Advanced Machining Processes
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Lecture 23
Anode Shape Prediction and Tool Design in ECM

Welcome to the course on advanced machining processes. Today I am going to discuss with you about the anode shape prediction and tool design in electrochemical machining.

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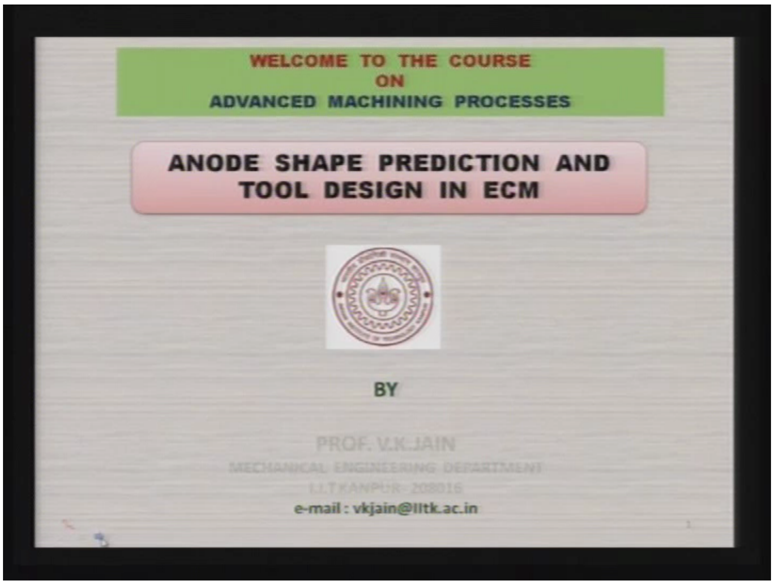

Organization of the talk is first I will give you introduction to the tooling design in electrochemical machining. Then what is anode shape prediction in electrochemical machining? After that I will discuss various approaches for anodeshaped prediction including cos theta method. Then cos theta method will be discussed for tool design in electrochemical machining and finally a very brief introduction will be given to the correction factor method suggested for tool design in electrochemical machining.

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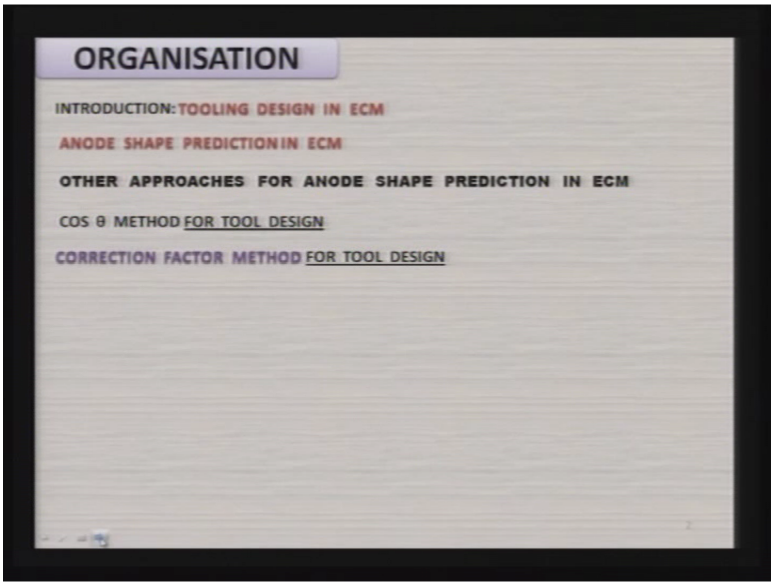

Introduction to tooling design in electrochemical machining.Anode shape production and tool design in electrochemical machining are the two different problems. The first one anode shape prediction, we are discussing about the shape finally obtained on the workpiece and in the second one that is the tool design in electrochemical machining we are designing the shape and size of the tool so that we get the required shape and size of the workpiece.

So there are various methods that have been proposed by various researchers for workpiece that is the anode shape prediction. First one was proposed by Tipton and that method is known as cos theta method, very simple useful method. Second one conducting paper analogue method which is more of experimental nature. Then Production Engineering Research Association UK proposed a method for anode shape prediction.

Then various researchers have proposed empirical approaches for the prediction of the shape of the workpiece after electrochemical machining. This includes the prediction of the interelectrode gap in various zones during electrochemical machining as we will discuss in detail. Then after that we will discuss the nomographic approach for the prediction of the anode shape. And finally the complex variables approach that was proposed by (())(03:11) that will be discussed.

Later on some of the researchers who have interest in the numerical analysis approaches they proposed finite difference method, finite element method and finally the boundary element method was also proposed by a couple of researchers from England. Finite element method was proposed from India by Jain and Pandey. And finite difference method was proposed again from England by a group of researchers which includes (())(03:48).

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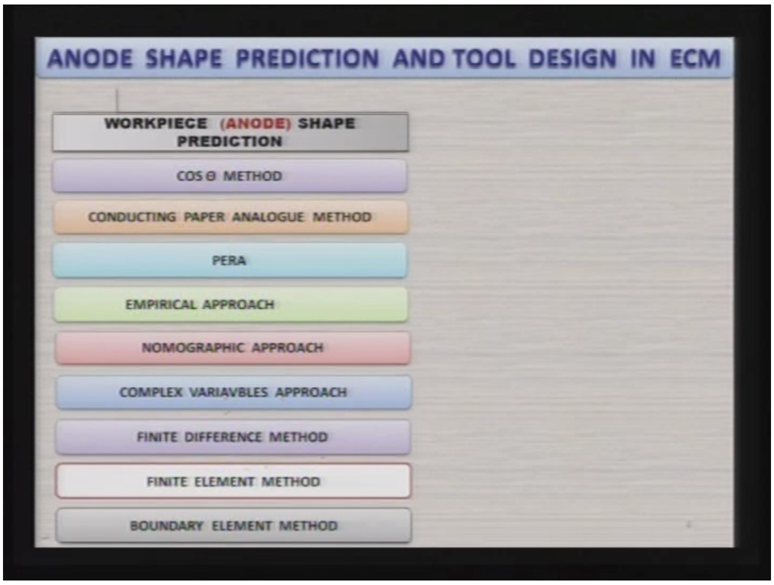

Then there are various approaches or methods that have been proposed for design of the shape and size of the tool that is the cathode. The first one initially was proposed by Tipton and that method is known as cos theta method for designing the tool. The second one is the complex variables approach which was proposed by (())(04:19) and this is more of theoretical nature however there was a big difference or deviation between the theoretical results and experimental results.

Then the finite difference method was also proposed by a group of researchers from the Manchester (())(04:41). Finite element method that was proposed from India by Jain and Pandey and boundary element method again was proposed from the England by a couple of researchers.

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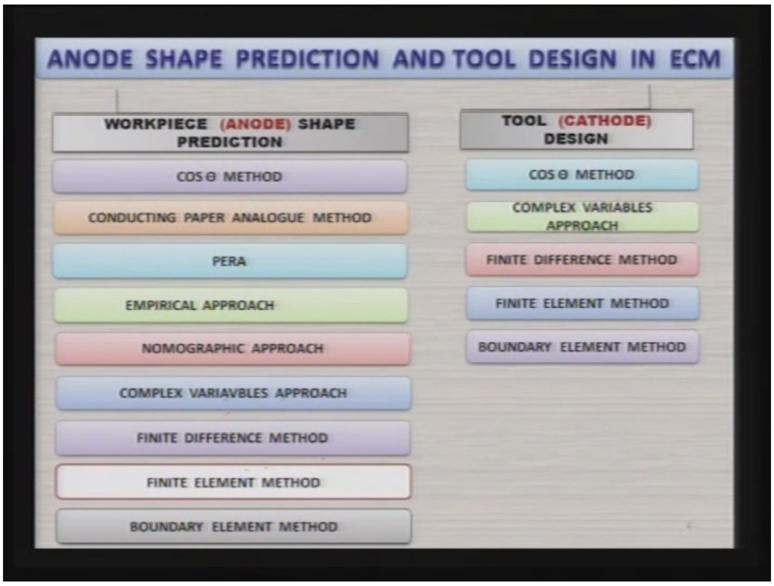

Tooling design in electrochemical machining. Anode shapeprediction that is also known as analysis problem. The (pro)analysis problem deals with the prediction of work profile obtainable from a given tool while operating under the specified machining condition. That means machining conditions and shape of the tool are given to the operators and what shape and size of the workpiece you are going to get can be predicted by various methods.

On the other hand design problem (bes) decides or which designs the cathode or the toolshape that design problem deals with the computation of the tool shape and size which under specified machining conditions would produce a workpiece having a prescribed shape, size, accuracy and surface finish. And detailed discussion of the tooling design in ECM is given in the paper by Jain and Rajurkar which was published long back in the journal of push engine engineering.

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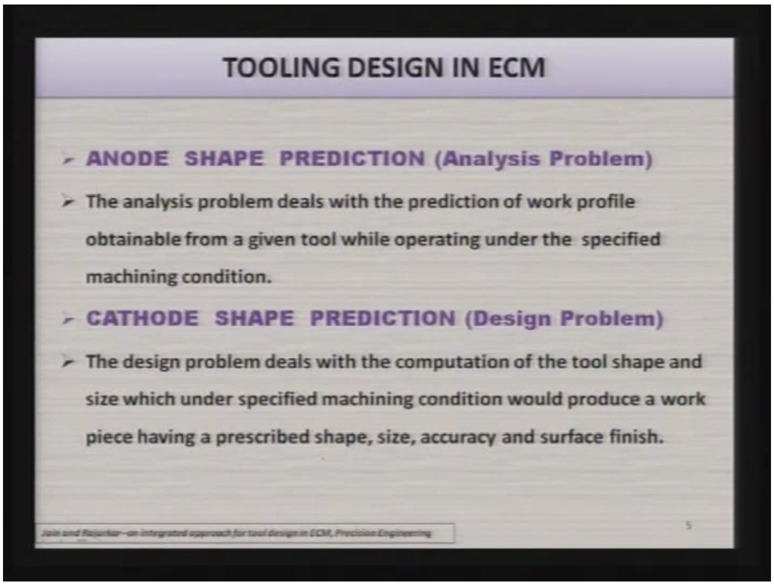

Anode profile that will be obtained after electrochemical drilling operation with bare tool because as we have already discussed you can have the various kinds of the tools. It can be bare tool, it can be coated tool or it can be bit type of the tool and that tooling design for all the three cases will be quite different. So I will give you an overview of what this tooling design means in electrochemical machining which includes various kinds of operations performed in electrochemical machining.

One of them is the ECD that is electrochemical drilling. Now this is the shape of the workpiece which you will obtain during or after electrochemical drilling has been completed. I will just try to explain it as you can see here, this is the tool and through this the electrolyte is being supplied and you can see the path of the electrolyte being followed as can be seen over here. It is the outward mode of flow of the electrolyte that we have already discussed.

