Advanced Machining Processes
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Week - 05
Lecture - 12
Electrochemical Machining-V

Hello, and welcome back to this Microsystems for Advanced Manufacturing Processes. A brief review of the previous lecture, what we had tried to do last time was to design the electrolyte velocity and pressure between electrodes during an ECM operation. And we saw that the velocity is actually limited by the fact that the amount of heat that is translated by the electrical power coming into the electrolyte is carried away assuming that there is no conductance across the tool workpiece surface. And the velocity should be designed in a manner so that the overall temperature of the electrolyte does not cross the boiling point. Also, what is important is that the velocity is also limited by the pressure scale where the pressure comes due to 2 factors. One is the inertial component which is relatively a lower term particularly because of creepy flows or you know low Reynolds number flows which are executed in the small equilibrium gap that is in question.

And so therefore, the pressure component given by the surface forces, the viscous forces have to be matched with the ultimate yield stress of the material on one side. So, that is what limits the velocity, the design velocity of the electrolyte. So, what augments the velocity is the fact that the temperature should not go below the boiling point. And what limits the velocity is the fact that the pressure which is generated because of the viscous effect of this velocity should not go above the ultimate yield stress of the material.

So, we also sort of tried to investigate various effects of the heat and hydrogen generation on ECM process between the electrodes on the electrolyte. And we were looking at some of the causes of surface finish due to the ECM operation including selective dissolution, sporadic breakdown of anodic film, flow separation, formulation of eddies, evolution of hydrogen gas so on so forth. So, we had already seen how 2 phases in an alloy A and B with different dissolution potentials would have a self-roughening effect as opposed to the general self-levelling effect of an ECM process just because of the fact that the potential of 1 phase may be slightly higher over the potential of the other phase. So, it was a very interesting case that we analysed where roughness automatically gets generated because of difference in the dissolution potentials of the 2 phases. The other fact is about you know the sporadic breakdown of anodic film which we will just about see today and all these different causes varying from 2 to 4 we will try to evaluate today after going through a brief recap of the selective dissolution potential.

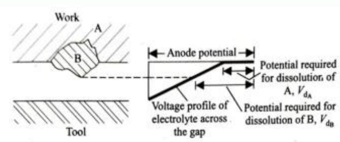
So, here you can see that there are 2 phases B and A where there is a difference in the dissolution potential V dA, dissolution potential of A is lower in comparison to V dB and therefore, there is a self-roughning where the B phase only gets dissolved when it hits this particular plane. This is just for the sake of repetition that I am doing. So, if we really compare both the cases. So, the electric field which is also proportional to the current density because electric field times the conductivity becomes the current density. Actually, if you look at this gap is y between tool and the surface A and the available dissolution potential for A is V dA.

So, V minus V dA by y is the electric field across this particular gap if we consider V dA potential or dissolution potential of A and if we consider that of   V then the gap reduces to y minus delta thereby the field becomes equal to V minus V dB by y minus delta. And typically, these electric field should be similar to each other because they are with 2 equipotential surfaces in question and there should not be really much variation at least at the flat phase of this B surface and the flat phase of the A surface. We are not considering corners here where the field lines would automatically coil and would produce a considerably varied density here. So, this is how the electric fields of the A part of the surface and the B part of the surface would compare. And from this expression, we really can get a value for this delta.

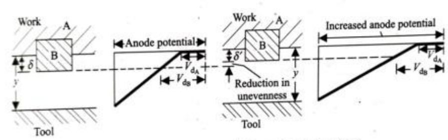
So, the delta thus can be found out by this expression 1 minus V minus V dB by V minus V dA times of y. Just say, algebraic manipulation from this particular equation here and so, you can really find out what is the surface roughness if you knew the dissolution potentials of the phase A and B and you are aware of the gap when the 2 surfaces in equilibrium. So, this can be the equilibrium gap. So, that is what selective dissolution would mean. The other very interesting factor which affects the surface roughness is the sporadic breakdown of anodic film.

