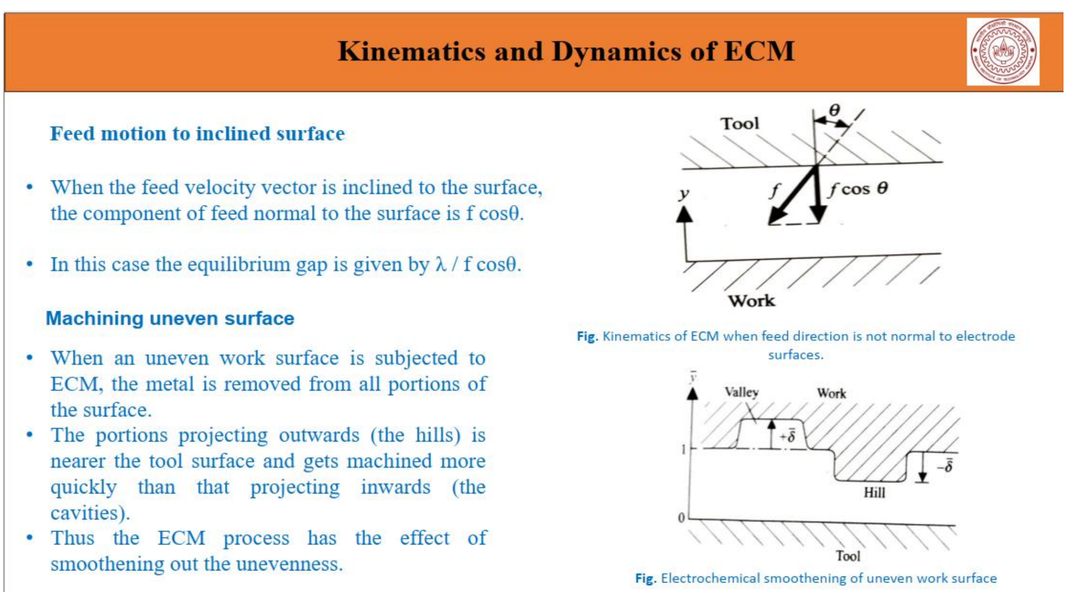
So, typically when we are saying at time instance 0 t dash is 0 and y dash is y0 dash this is y0 by ye at some particular beginning time of the process this becomes just a ratio of y0 with respect to the equilibrium gap. So, we put these values here. So, t dash 0 is 0 here and we get 0 equals minus y dash 0 minus ln 1 minus y dash 0 plus K, and K becomes equal to y dash 0 plus ln 1 minus y dash 0. So, that is what the value of k is and if we substitute this value of K back into the equation in question then the formulation that would finally, have would be of the type t dash equal to minus y dash minus ln 1 minus y dash plus K value which is y0 dash plus ln 1 minus y0 dash. In other words, t dash can be expressed as y0 dash minus y dash plus ln 1 minus y0 dash by 1 minus y dash.

So, that is how the time ratio can be expressed in terms of the length ratio where this ratio is with respect to either the equilibrium gap ye and the time ratio is with respect to the amount of time which is needed by a tool going through a feed f with respect to the workpiece to cover that equilibrium gap ye. So, that is how you basically try to the plot the various relationships together and obtain a relationship on a ratio scale and this ratio is valid over all the different scales be it meso, be it micro, be it nano, be it macro any scale this ratio would be valid because it depends really on that length scale or the time scale for that range of dimensions that are in question. So, now let us try to make something useful out of this plot and try to plot the parameters t dash and y dash and see the various interpretations of what is important out of this equation. So, if we really plot the t dash and the y dash together in a sort of x y plot like this you can find out that for various values of initial gap time t equal to 0 you know there is a plot which is for time t equal to 0 y 0 is 4 there is a plot at time t equal to 0 y 0 is 3 or 2 or 1.5. So, these are different initial gaps for the process.

So, you are plotting y dash on the y-axis here and t dash time scale on the x-axis here and you see eventually that after a certain t dash is achieved after a certain t dash value is achieved all these y dashes come very close to 1 which means that as you know by definition y dash is nothing, but y by ye. So, this coming close to 1 means that all gaps whether it is higher gap 4, 3, 2, 1.5 so on so forth is basically tending to the equilibrium gap corresponding to y dash equal to 1 with time. So, if you look at this paradigm you can always see clearly that ECM or electrochemical machining is a sort of equilibrating process and the perturbations on a surface or the roughness of the surface really are levelled to a point when the value of y becomes equal to be whatever gap to start with it becomes equal to at a certain time scale or time ratio it becomes equal to the equilibrium gap.