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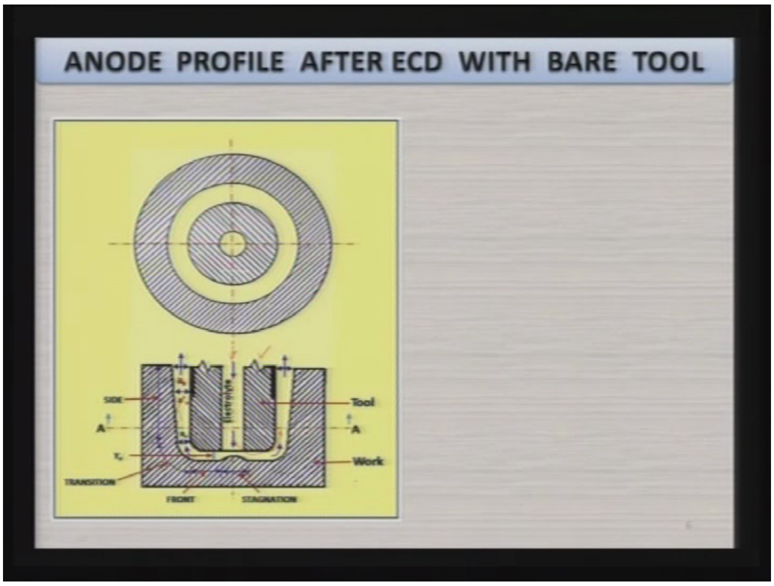

Now the important thing to see here is various zones. One zone is known as the stagnation zone which comes just below the hole through which the electrolyte is being supplied through the tool. And the zone adjacent to this zone on either side is known as front zone where thefeed isnormal to the workpiece and feed they have the same direction.

And then there is a transition zone which is produced due to the corner of the tool and this zone is quite critical and difficult to really predict theoretically. And then last is known as side zone. Rest of the zone is known as side zone where again the interelectrode gap will be varying. It will depend upon whether tool is coated tool, bare tool or bit type of the tool. As you can see here in the front gap the interelectrode gap is designated as Y e which is equilibrium interelectrode gap.

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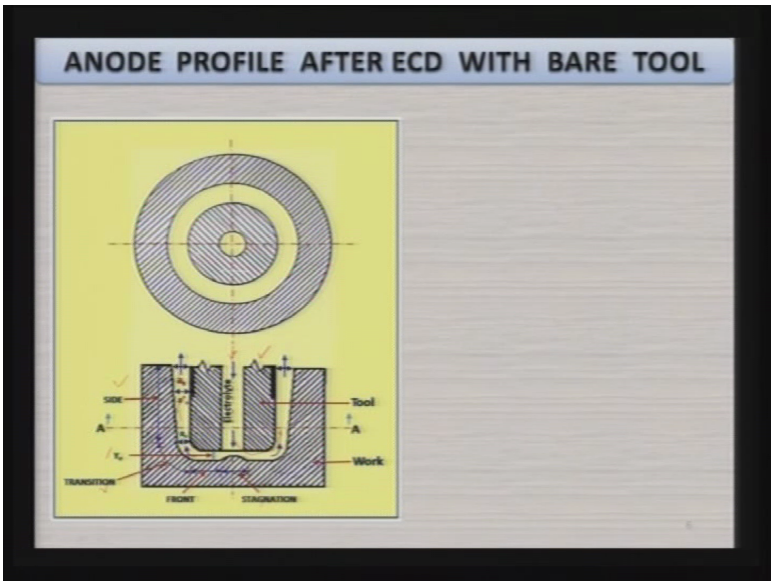

It is assumed that the equilibrium gap more or less is the same in the whole of the front zone although it will be slightly varying due to the change in the conductivity along the flow direction or electrolyte flow direction. Then at the end of the transition zone you can see A 0 isthe interelectrode gap and if you go further then finally at the end it becomes A a or in between A s or A dash s. So this you can see here continuously the interelectrode gap is varying and accordingly the shape of the workpiece is also varying.

So what we do really in anode shape prediction that we try to predict at small interval the interelectrode gap in all the four zones that is stagnation zone, front zone, transition zone and side zone and then join these points of interelectrode gap on the workpiece surface and then you will get the shape of the workpiece as well as the size of the profile that you have obtained on the workpiece.

So schematic diagram of electrochemical machining with outward mode of electrolyte flow that you can see here. This is the top view and this is thefront view. So zone 1 is the stagnation zone, zone 2 is the front zone, zone 3 is the transition zone and zone 4 is the side zone.

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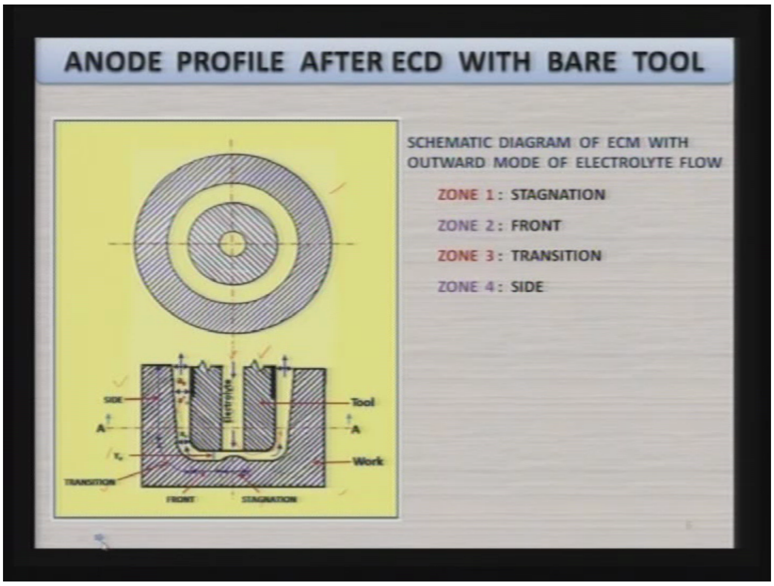

Now anodic dissolution from side surfaces. Now we have seen drilling. Now this gives just a schematic diagram how the dissolution is takingplace in case of insulated tool and bare tool. Now in case of insulated tool which is fully insulated only bottom part is bare. So you can see the interelectrode gap in case of insulated tool is constant in the side gap or side zone while same is true in case of front zone.

But if you see the case of bare tool the interelectrode gap is continuously varying in the side zone as you can see over here while in the front zone it is more or less the constant. So this gives an overview of how the shape of the workpiece is going to vary in case of electrochemical drilling with bare tool and coated tool. And this is the workpiece as you can see in both the cases.

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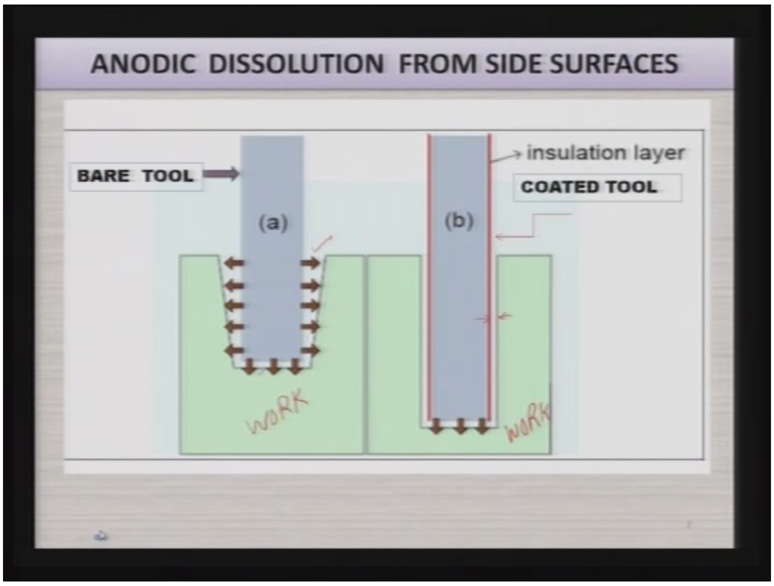

So what is the jobin anode shape prediction that we are supposed to predict what shape of this workpiece we are going to get? And if we can predict the shape of this workpiece then we should design the tool in such a way that we get the desired shape of the workpiece after electrochemical drilling operation or for that purpose any other operation. And these figures are taken from the paper by Park, Kim and Chu published in the year (19)2006.

Now let us see anode shape prediction method in detail and what it deals with? What is anode shape prediction in electrochemical machining? Let us try to understand it first. Consider the case of electrochemical drilling as I have shown to you in the earlier slide for understanding the process of anode shape prediction.

While we are trying to predict the shape of the workpiece that you are going to obtain after electrochemical drilling operation, for that matter not only drilling operation you can say plane parallel electrode machining or any other purpose, you are given the following things.

You are given the machining conditions that includes voltage across the electrodes, interelectrode gap that is normally the initial interelectrode gap, electrolyte conductivity that is again the electrolyte conductivity at the (())(13:08), electrolyteflow pressure or you can calculate electrolyte flow velocity, electrochemical equivalent of anode material. Now here you are given the feed rate also which is not mentioned.And feed rate given to the workpiece.

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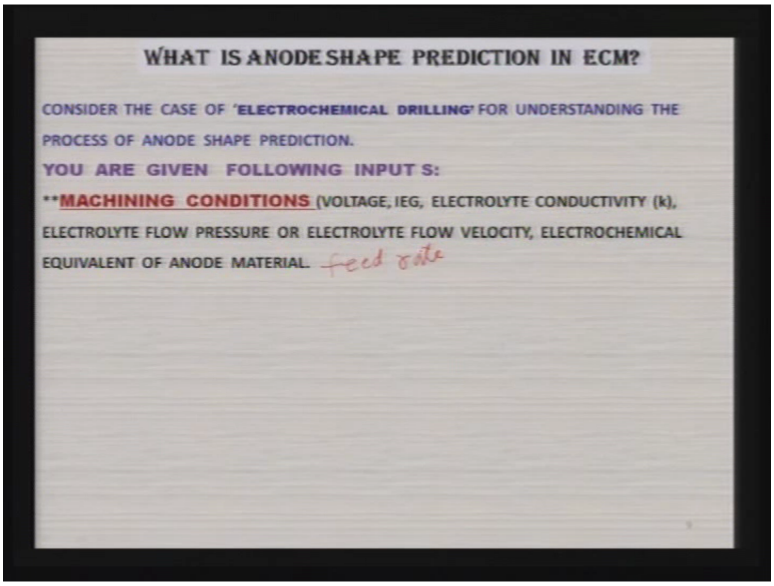

Tool profile, because for any machining operation you are given the machining condition as well as shape and size of the tool. That means if you are considering 2D problem then you will be given X and Y coordinates of the tool at different points. Now using a particular method as I have mentioned in the earlier slides, you can use one of the various methods for prediction of the anode shape.

Numerical methods are like finite element method, finite difference method, empirical method, cos theta method or any other method depending upon your acquaintance and convenience. Calculate interelectrode gap at different points along the tool axis. Finally these points should be joined to get the obtained anode profile. As I have already mentioned like this shape that you have obtained in different zones.

So what you are supposed to do? You are supposed to calculate interelectrode gap at different points like this and once you obtain these interelectrode gap at different points then you join it to get this as the shape of the finally drilled hole. So it will look like this. As you can see here. So really speaking what you are supposed to do was this thatsay supposethis is the tool and hole is there like this.

So what you are supposed to do really, you are supposed to calculate interelectrode gap at different appropriate intervals in different zones and once you are able to calculate these interelectrode gap Y 1, Y 2, Y 3, etc. then you should join them. Whether this variation is linear or nonlinear depending upon that you can join these points and to get that desiredanode profile.