Selective dissolution

- When the potential gradient is higher, the unevenness is less.
- Figure (b) shows two situations with different potential gradients, the other parameters remaining the same.
- It is obvious from this figure that the height of the projection of a grain of the constituent B is less when the potential gradient is higher.
- An approximate expression of the projection height can also be derived as below:



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



(b) Reduction in unevenness with increase in anode potential

comparing both electric fields

$$\frac{V - V_{dA}}{y} = \frac{V - V_{dB}}{(y - \delta)} \quad \text{where } V \text{ is the anode potential}$$

$$\Rightarrow \delta = \left(1 - \frac{V - V_{dB}}{V - V_{dA}}\right) y.$$

Let us see how it happens. So, the main reason for the sporadic breakdown of the anodic film is the gradual fall in the potential difference between the work surface and the electrolyte in the region away from the machining area. Obviously, because let us say this is the electrode here and there is a certain field which is created in this particular gap which is represented by these lines of forces. So, fields slightly curl around the corners, and it is also reasonable to assume that this field here can extend farther away from the tool surface as well. Because field is actually as it goes away from the tool it varies as a or it falls down as a inverse square of the distance r.

So, the field varies as a square of distance from the electrode onwards towards the remaining part of the surface. But there does exist a field. So, for example, if this is the particular potential function which is available to this surface it slowly goes down as the distance increases as a square of r.

But there does exist some value here like for example, at the point P1 it may be VP1 at the point P2 it may be VP2 so on so forth. So, there are some finitely existing values of the fields which escape even though the tool is placed at some distance away from the surface.

Sporadic Breakdown of Anodic Film

- The main reason for the sporadic breakdown of the anodic film is the gradual fall in potential difference between the work surface and the electrolyte in the region away from the machining area.
- The figure on the right shows the variation of the surface potential of the anode in this region. Here, till the point P1 the potential is enough to cause the dissolution of all the phases.

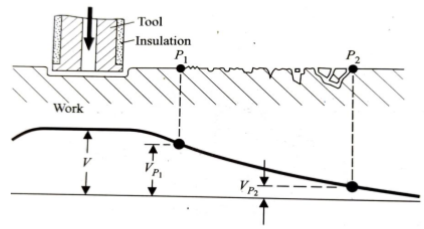


Fig. Surface unevenness due to sporadic breakdown of anode

- At P1, the avialable potential falls below the dissolution potential of one phase, and so the anode stops dissolving.
- Beyond P1 the anode surface potential continues to drop and an increasing number of phases stop dissolving, resulting in an uneven surface.
- Ultimately when only a few phases remain active and dissolve, a concentration of the electric field results since the active phases occupy a portion of the anode surface.
- This field concentration causes these phases to dissolve very rapidly, forming deep pits.
- Beyond the point P2 the anode surface potential falls to such a low a value that no dissolution takes place.

This is all covered with electrolyte because naturally the electrolyte flows around this gap and flows over the surface and everywhere else and it flows into the tool from this entry point here in the centre. So, supposing if there is an alloy in this particular region and particularly in the region P1 there may be a phase where the potential which is available here is greater than the dissolution potential of that particular phase available at P1. So, there would be selective dissolution at P1 by obviously, by the reasons shown before. And so, dissolution potential of 1 phase would ensure that only 1 phase comes out. So, you can see here this roughness which is created is because maybe 1 of the phases here in this particular zone or in this particular zone may be had the available potential VP1 to be greater than their own dissolution potential.

So, you can call it Vd of a phase may be at P1 and that came off and because of coming off, you have this roughness or tethered surface which results because of that. Obviously, if there are corners and bends which are represented by the selective removal of 1 of the phases. These corners would further lead to the coiling and the curling of the fields and so the line density in these points would increase tremendously and because of that there would be more dissolution which is available because of increased line density. So, the field concentration causes the phases to dissolve very rapidly further because of selective dissolution and formulation of these corners, the sharp corners. So, certainly, this is something which is highly undesirable for an ECM process, and this can be 1 of the main mechanisms for introducing surface roughness in an ECM although the ECM is supposed to be a self-levelling and a very smooth operation.

The other important factor which is responsible for the creation of surface roughness is the formulation of eddies and the separation of the flows. If supposing there is a rough surface which has been created because of the selective dissolution of the field due to an electrochemical tool, it is always proper to assume that there may be a case of local circulation particularly when the electrolyte is flown in both the directions like this. So, the electrolyte flows over the surface and there are these cases of local circulations which would exist over such crevices and corners. Meaning thereby that there are these eddies and vortices which are created close to these corners because of the surface perturbations which is the surface. It is no longer a plane surface there are selective resolutions because of which there is a lot of this cornering effect, chamfering effect which is present at various points here.