So, it is a case where the feed and the dissolution rates are same to each other. So, whatever be the condition in terms of gaps starting gaps between the electrode and the tool eventually at a certain constant feed rate it would arrive on to the equilibrium gap. This is a very important conclusion out of all this dynamics and kinematics of the whole ECM process that we have done so far. So, basically, the as we have seen that it is a self leveling process the ECM is a self-leveling process and let us look at all these from a perspective of defects in terms of valleys and hills on a surface of a certain roughness and then let us see if we can do something in terms of plotting that roughness function with respect to all these different y dash t dash so on so forth. So, that is should be typically our endeavour at this time.

Let us assume that the deviations from a desired surface as written here are the defects characterized by non-dimensional depth or height delta dash. Now, let us look at it in a little more details as illustrated in this previous slide here that we are working with the uneven work surface subjecting it to ECM. The work surface is shown here. So, there are certain valleys in the work surface there are certain hills, and these hills and valleys are all separated by delta dash whether in the positive or the negative direction. So, these are the sort of defects average defects which are there on the surface which eventually the ECM process should level to a certain mean value.



So, the portions are projecting outwards the hills is nearer to the tool surface this being the tool. So, these hills are nearer, and simultaneously the amount of electric field which would happen between the hills and the tool would be more the lines of forces would be more because electric field is potential difference divided by d, d is lesser here. And the valleys are at some distance from the tool which are higher diameter and therefore, if you assume the same potential difference V over another distance d1 where d1 is much greater than d2. So, the amount of electric field available here is much more sparse and as you know that electric field and current density are sort of directly proportional to each other, and current density is the cause of movement of ions or machining therefore, current density is very high where the field is higher and very low where the field is lower. So, this guy gets dissolved away at a faster pace and this at a slower pace eventually equilibrating on the same surface.

This is same as saying that ECM is a die-sinking process as we have mentioned before many times while introducing this topic of ECM. So, therefore, if you look at the portions projecting outwards, they get machined more quickly on the projecting inward portions like cavities they would not get machined that quickly and therefore, there is a smoothening out of the unevenness. So, if delta dash be considered as the desired deviation in terms of defect from a mean value of the surface. We can have an equation of delta dash in terms of t dash, t dash as you know earlier is the ratio parameter between the gap at a certain point y per unit the way that equilibrium gap or the time taken by the equilibrium gap to be moved. So, t divided by ye by f is what the t dash was before.

So, depending on whether the defect is a valley or a hill. Since, delta dash equals y minus the equilibrium gap let us say eventually the gap which would come is ye and delta dash is really how much above the equilibrium gap this ye is. If you assume that the surface has become even at equilibrium from this position it goes to this position at equilibrium. So, y minus ye is delta and so, this is delta, not delta dash I am sorry and delta dash is the comparison of this delta per unit the scale which is available, or the length scale which is available which is really the equilibrium gap.

So, delta by ye. So, this becomes equal to y by ye minus 1 and y by ye as you already know is y dash. So, it is y dash minus 1. So, delta dash emanating from this delta the difference between the equilibrium gap eventually ye of a hill or a valley. Let us say this is the smoothening line which corresponds to this line here. So, this is ye. So, if it is above ye or below a ye it could be a plus delta dash or minus delta dash as we have seen before as has been illustrated before. So, therefore, you know in the same manner as you have illustrated this particular gap for a certain delta, delta is essentially a case where y equal to delta. So, the same equation should hold valid. So, therefore, t dash can be written down as some delta 0 dash at time t equal to 0 assuming delta being equal to delta 0. So, delta 0 dash minus delta dash plus natural logarithm of delta 0 dash divided by delta dash.

And therefore, the whole idea is that the t dash that we are looking into is actually equal to this delta 0 dash minus delta dash plus ln delta 0 dash by delta dash. Theoretically, if we look at when this delta would go to 0. So, it would take an infinite time to remove the defect completely, because delta going to 0 means delta dash going to 0, and delta dash going to 0 means that this t dash which is exactly equal to t divided by ye by f, if you may have recalled the way that time scale was defined would also depend on this ln of 1 something by 0 ln of infinity. So, it is undefined. So, theoretically, it should take almost an infinite time for the delta dash to completely go to 0 which may not be possible.