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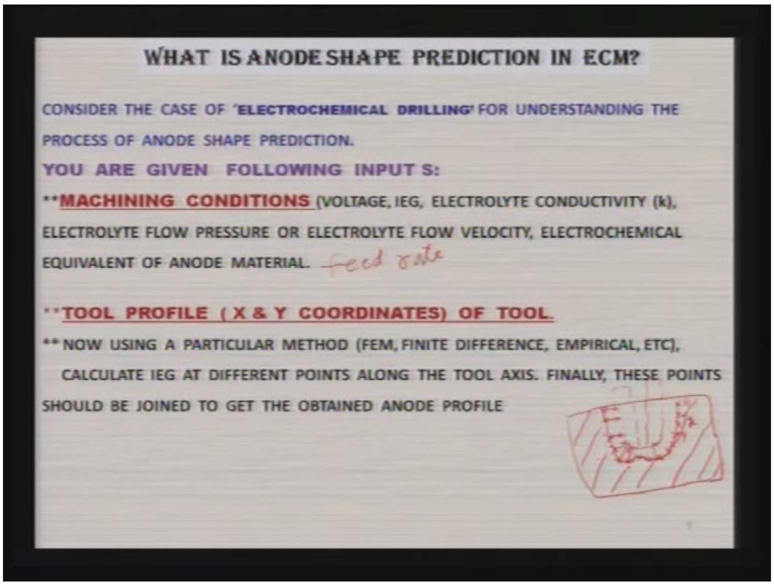

Now not only the drilling operation, you can do the plane parallel electrode machining. You can see here that this is the tool and this is the workpiece. Now you are given say if you take the 0 feed rate, not necessarily that always you will have some finite feed rate. In some cases you can have the 0 feed rate also.

You may be given electrolyte flow velocity that is over here at the (())(16:08),initial temperature of the electrolyte and T 1 can be the final temperature over here at the end when it is coming out and other details are given as I have mentioned earlier. And so initially the interelectrode gap at every point will be the same as you can see over here. And this interelectrode gap has been discretized to solve this particular problem with the help of finite element method.

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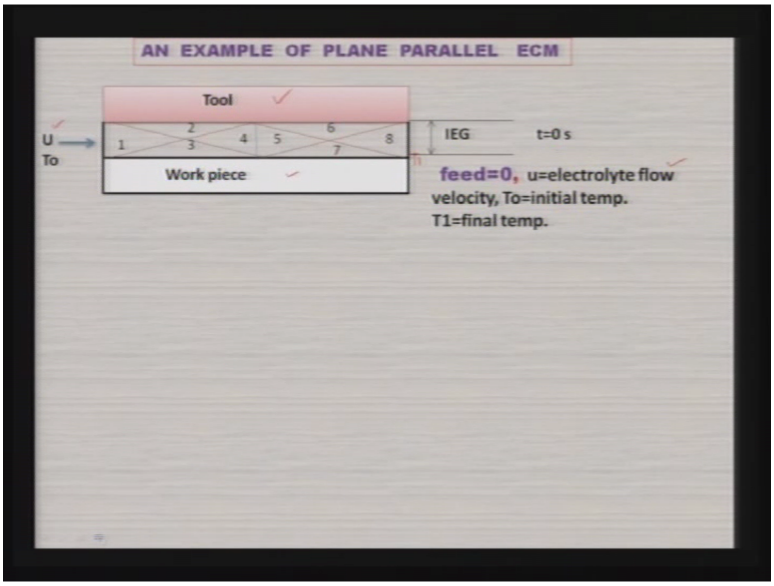

Now this is at the 0 second time. Now once you have done the machining then what will be the shape of the interelectrode gap? As you can see here that this is the initial one. Now as you move in the forward direction or in the direction of flow of the electrolyte the interelectrode gap has increased because feed rate here is 0 and material is being continuously dissolved from the workpiece. So definitely the gap between the tool and the workpiece will keep increasing and at different points you can see the gap is continuously increasing.

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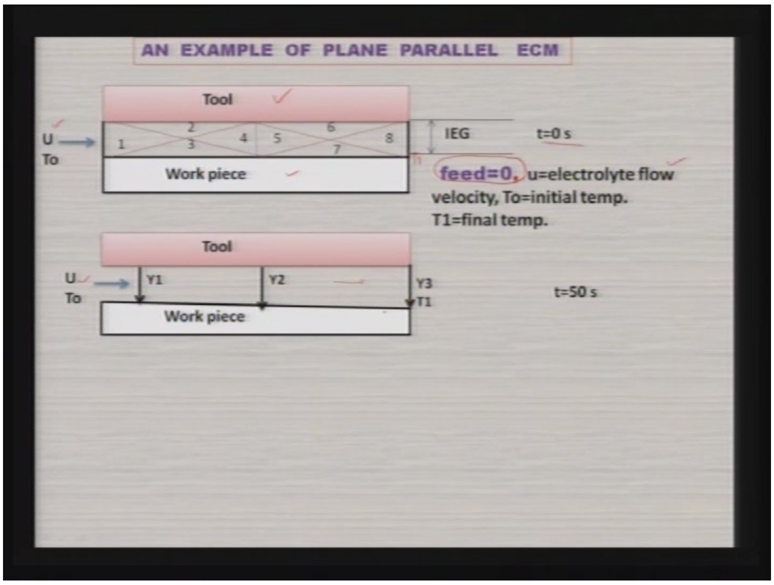

How this gap is changing? This will depend upon what are the various assumptions that you have made during computationfor plane parallel electrode machining. Now as the time furtherincreases you can see the interelectrode gap has further increased and so in this waywhen 100 seconds has become, this gap Y 3 has become higher than the Y 3 at the second stage, Y 2 is also higher thanthe second stage and Y 1 is also higher than the second stage.

And so you can see with 0 feed rate the interelectrode gap is continuously increasing but this is not a really what we want.

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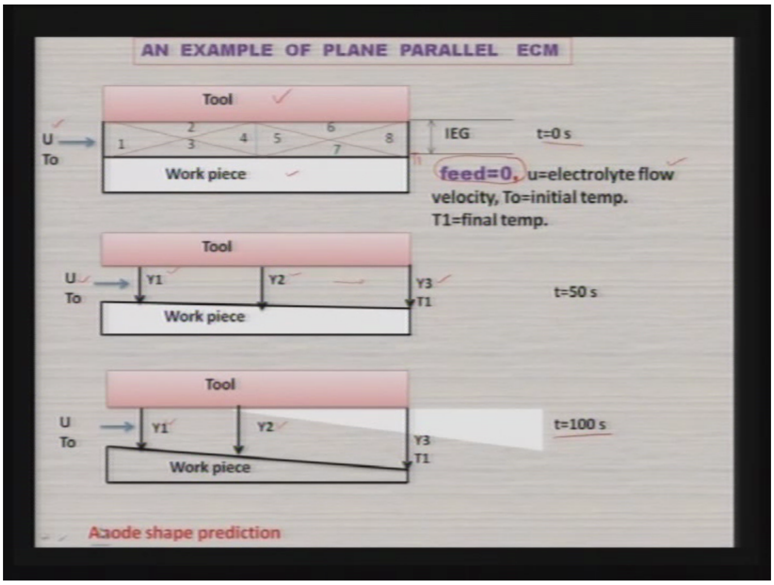

Normally in case of electrochemical machining we normally give a finite feed rate. So let us assume that feed is equal to f 1. Now this feed is to be selected very carefully. The simple rule is the feed rate should be equal to the linear material removal rate. That means f should be equal to MRRL, linear material removal rate. That we have already discussed what is this linear material removal rate? Then you will get interelectrode gap all the time as Y e.

But that is not very true because as the electrolyte flow along the flow direction then temperature of the electrolyte is changing. If temperature is changing (electro) electrolyte conductivity will change, conductivity changing then current density will change and current density is changing then linear material removal rate will be different at different point. So really speaking throughout the interelectrode gap the equilibrium gap will not be constant rather it will be different at different points.

So you can see after a certain period of time say 50 seconds you can seehere the gap was same at different points but in this particular case the gap has changed constantly. Y 1, Y 2, Y 3all the three are different from each other while here Y 1, Y 2, Y 3 like this. Y 1, Y 2, Y 3 they are the same at t is equal to 0 second.

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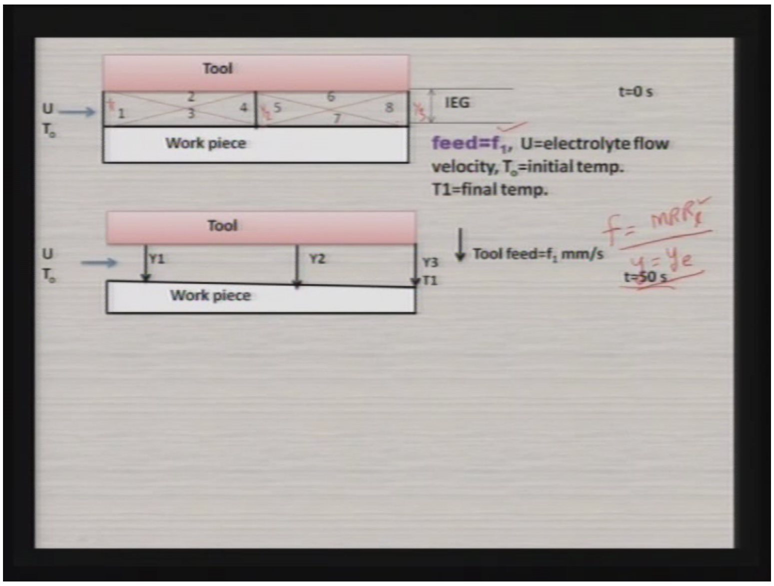

And here also it is slightly changed but not as much as in the particular earlier case and this is the feed rate is f 1. So this is the way you predictthis. What you have to do here is that at every point you predict the interelectrode gap. Take many points over here. Larger the number of points you take and then more accurate will be the prediction of the anode profile. Now you find out this and then join them in a proper way, you will get this as the workpiece profile.

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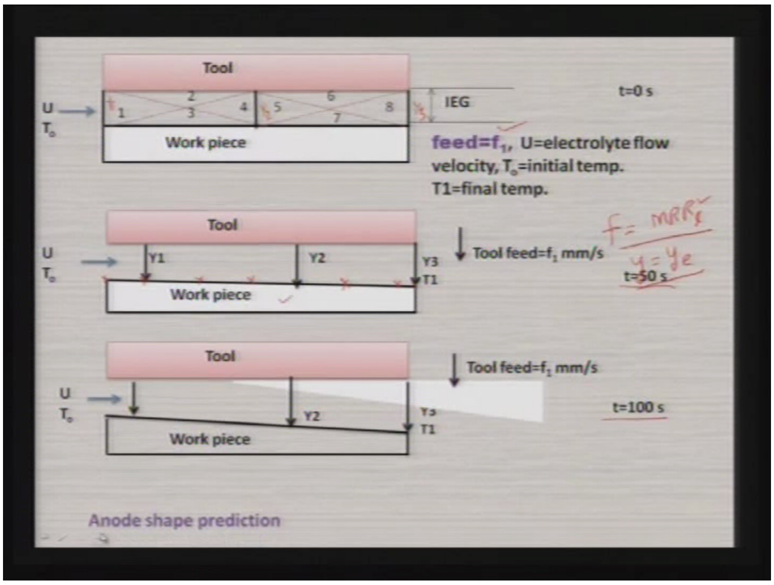

Now as I have mentioned there arevarious methods of prediction of the anode shape. Many researchers have analyses using the numerical analysis techniques. Now this definitely requires high speed computers. Now what steps you are going to follow for predicting the anode profile using the numerical analysis approach. Say steps you can see here. First decide the type of analysis you want to conduct. Whether it is 1D, it is 2D or 3D. Normally it is 2D or 3D.

Then (conna) collect the initial data that means the variables and constant values of the some of the variables and varying values of the variables. Something like conductivity, initial temperature, voltage applied and so on. That we have already seen. Then perform preliminary computation. In some of the cases you may have to conduct certain calculations before really starting the numerical analysis method.

For example you may have to calculate the electrolyte flow velocity if you are given the cross-sectional area of the interelectrode gap at different points. So there may be other calculations if the alloys there in place of pure metal then you can havesome built-in program which can calculate the electrochemical equivalent of the anode workpiece. Then solve the finite element problem either as a temperature distribution problem or as the electric field potential distribution problem.