So, these local circulations are a cause for the debris particles which come out of this zone to keep circulating here without going further. And that may change the local conductivity because precipitates are 1 of again the responsible causes for change of the conductivity of the medium electrolyte. And eddies and vortices are something that you really do not want in ECM. The more streamlined operation the ECM would have in terms of electrolyte flow the better it is in terms of surface finish. But the more there is localization of flows and eddies and separation of flows at certain areas there may be local precipitate whirlpools which are formulated which have much more conductivity and therefore, more dissolution and that may create a pitting effect in some of the local zones.

So, a great care needs to be designed to be taken in designing the tool surface particularly. The same thing may happen to the selective dissolution of the tool as well. The surface may turn out to be rough with operations if there is an alloy tool which is used. And one needs to be very careful about these eddies and flow separations. So, this is another third reason for the surface roughness.

Finally, as I already have mentioned before the evolution of hydrogen gas is pretty critical. And if you can consider these tool-workpiece surface supposing the electrolyte starts flowing from this end into the gap at a certain velocity by the time it reaches at the other end here there is always an increase in the temperature. And let us say if hydrogen emanates as bubbles into this electrolyte the concentration local concentration of hydrogen in the electrolyte increases because of which there is a change in conductivity. And the hydrogen may be concentration may be lesser here, but by the time this goes ahead, and the hydrogen gets carried away more and more hydrogen packs off you know to this electrolyte. So, hydrogen concentration is greater here there is a density gradient which is created for the gas which is dissolved.

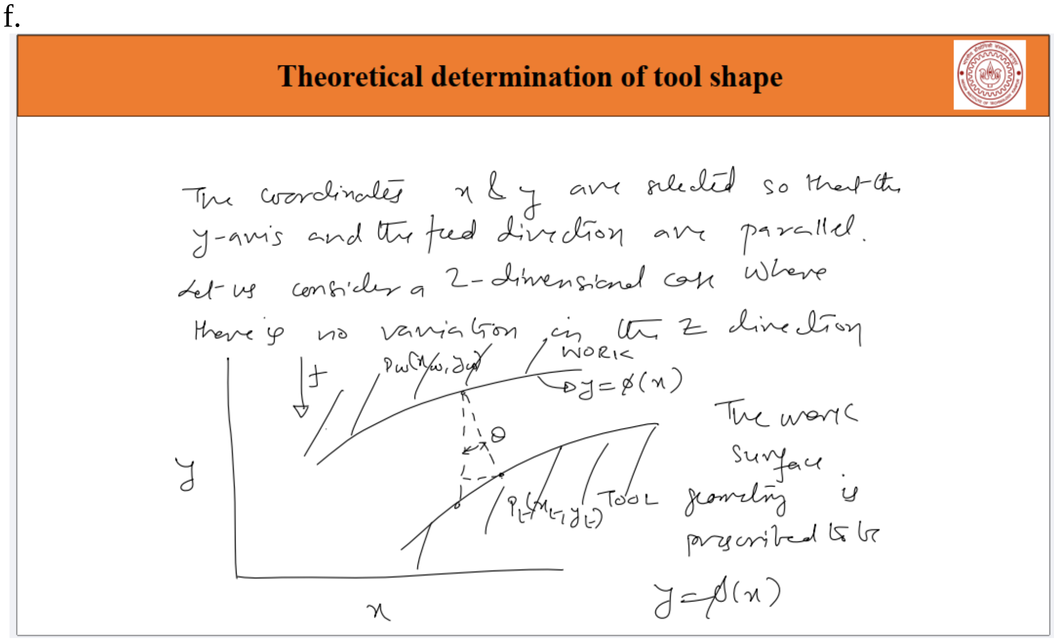
And therefore, the conductivity is varied across the length of the workpiece even. And because of that again there is a tendency of the conductivity to vary and also simultaneously the current density to vary. So, at one point where the current density may be more because of reduced hydrogen may have a slightly greater dissolution rate in comparison to the point where the current density is lower. And so therefore, again this can also result in some kind of roughness where some points may be moved or dissolved in a greater pace in comparison to the other points. So, there are 2 major aspects when we talk about ECM 1 is of course, the tool design and another is the flow design the system of flow you know.