But practically you have to just wait for and sort of value where this delta dash is so small that it is insignificant in comparison to maybe the equilibrium gap ye. So, you really need to wait for just a sort of time instance t up to which this delta dash may not be equal to 0, but very close or negligibly small and can be considered for all practical purposes to be 0. So, that is how you can get an idea of when a surface of a certain average roughness again given by delta smoothens out due to the smoothening effect of an ECM process. So, if you start with a certain roughness, start with certain surface roughness and your design specification says that you have to have a roughness which is within a tolerable limit which has been given let us say, or proposed by the design. You now have a basis of how much time you need to wait for an ECM process.

So, that a certain roughness to start with on the workpiece surface has been eventually smoothened to a desirable or a desirable tolerance or desirable roughness or a desirable tolerance value which has been specified by the engineering department of a certain component. So, this is an advantage of doing this scaling theory or scaling equation that you get time estimate of what would be the product surface roughness if you start with a certain. In this case, for example, delta is the roughness which you are starting with, and you are aiming for a delta to be so negligibly small where you can consider it to be insignificant. And therefore, t dash the time that is needed really time ratio that is needed for going from delta to that small value of delta which is negligible that is easily estimated by an equation like this. So, we can plot the various things together in 1 dimensional plot as has been illustrated here.

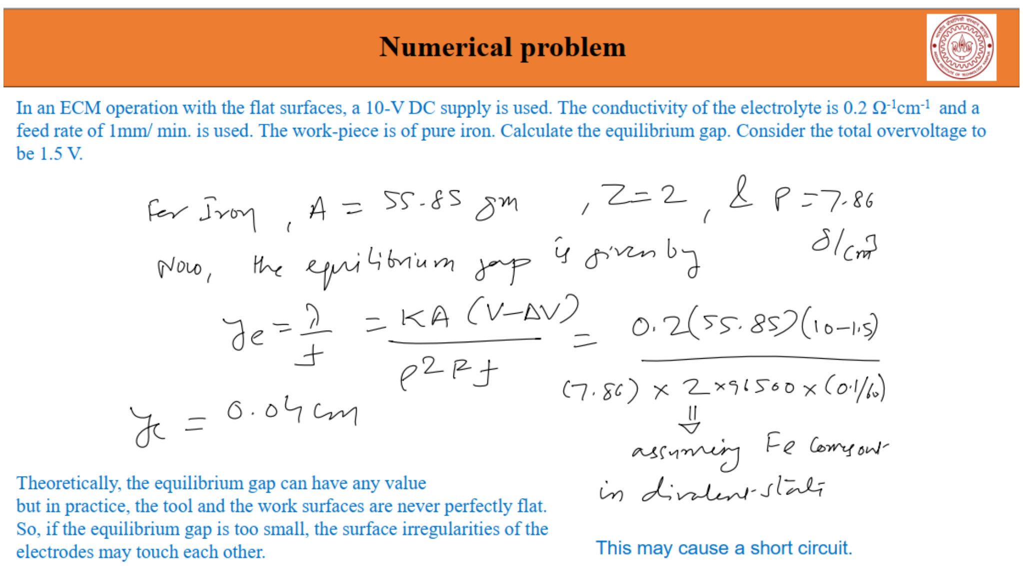
And as 1 can very clearly see there are let us say the hillsides and valley sides of the process where delta and the valleys can be minus delta sorry plus delta and delta and the hill side can be minus delta. And you can see that if the initial defect size is given on the x scale here meaning thereby that this corresponds to some delta 0. And delta 0 dash, of course, is what it is delta 0 per unit equilibrium gap is that is this time the roughness ratio. So, you are starting with this particular delta 0 value as you can see here and the delta 0 can be either a minus delta 0 if it is a hill or if it can be a plus delta 0 if it is a valley. And then on the y scale we are plotting here the depth of ECM in equilibrium gap units required to achieve the certain tolerance which is indicated.

So, these are really so, these really are the so-called depth of ECM in equilibrium gap units terms. So, the ratio of the depth that is needed in let us say the so, the y by ye value which is needed in terms of equilibrium gap units. And the tolerances that eventually come up or eventually are needed are indicated on these curves here. So, for example, if you want to achieve a tolerance of 0.01 that means, about one-hundredth of the equilibrium gap that is how I would like to mention this tolerance as.