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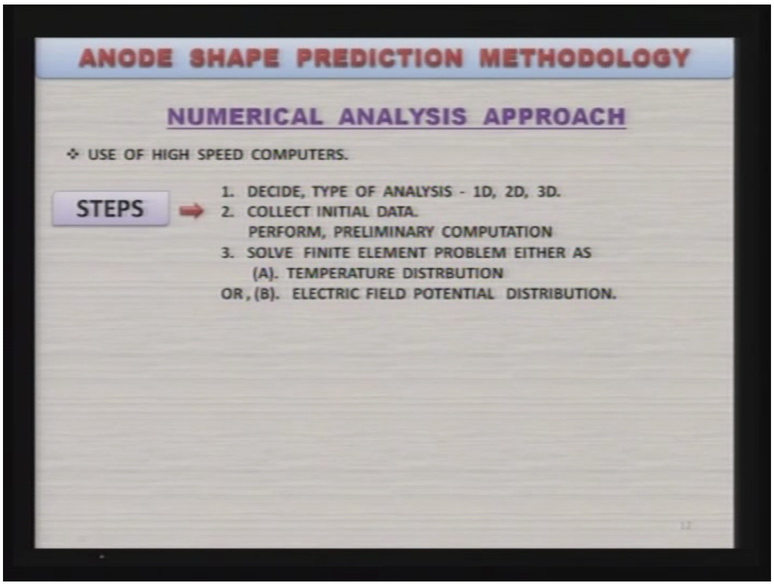

You find out these main variables after getting this variation of temperature or electric field potential at different points. Then secondary calculations are to be done. That meansif you have found the temperature then you have to calculate the current density,(electri) electrolyte conductivity and so on. And finally you will calculate the interelectrode gap. After that calculate secondary variables such as temperature, distribution.

If it is an electric field potential distribution problem, electrolyte conductivity, current density, etc. Then calculate interelectrode gap along the electrolyte flow direction as I have shown in the earlier slide for plane parallel electrode machining or before that I have shown it for the electrochemical drilling operations. And using the computed interelectrode gap at different points make anode profile by joining them appropriately and that is what you call it as anode shape.

The goal is to determine interelectrode gap atdifferent nodes on the workpiece surface and finally to predict the profile or the shape and size of the workpiece variation along the electrolyte flow direction.

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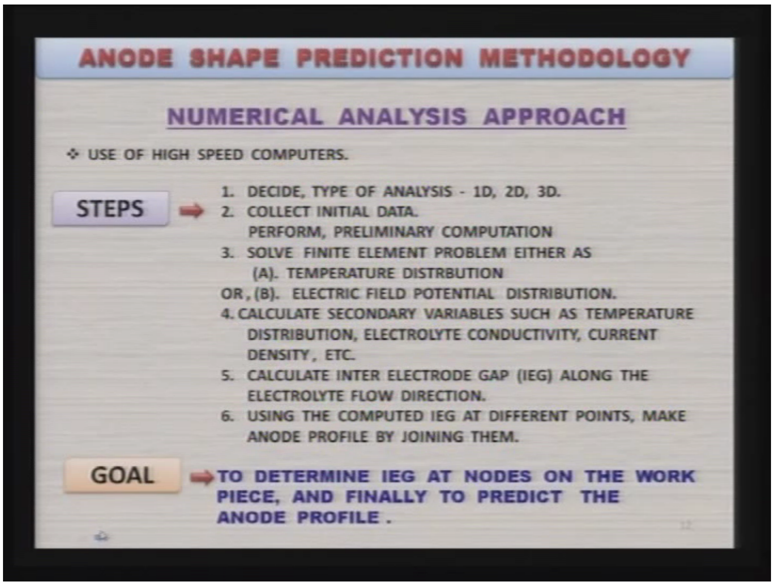

Suppose it is a temperature distribution problem then use appropriate differential equation to evaluate temperature distribution along the electrolyte flow direction. Real life problems are not as simple as plane parallel electrode problems. They are verycomplicated.Interelectrode gaps are there and in those cases you have to go, if you want to predict it accurately, for numerical analysis techniques like finite difference method, finite element method, boundary element method.

And then from the above temperature distribution calculate electrolyte conductivity at different points because electrolyte conductivity is a function of the temperature of the electrolyte.After that find the effective feed rate at different points because as I mentioned earlier that suppose this is the workpiece and tool is being fed normal to the workpiece surface then feed rate will become whatever is the feedrate of the tool.

But if the workpiece is inclined like this and tool is being fed like this then you have to calculate what is going to be the feed rate at different points of the workpiece if it is curved one or having different curvature and then f will not be equal to the actual f t that you are giving. But it will be a component of that. So you have to calculate effective feed rate at different points.

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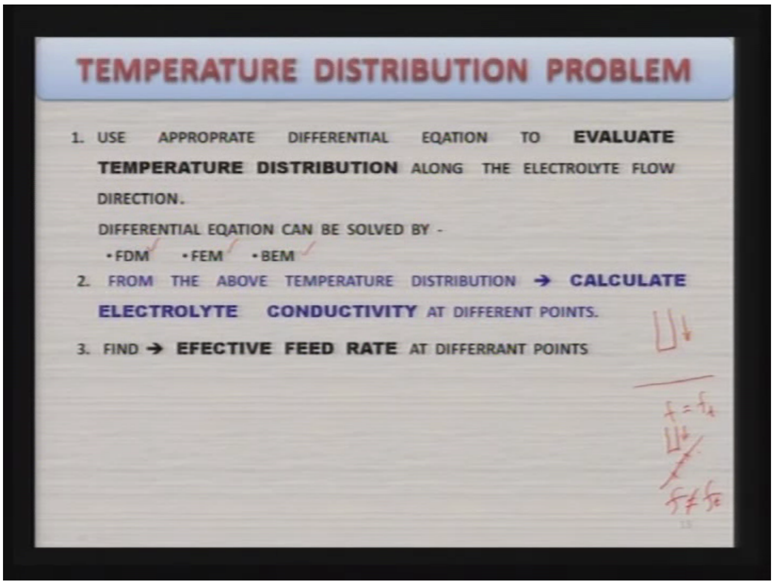

Assumption, now how to calculate this effective feed rate I have already discussed while discussing the theory of electrochemical machining. Here you are making the assumption that Ohm's law is followed. That means while computing the current density at different points you are assuming that the current flow lines are straight and perpendicular to the surface of the workpiece.

Using J, after calculating the current density calculate interelectrode gap at different points along the electrolyte flow direction and thismay be any shape of the workpiece. And after finding out the interelectrode gap at different points, plot anode shape from interelectrode gap by joining these interelectrode gap at different points.

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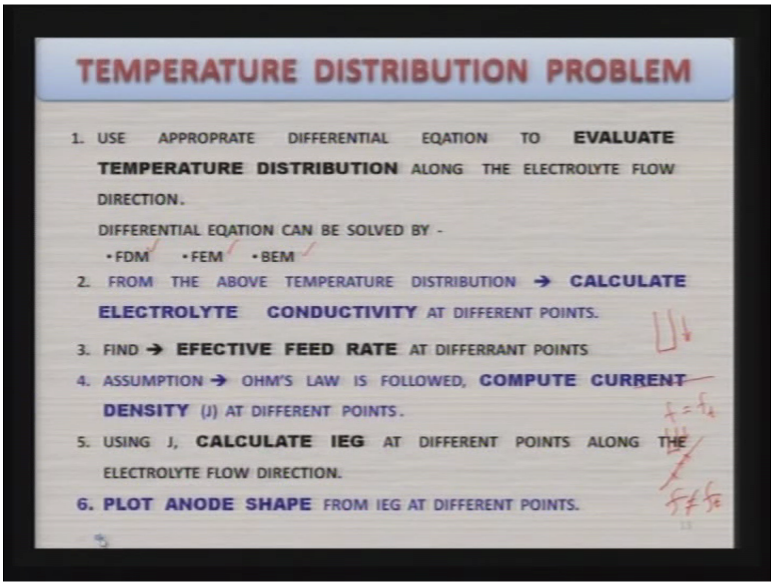

Now there are certain limitation of this particular method that Ohm's law is obeyed which is really not true especially when interelectrode gap is not plane parallel as in case of plane parallel electrode machining then Ohm's law does not hold true. Lines of electric field potential are not always straight and normal to the electrode surface especially when a curved zone is analyzed, then Ohm's law does not hold true.

Hence the solution of Laplace equation is always recommended and it is the reason why researchers have adopted finite difference method or finite element method or boundary element method.

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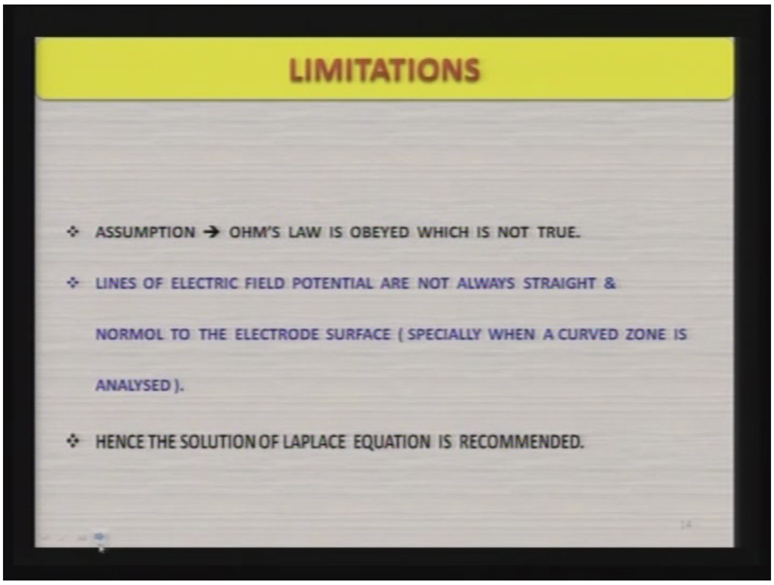

Now when you are using electric field potential distribution method or numerical analysis is being used then calculate electric field potential by solving Laplace equation in 1D, 2D or 3D depending upon which problem you are solving. Now just like given here in 3D, del 2 phi over del x 2 plus del 2 phi over del y 2 plus del 2 phi over del z 2 is equal to 0.

And initial conditions are phi is equal to 0 at the cathode and phi is equal to E v is equal to A v minus delta A v at the anode where A v is the applied voltage across the electrode and delta A v is the overpotential that exists at that particular point. So you can find out from these two data the effective voltage E v. Now then calculate the current density J.Using this equation after finding out the current density you can calculate the temperature distribution along the electrolyte flow direction that is the X axis.

Here it is assumed that the electrolyte is flowing along the X axis. That is why you have here del T over del x is equal to V minus delta V square divided by U 0 rho e C e Y 0 square is equal to A k. Now here you can see that here k is missing. So you can see that this is the delta like zone over there delta V. So you can see here that except k all other terms can be considered as constant in a very small area or zone rather because here what we do that many are using finite element method or finite difference method or boundary element method.

The size of the element is verysmall say less than a millimeter size of the element. Then in that particular small size of the element and for a very short period say less than a second or 1 second, the change in theelectrolyte flow velocity U 0 will be negligible.

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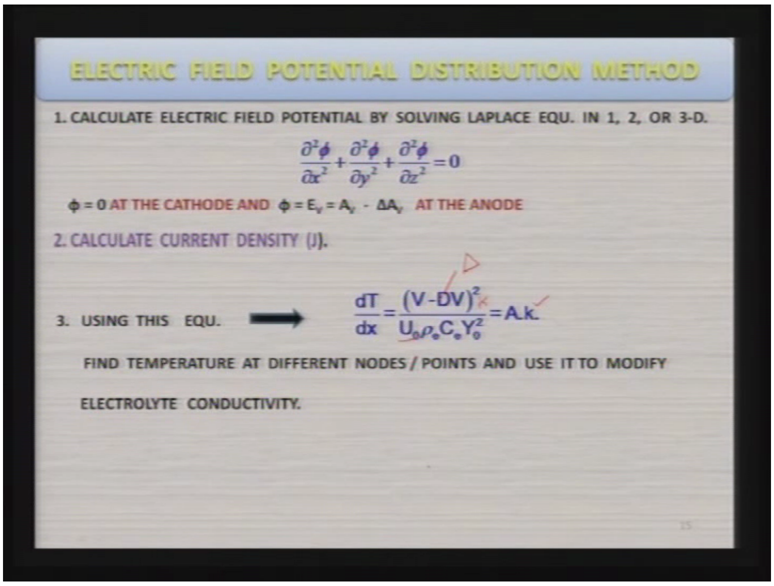

Same way change in the specific heat C e of the electrolyte over this region will be negligible and change in the interelectrode gas will also be verysmall. That is why all these parameters can be considered as constant and k is the conductivity of the electrolyte. So find the temperature at different nodes points and use it to modify electrolyte conductivity that is k. And we already know that k is equal to k 0 1 plus alpha delta t. That I have already explained or if you are taking into consideration byte fraction then it becomes 1 minus alpha V raise to power n.

You can check it from the nodes and then you can calculate this and then you can find more accurate temperature distribution along the electrolyte flow direction. Then compute the current density at different points. And after computing the current density compute the interelectrode gap at different points. Connect these interelectrode gap points and predict the anode shape as I have already explained.

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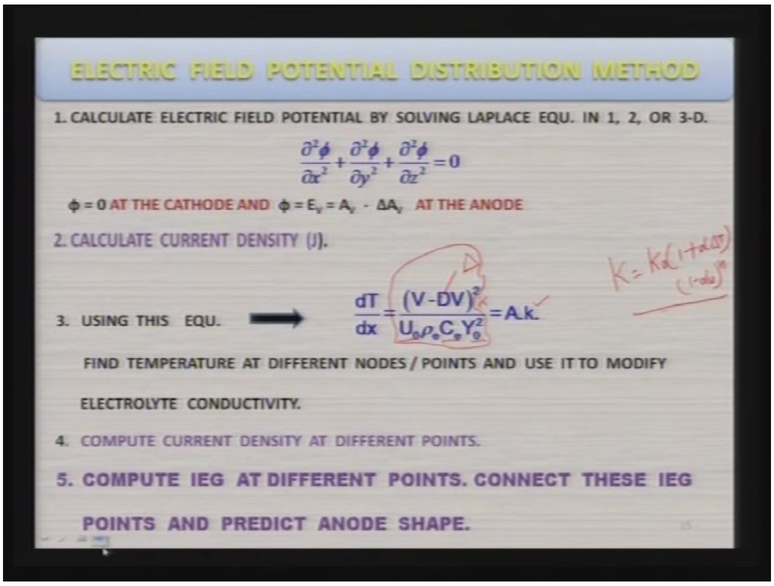

Now saying procedure which I have mentioned is shown over here in the flowchart. Flowchart for anode shape prediction procedure using finite element method. Now when you are starting it read the given data and print input data. Given data includes all the machining conditions and tool profile. And that is x, y or x z or y z coordinates of the tool. Then general nodal coordinates, then you have to discretize the interelectrode gap that is the gap between the tool and the workpiece as I have shown over there earlier.

You have to discretize it into the different parts depending upon like 1, 2, 3, 4 and then coordinates of 1, 2, 3, 4, 5, 6, 7, 8 or whatever is the discretization. Then you have to generate automatically with the help of the software the coordinates of different points. Because there are maybe hundreds and hundreds of points for which you have to generate the coordinates and which have to be analyzed. It is not only five or six points.

Then generate the stiffness matrix.this can be understood by those who know or who have the idea about the finite element method. You have to develop the stiffness matrix and compute number of computation cycles required to drill the hole to machine the workpiece surface.

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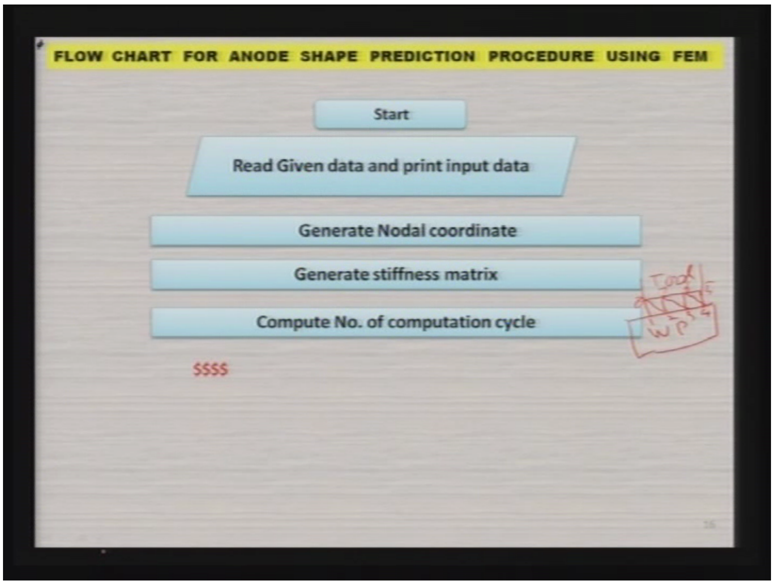

Then computer feed rate in different zones as I have mentioned in the earlier slides that if the feed rate is not normal to the surface of the workpiece then the feed rate directions rather is not normal to the workpiece surface. Then you have to calculate the effective feed rate at different points which are to be analyzed just like points1, 2, 3, 4 in this particular case.

Then apply boundary or initial conditions as I showed you earlier also just like phi is equal to 0 at the cathode and phi is equal to V minus delta V at the anode andthere will be other boundary conditions also. Then solve the equations that is the Laplace equation to evaluate the potential distribution or temperature distribution at different nodes. Then compute the change in the electrolyte temperature at different points.

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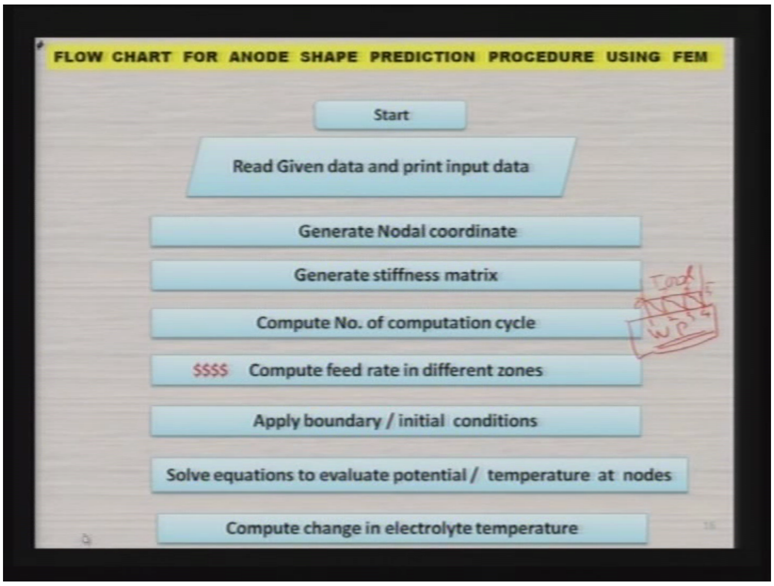

After computing this compute electrolyte conductivity. Now if feed rate is 0 then compute Y for 0 feed rate. If feed rate is not 0 as I have shown you that means f is not equal to 0. Then compute Y that is the interelectrode gap for finite feed rate at different nodes. Find the current density again. Compute linear and volumetric material removal rate. Then reassign Y coordinates for side flow because this process will be different for plane parallel electrode machining or electrochemical drilling or other kind of the complicated shapes.

So you have to change this procedure slightly depending upon the type of the workpiece. Then modifyV for new values of, these are check if machining cycles are complete for new valuesby the interelectrode gap. Nowhere I have shown three stars. This indicates that if suppose total time required for machining is 100 seconds and by the time you come over here it is only 50 seconds, then you have to again go back to the earlier one where I have shown at four stars.

Go to that particular point and then again redo the whole thing for the new coordinates of the different nodes and then recalculate the potential distribution, temperature, conductivity, interelectrode gap and so on. And this process will keep going on unless all machining cycles are completed. And then after that you print the results and then end and then stop.

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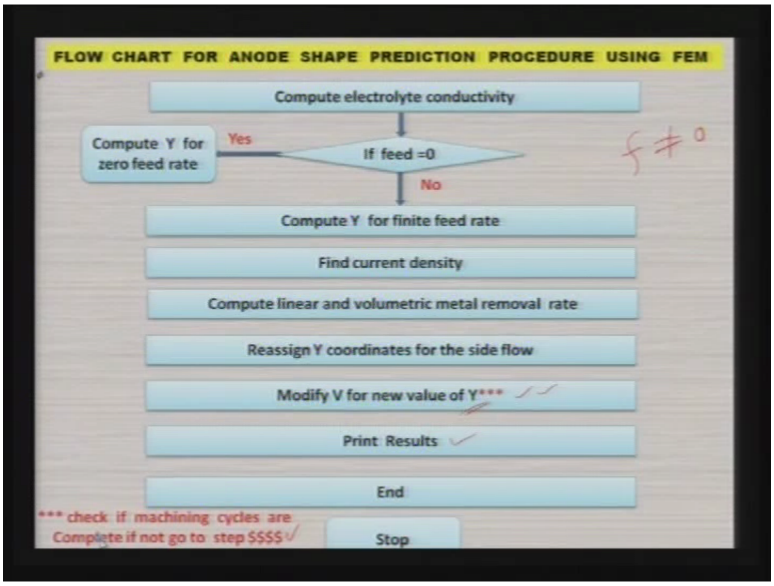

So this is the procedure that you can follow for prediction of the anode shape in case of ECM using finite element method, boundary element method or finite difference method.Now this is the numerical analysis method that I have explained to you. There are various other approaches for anode shape prediction in ECM that have been proposed by various researchers.

The basic reason is that it is really difficult to accurately predict theflow line or electric field flow lines in the interelectrode gap and then making all these calculations become cumbersome. So many researchers have proposed empirical approachor nomographic approach which are much simpler than these numerical analysis approaches. So some of these approaches I am going to discuss in this particular case.

Now let us discuss some of the other approaches proposed by the various researchers. Empirical approach which tells you really the interelectrode gap and some of the zones and these equations which are empirical in nature have been proposed based on very limited number of experiments. And the caution to be observed here is that these equations are applicable only for those workpiece material, those machining conditions and to some extent those tool material also.

So they cannot be the generalized approach. And second thing one has to be careful that most of these researchers have propose only interelectrode gap in either one zone or two zone, not in all the four zones as we will see as we proceed. So exact path of electric current flow lines within a complex interelectrode gap is difficult to determine analytically. That we have seen and I have mentioned.

Empirical equation suggested by Konig and Pahl of Germany to evaluate interelectrode gap a 0 at the start of the transition zone is given as follows. That is a 0 is equal to r c raise to the power point 35 multiplied bypoint 35 into 10 e multiplied byY whole raise to power point 5.