So, you have to start with a certain initial defect size let us say delta 0 dash. And then you have to move so much in terms of units of equilibrium gap for this tolerance to come up or for example, if you want almost 2 percent tolerance on the equilibrium gap. So, you will have to move so many units in the as mentioned in the y scale here in terms of equilibrium gap units. So, this much distance you have to move for eventually getting a 0.02 tolerance or if it is a 5 percent tolerance or a 10 percent tolerance you have to move correspondingly so many you know distances in terms of the equilibrium gap units that means, the y value essentially for hitting this tolerance.

So, therefore, it is a very clear-cut specification sheet which has been generated which mentions about from what defect size or initial size of the defect how much y has to be moved by a particular workpiece towards the tool. So, that you can achieve a certain percentage of the equilibrium gap as the tolerance size. So, that is how the whole plot has been made generated and this plot can be used as a sort of thumb rule for you know process engineer who is working in a ECM process. So, the plot is different if you go towards the plus delta side that is the valley side and it is different for the minus delta side the hillside for obvious reasons that this gets depreciated much more faster than sorry this gets depreciated much more faster the hills get depreciated much more faster than the valleys because the gap of the hills are lower with respect to the tool and the electric field intensity and the current density is much higher as has been explained before.

So, let us actually now look at some numerical design problems. Let us say in an ECM operation with a flat surface as you can see here a 10-volt DC supply is used and the conductivity of the electrolyte is given here as 0.2-ohm inverse centimetre inverse the feed rate of 1 mm per minute, and workpiece is of pure iron meaning thereby that there is a machining the surface to be machined is that of iron. So, all the parameters related to the electrochemistry of iron needs to be known here and you are wanting to calculate the equilibrium gap and you consider that the total delta V the over voltage which has to be also taken into the design voltage is 1.5 volts. So, let us find out first of all what are the different parameters for the workpiece material that is iron.



So, for iron Fe the atomic weight of iron as you know is 58.6 grams. Iron normally dissolves in divalent state ferrous state Fe plus 2. So, that is equal to plus 2 at least the lowest valence state is treated here and then the density of iron is 7.86 grams per centimetre cube. And as we know that the equilibrium gap y   is given by lambda by f and lambda is conductivity times of the atomic weight of the particular species V minus delta V where V is the applied voltage delta V is the over voltage divided by rho Z F coulomb or 96500 coulomb or Faraday's constant times of the feed rate f. And we already know that the feed rate is given to be 1 mm per minute meaning thereby it is 0.1 centimetre per 60 seconds. So, this is in centimetre per second 0.1 centimetre per 60 seconds. And we first find what ye is. So, the conductivity is 0.2 ohm inverse centimetre inverse atomic weight 55.6 times of V minus delta V as you know 10 volts is available voltage the over voltage is 1.5. So, you have 10 minus 1.5 as the V minus delta V term divided by 7.86 gram per centimetre cube which is the density times valency which is plus 2 times of the feed rate which is 0.1 by 60 times of this 96500 coulombs which is the Faraday's constant corresponding to this feed rate. And therefore, this can be calculated to be 0.04 centimetres which is actually about 0.4 millimetres or

400 microns and that is about how the equilibrium gap would typically look like.