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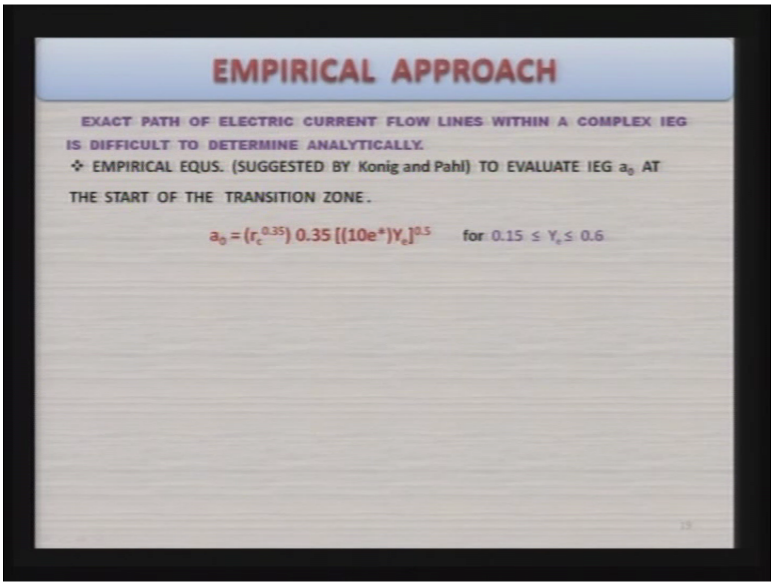

Now here r c is the tool corner radius, Y e is the equilibrium gap and this equation is applicable for Y e greater than point 15 and less than point 6 millimeter. And r c that is the corner radius should be greater than or equal to point 5 millimeter and less than or equal to 5millimeter. These were the conditions under which various experiments were conducted by Konig and Pahl and they proposed this particular empirical equation for that purpose. And e star is the Euler number which is constant.

For the case of tools partially or fully coated on side wall and having r c greater than or equal to 1 millimeter, less than or equal to 5 millimeter, that is tool corner radius. Konig and his group proposed another equation that is a 0 is equal to point 1 plus Y e multiplied bypoint 314 r c plus 1 point 17 for b b is equal to 0. That is bare bit length of the tool and for Y e greater than point 1 and less than or equal to point 7 millimeter, b b is nothing but say suppose this is the tool and whole of this tool is coated with the insulated layer. That means it is like this, right?

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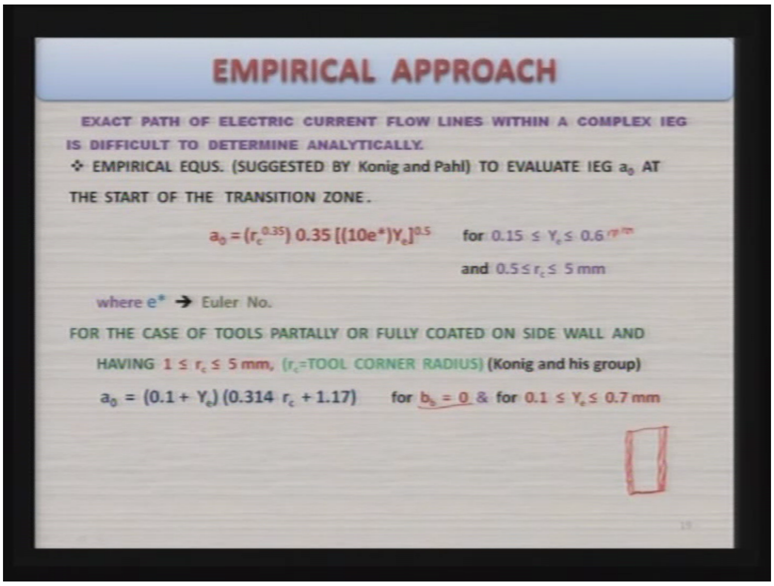

So that means whole of it is coated, machining is being done by this front area of the tool only not from the side. Now if b b is greater than or equal to 1 millimeter then this is the equation that they have proposed. That simply means as you can see here that say suppose this is the tool then this is coated up to this particular point and this bare length of the tool, this is known as b b bare bit length. And this should be greater than or equal to 1 millimeter. Then this particular equation holds good.

Above equations are reported to yield erroneous results at low feed rate. Now there is another parameter which affects all these equations is the feed rate. If feed rate is verylow like point 006millimeter per second and if equilibrium gap is large greater than or equal to 1 millimeter then these equations do not give very good results.

Another point to note here is as we had seen earlier that there were four different zones and in the side gap there were three different kinds of interelectrode gap depending upon how long is the coating on the tool. But here they have proposed only one simple equation for one particular interelectrode gap.

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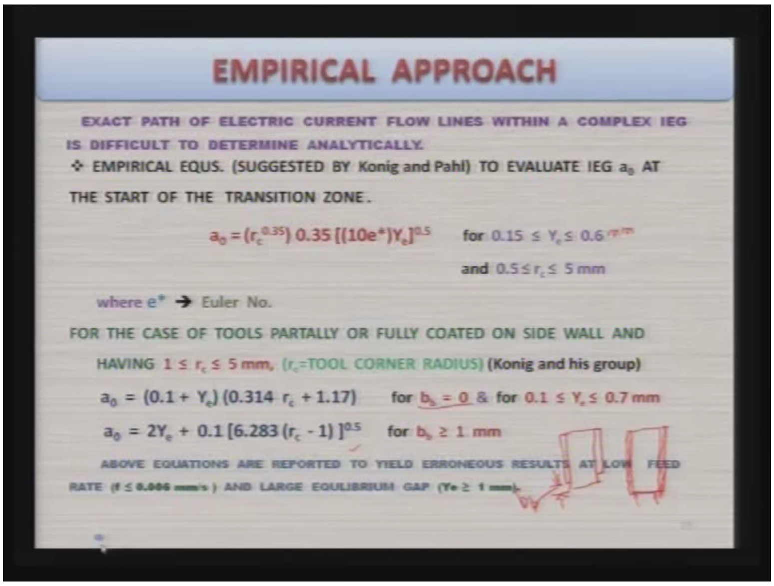

So really speaking this kind of approach cannot be applied forfull anode shape prediction. However it can give you interelectrodegap in a certain zone only. This is the paper which we have referred for this. So you can see here various zones. I am repeating this figure. Now this is the a 0 for which they have proposed the equationsand this is the a 0 at the start over here at the transition zone because here the transition zone is ending.

So it is just over here.Now the question arises what about a dash s? What about a a over here? So really speaking thisparticular approach cannot be applied for prediction of complete anode profile.

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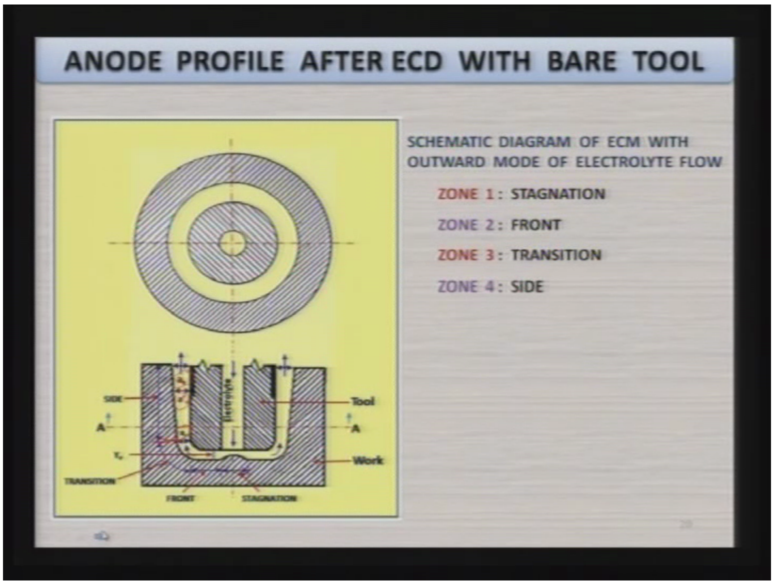

Same way Jain, Jain and Pandey also proposed one equation. Again the same way that they have proposed this very simple equation for the prediction of interelectrode gap in the beginning or end of the transition zone. Again the same weakness over there. R c 1 and R c 2 depend on many factors like tool and work material combination, electrolyte, etc. Equations to evaluate a s and a s dash in the sidezones under coated and bare part of the tool are machined.

Later on in the same paper they have given the equation for a s that is given over here that is a s is equal to 2 b b, that is the bare bit length, multiplied by Y e plus r c raise to power point 7 into point 123 10 e star multiplied by Y e raise to power point 5 and point 65 Y e. Now as dash as I showed in the earlier slide that a s and a s dash we are missing. So this is the equation which they proposed for the prediction of interelectrode gap in that particular zone. And this has been reported in this particular paper also.

So what it shows that again there are so many assumptions because a s and a s dash may not be constant in the whole zone and if you are following numerical analysis technique that I have already explained then you can predict these side gaps a 0, a s, a s dash much more accurately than with the help of these equations. But these equations are good enough for approximate prediction of anode profile.

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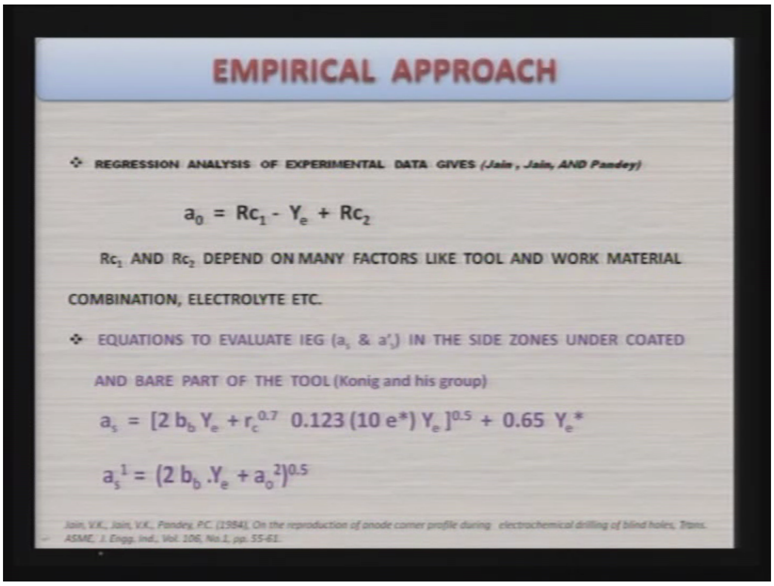

Now there is another approach that is known as nomographic approach where again this was proposed by Konig and Pahl in the beginning when this ECM process was getting more and more popularity because such approach are very easy to apply specially by the industry people. Now here you can see three nomograms are given.

One in this particulara g is nothing but the interelectrode gap y and you can see here r is the tool corner radius so this one gives the relationship between thevarious tool corner radius and interelectrode gap. Then again herethis one isyou can see bare bit lengthgiven over here and this graph will give you the value of a s.

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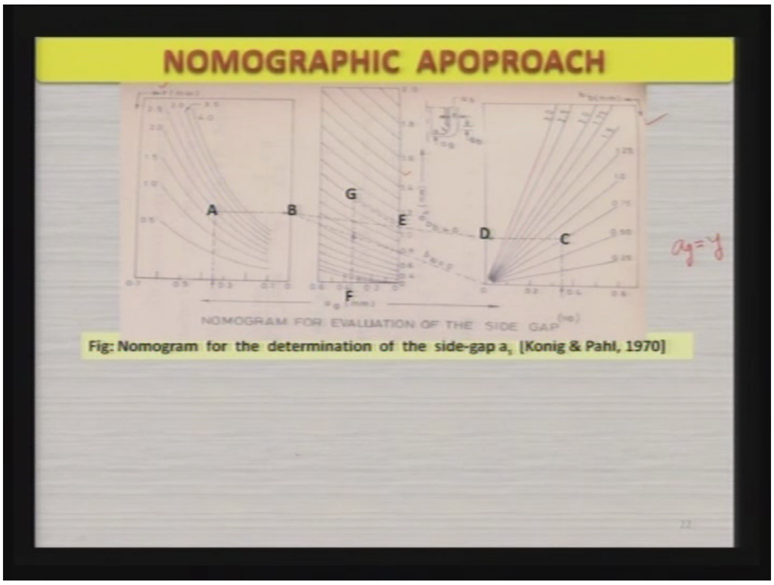

Now what you have to do? I have explained here in different lines. For the calculated A g that is the interelectrode gap and r that is given over here corner radius, find point A. Nowsuppose we are given here point 35 as the interelectrode gap and there is certain say 2millimeters as the tool corner radius then you get the point A. Now a line parallel to the x axis which cuts at point B is drawn from point A so you will get the point B over there. Our mindedobjective is to find out the value of the a s for this particular conditions.

Then for A g that is the interelectrode gap and bare bit length b b that is given over here as you can see find pointC, from C draw a line parallel to this. Now what you have to do? We are given this interelectrode gap already that we have taken over here. Same interelectrode gap draw a vertical line and then take the bare bit length over here that is point 7 millimeter. Wherever it cutsfrom here you draw a line parallel to the x axis, you will get the point D.

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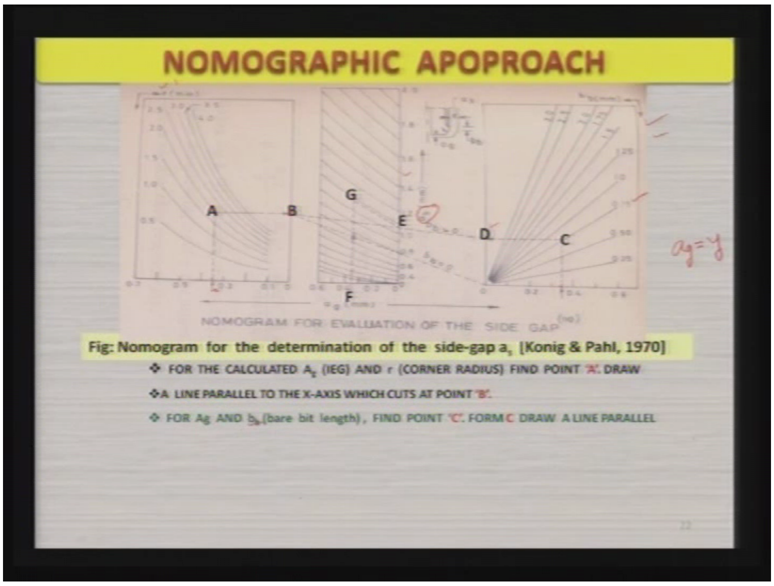

Now what you can do? You join the point B and point D such that it will cut at point E on the middle nomogram.Now when it cuts at point D, just see to the x axis to cut it at point D. Thenjoin D and B. Join this particular point and this particular D and B so it will cut itto cut at E. Find point F from interelectrode gap, draw a vertical line. This is the interelectrode gap that we already know because here also we have it, here also we have it.

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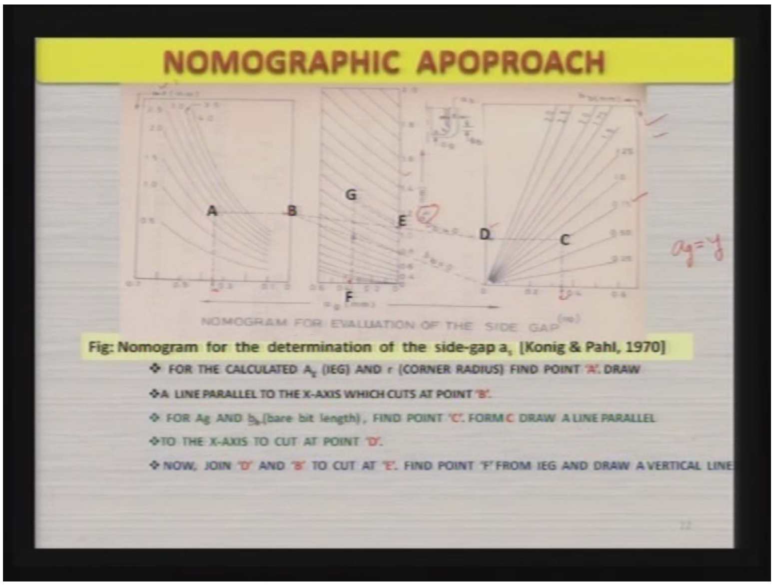

From here draw a vertical line. Now after drawing the vertical line, from F draw a curve parallel to the plotted curve to cut vertical line at G.From point E draw a curve parallel to this (parti) because you can see various curves are plotted here. From pointE whenever it is cutting you draw a curve parallel to this and draw a vertical from pointF, so both of them will cut at point G.

Now at this point G you canrather interpolate because we know this point G lies between a s of 1 millimeter and 1 point 2 millimeter. Sorry this is 1 millimeter, this is 1 point1, this is 1 point2. So this lies between 1 and 1 point1. So from here you can find out what should be the side gap at point G and so with the help of this you can predict the side gap and that is shown over here that is their objective.

Because this side gap will be constant because the tool is coated more or less fully coated except a very small part that is shown here by b b and that we have assumed here as point 75 millimeter. So for this kind of the tool we can find out what is going to be the interelectrode gap a s? And this interelectrode gap is nothing but the over cut in the side gap. So you can predict, except this small part here, over cut in the side gap can be predicted by this particular method and it is very simple to use on the sharp floor.

If you are given or if you know the interelectrode gap, if you know the tool corner radius, if you know the bare bit length, all theseare known in advance then you can predict what is going to be the side gap for the given machining condition. Mind it, if machining conditions are changed then this side gap is also going to change. So again this was taken from the paper by Konig and Pahl.

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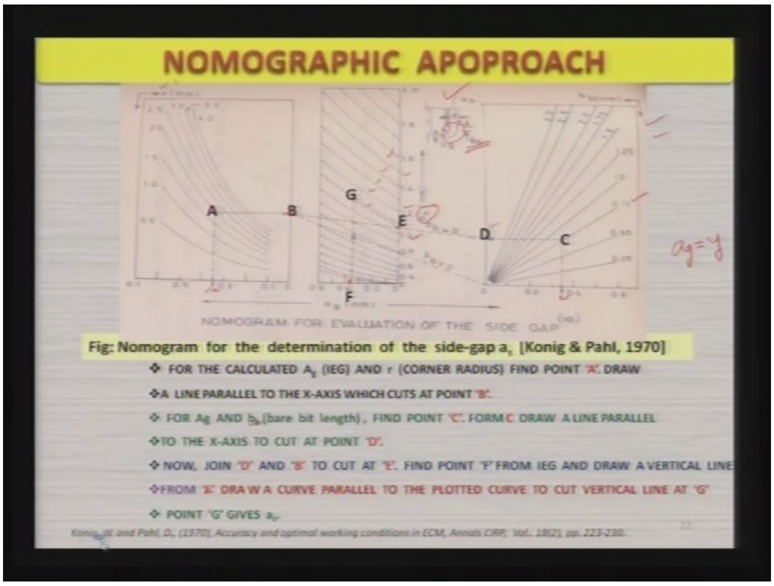

Now cos theta method as I have mentioned can be used for anode shape prediction as well as for tool design purposes. So what I am going to discuss is I am going to discuss this cos theta method for tool design purposes. This method was proposed by Tipton. Now there are certain limitations of this cos theta method that it is applicable when angle between feed direction and normal to the workpiece or tool surface is gentle. That means no sharp corners are there. This method was proposed by Tipton. It is not applicable in case of sharp corners.

It is applied for three reasons as we will show it for theta is equal to 0 degree, theta is equal to 90 degree and theta somewhere in between 0 and 90 degree. Figure will be shown in the following slide. Now here IEG that is interelectrode gap is (gi) abbreviatedas Y suffix e and fortheta greater than 0 degree and less than 90 degree.Interelectrode gap parabolic in shape if theta is equal to 90 degree. If theta is 90 degrees that means the feed rate is 0.

Just like I will show you the example, suppose this is the tool and this is the workpiece over here. Now here normal to this the workpiece surface and feed direction is this. So the angle between this and this becomes 90 degree. When this angle theta is 90 degree then the shape of the workpiece that you are going to get will be parabolic in nature. This is the shape of the workpiece that you are going to get parabolic in nature after electrochemical drilling.

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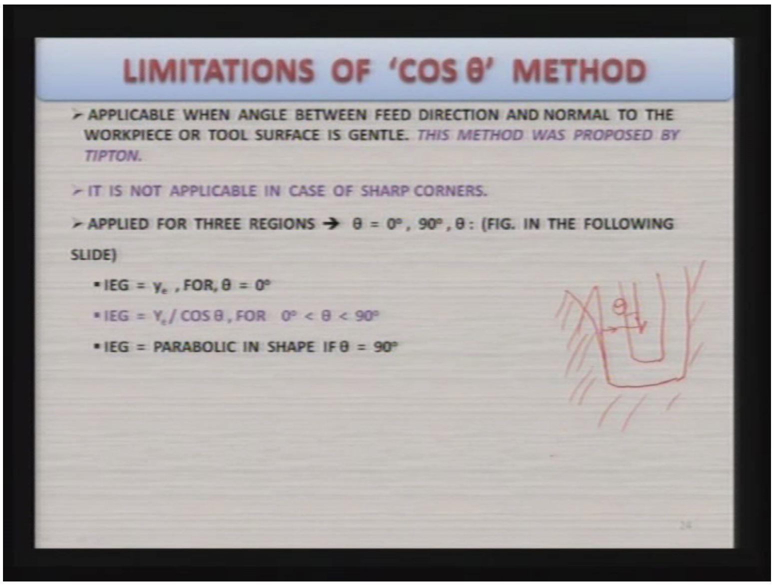

And this shape we have discussed while discussing theory of electrochemical machining also. So cos theta theory is not applicable to regions shown by dash,I will show you in the next slide. Assumption here is that current flow lines are straight, parallel and normal to the work, tool or both surfaces. That means Ohm's law is being followed. It assumes tool and workpiece surfaces are uniform in Z direction. That simply means that only 2D problems are solved by this particular method.

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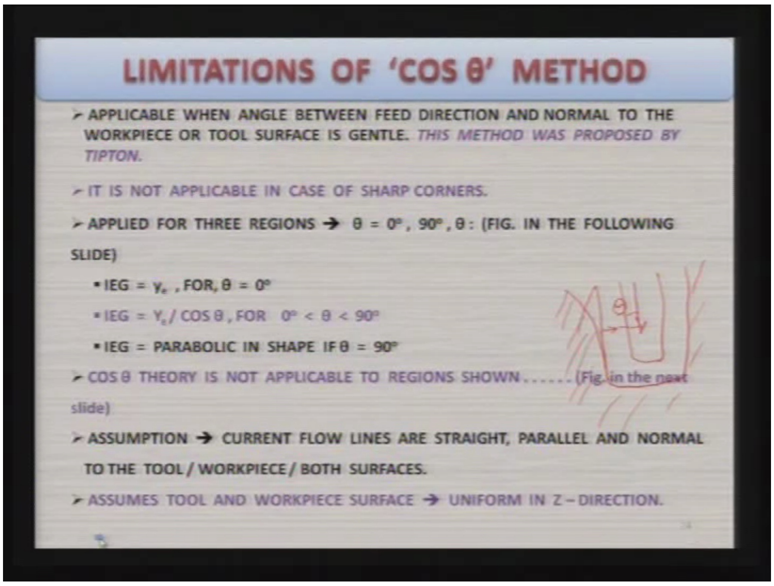

Let workpiece surface be expressed as Y is equal to f x whereY is a function of x coordinate. Now point A on workpiece transferred to point B on the tool. Let us see it here.These are the three zones which I mentioned in the earlier slide that one is the here whereinterelectrode gap is equal to Y e, equilibrium gap. And this is thetool and this is the workpiece and this is the parabolic surface that it is going to get if the normal to the workpiece surface and the feed direction theyare in the same direction.