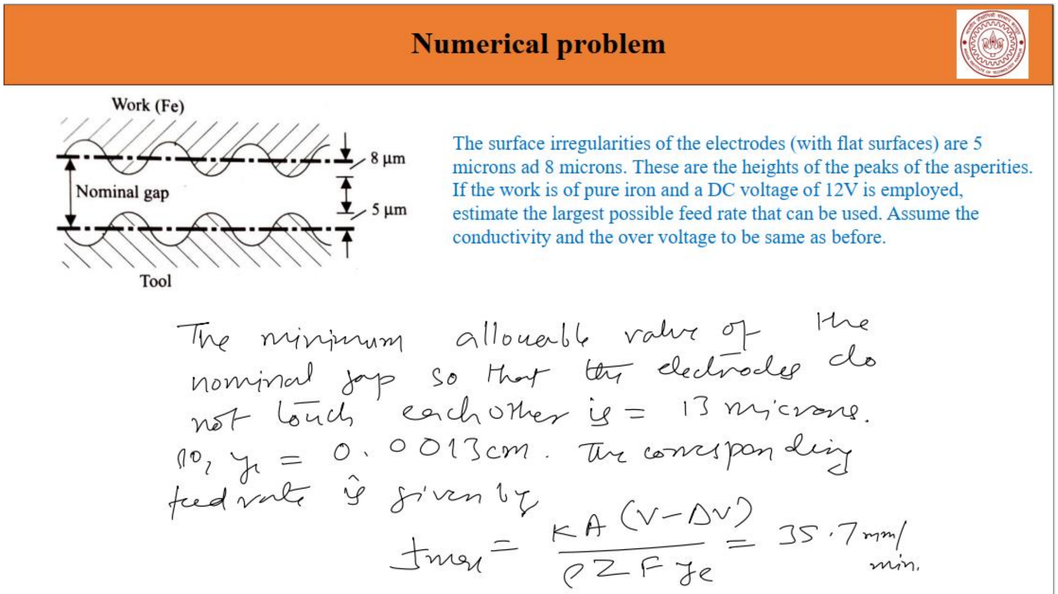
So, you can have an estimate of what is the level of gap that we are talking about 400 microns is actually 4 times the diameter of human hair. So, that is how small the equilibrium gap is in any electrochemical machining process. And you can assume that the amount of pressures that are generated by the fluid which moves through such a small gap is huge. And therefore, sometimes if the pressure values are rhyming with the ultimate yield stress of the material, then there is a possibility of the surface getting deformed the electrode surface getting deformed because of the pressures which are generated by the so-called electrolyte. So theoretically, the equilibrium gap though can have any value, but there is 1 small constraint that is important to be mentioned that for rough surfaces if the average roughness is above 400 microns, then in that case 400 microns cannot be an equilibrium gap because it will result in shorting of the 2 surfaces.

And so that practical constraint has to be taken into picture that what is the average surface roughness, and the equilibrium gap also has to be always at least more than twice the surface roughness. So, that is how we have a thumb rule of how you can position this the tool with respect to the workpiece ab initio when you start the process. So, that is about how ECM process would function. Let us actually do another numerical example here of surface roughness with respect to the gap. So, you know that this is a highly irregular surface as you are seeing here of the tool as well as the workpiece and the surface irregularities of the electrodes are 5 microns and 8 microns with respect to flat surfaces respectively.

Thereby meaning that these are the irregularities with respect to the mean value of the surface and in 1 case it is 8 microns in the case of workpiece in case of tool it is 5 microns. So, the total amount of equilibrium gap at least needs to be 8 plus 5 that is 13 microns for the process to be without short-circuiting and still go on. So, if supposing the work is again of pure iron, we assume iron for sake of convenience here as well iron is in fact, the most machinable material with ECM process also, and a DC voltage is employed of 12 volts. So, you estimate the largest possible feed rate that can be used, and you assume the conductivity and over-voltage to be the same as before.

So, here, for example, the minimum allowable value of the nominal gap. So, that the electrodes do not touch each other is about 13 microns. So, typically the ye value in terms of centimetres is 0.0013 centimetres. The corresponding feed rate f is again given by the equation K A V minus delta V divided by rho Z Faraday constant times of the equilibrium gap. And we know pretty much everything we know that what is the conductivity we can assume it to be the same as the previous question 0.2 ohm inverse centimetre inverse. This is known as 56 grams this is about 12 volts over voltage employed can be treated to be the same that is 1.5 volts and then of course, you have the density of iron as 7.86 grams this can be plus 2 this can be 96500 and ye here is defined by this process as 0.0013 centimetre.

So, the maximum allowable feed in this case also gets defined as 35.7 millimetres per minute which suggests that the feed rate cannot really go on increasing it is really limited to the amount of average roughness which is available on the surface here. So, that it does not have to go so close to a surface that there is a shorting or you know the ECM process modifies because of that shorting effect. So, I think we are towards the end of today's lecture, but now as we go on, we will see some of the other parameters of design which are needed for an ECM process. For example,



electrolyte circulation or electrolyte boiling and these phenomena would be very important because in a MEMS scale when we apply such processes because the feature sizes are too small they are more amenable to thermal energy you know to getting heated up and getting evaporated or getting faster dissolved and therefore, one has to be very careful to design even the electrolyte as a small simple thing as simple as even the electrolyte velocity in that process. So, with this, I would like to end today's lecture. Thank you.