And then if this theta is less than 90 degrees, here it is 90 degrees, if theta is less than 90 degrees then you are going to get interelectrode gap or as Y e over cos theta. That is what shown over here.

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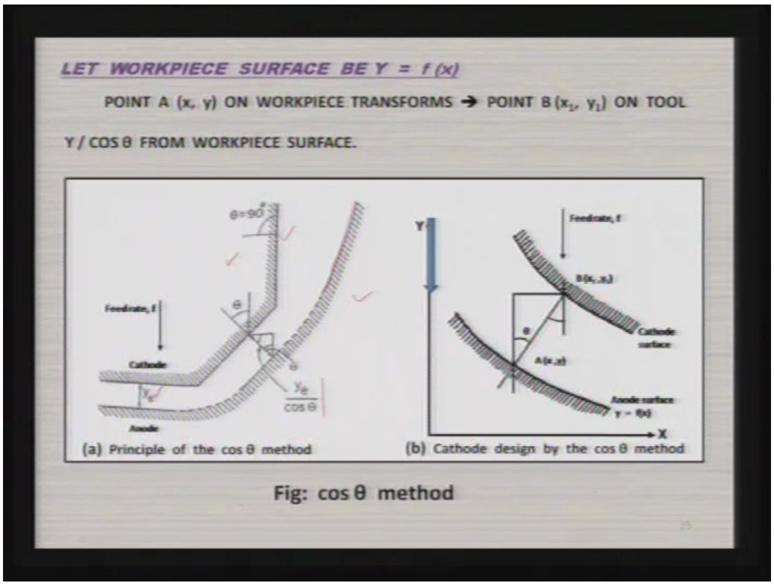

Now let us see on the right side what it says that point A on workpiece transform to point B on the tool. This simply means suppose this is the workpiece A and we are designing here the shape of the tool based on the shape of the workpiece that we want. So it says that for this particular condition point A is transformed as the pointB. That means point B will give theworkpiece surface as point A.

Now here the coordinates of A are x y and coordinates of B are x 1 y 1 and y is increasing in this particular direction and x is increasing in this particular direction. This is the point to be taken care of which is shown over here by the feed direction.

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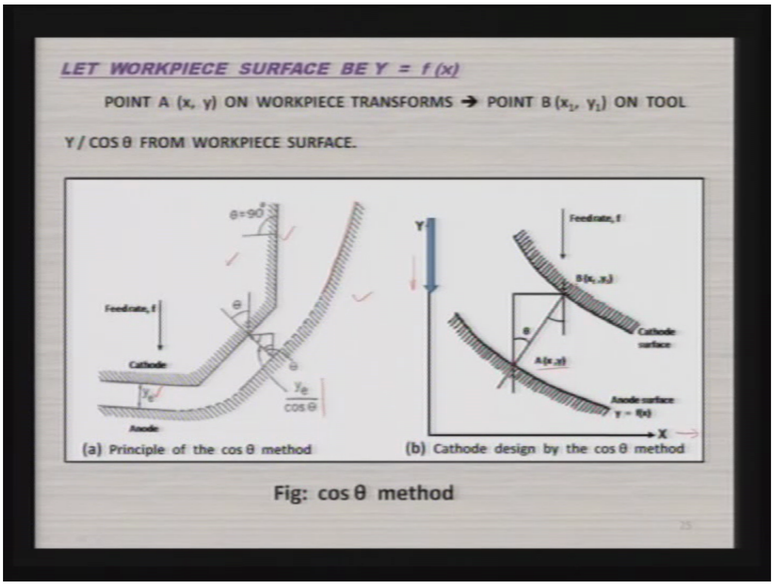

So this we have to keep in mind while discussing this particular method. So here I have reproduced the same figure. You can see y minus y 1, so this is the y and y minus y 1 becomes A B cos theta.A B is this particular line. A is here, B is here. So A B cos theta becomes this particular interelectrode gap, equilibrium gap A B cos theta and A B is nothing but Y e over cos theta into cos theta, so you get Y e.

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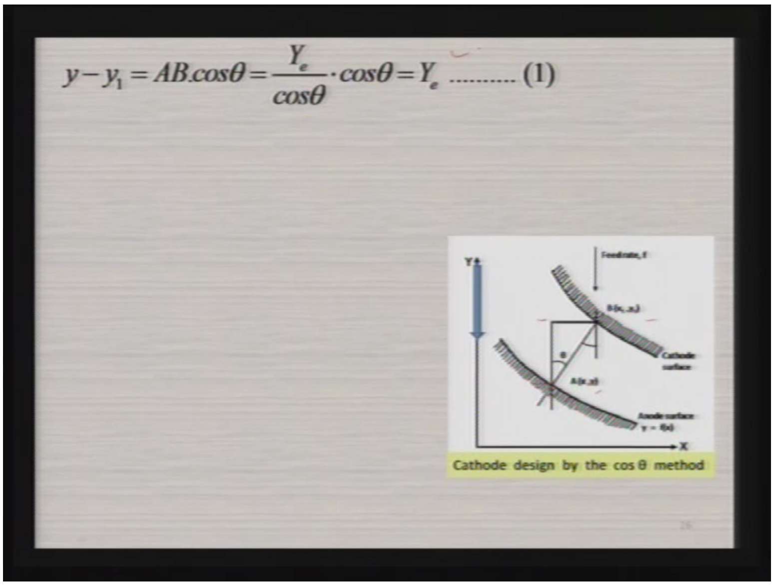

Same way x 1 minus x will become A B sin theta that is this one, A B sin theta.And A B we know Y e over cos theta multiplied by sin theta,so we get Y e over tan theta. And we know that any curved surface on y x axis d y over d x is given by tan theta, that is shown over here. D y over d x that is given by tan theta. So we can write y is equal to y 1 plus y e from the equation 1 that is this one.

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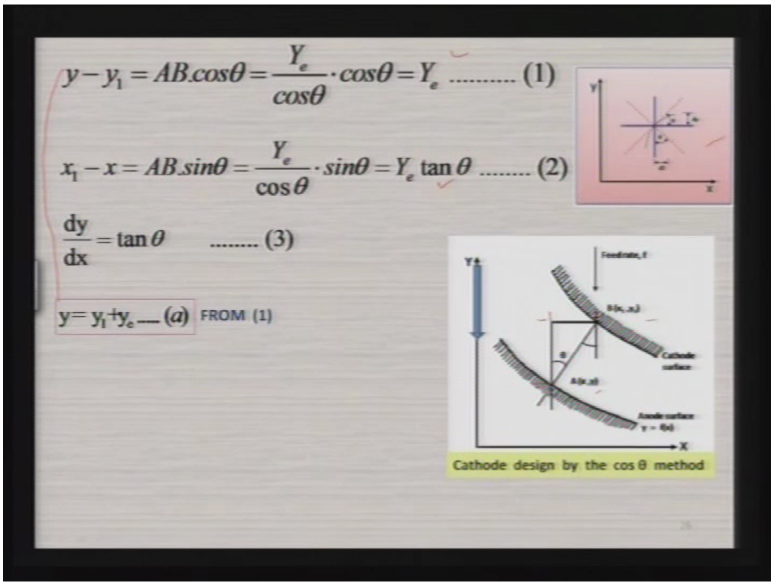

Now we can also write from equation 2 that x 1 is equal to this one. This equation can also be written as x 1 is equal to x plus y e tan theta and tan theta can be replaced by d y over d x. So that is given over here. So x 1 becomes x plus y e, d y over d x. And we know as we have in the beginning said thaty is a function of coordinate x. So we can assume a particular profile of the workpiece.

Now so we can write down herethis equation y e is plus y 1 that is this equation can be written as y e plus y 1 is equal to f function of xthat we can write from this equation like this, x 1 minus y e, d y over d x. So this is the equation 5 we obtained from these equations.

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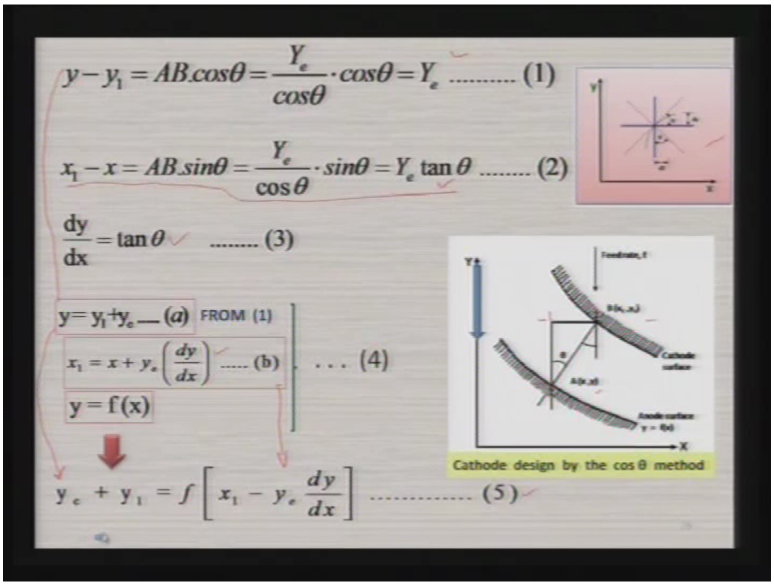

Now let us assume suppose the workpiece surface can be approximated by a series of parabolic arcs. Y is equal to a plus b x plus c x square.

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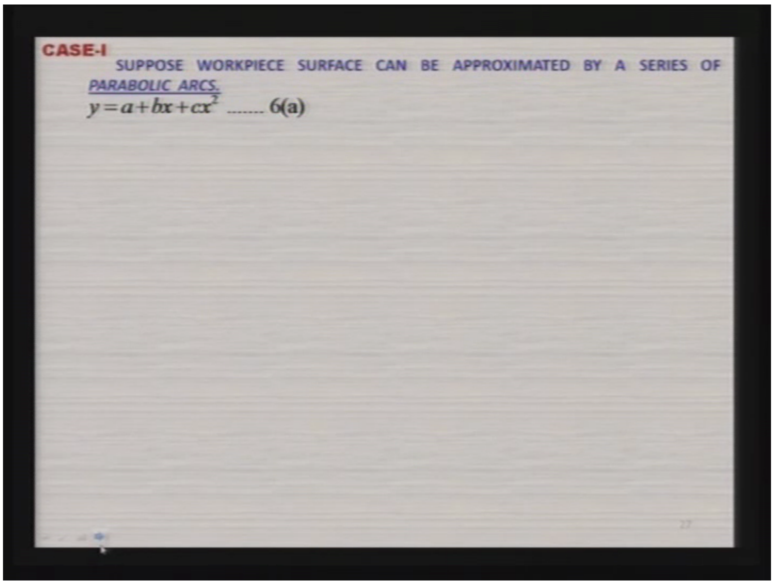

Okay.