And the tool design is important because of 2 reasons 1 is that the tool shape so desired is exactly the negative replica of the shape that you are wanting to embed or imprint onto a surface that is the basic principle of an ECM operation. So, particularly in microsystems technology when we are talking about some embedment some small feature which has to be created on the surface the exact contouring of the tool is very much needed. So, that the exact negative replica can be produced on the surface at that particular scale. And the other reason is that you know the electrolyte flow that the tool would have would really be creating a lot of effects on the overall material removal rate. So, therefore, the way that the electrolyte is flown, the way that the sides of the tool are insulated, the strengths and fixing arrangements of the insulation on to the tool they would be of great concern when we want to develop a good ECM process.

So, we will look at the first aspect now that is determining a tool shape. So, that the desired shape of the job can be achieved for a micro machining or for a machining condition. And in that respect, I would like to sort of propose a theory where we want to theoretically determine what is the tool shape based on a certain function which is known to be the final shape of the workpiece that you would like to generate using ECM. So, when a desired shape of the machined workpiece surface is known, and we want to somehow map the surface into a tool surface, and which is possible actually theoretically. I will just show you an approach where theoretically you can determine.

And so, the required geometry of the tool surface for a given set of machining conditions can be achieved very fast based on that. And the first thing that we need to know here is that the equilibrium gap between the anode and cathode surfaces can be expressed as ge dash is equal to the conductivity times of atomic weight of the material which is dissolved times of the voltage minus over-voltage potential which is available for the electrochemical process divided by the density of the material to be removed the lowest valency state of the material. And some other parameters like the Faraday constant, the feed rate supposing it is going at an angle theta. So, if theta is the inclination angle of the tool wrt with respect to the workpiece this can be called f cos theta. So, that is how you find out the equilibrium gap as we have seen before.

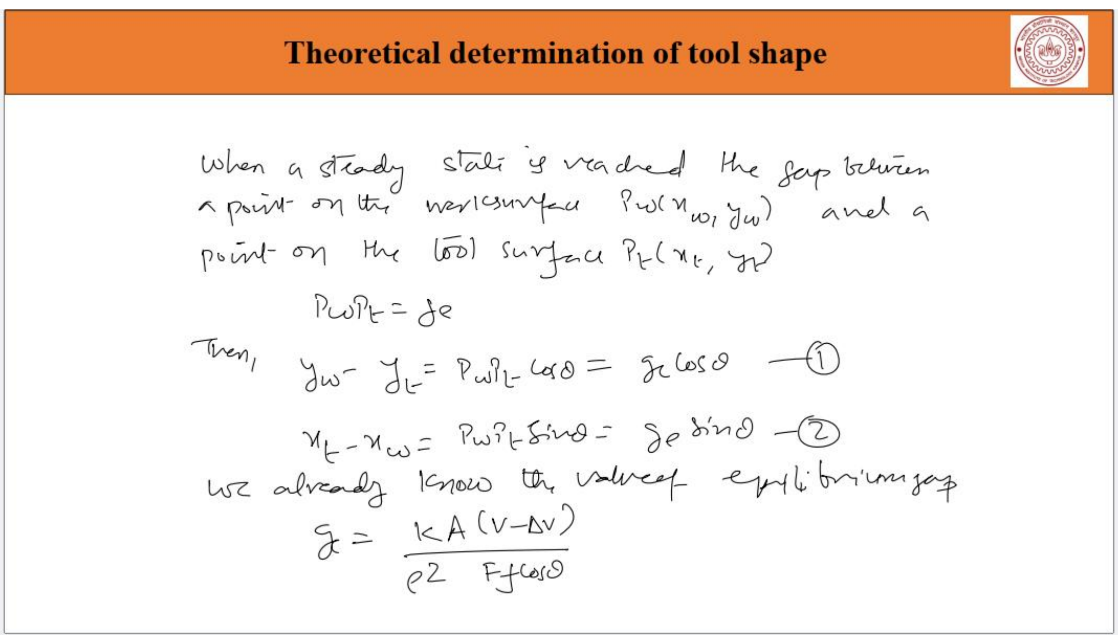
And let us actually now assume a certain random tool surface and workpiece surface as represented here. Let us say this is the x y plane and we are talking about a certain shape here of the workpiece. Let us say this is the shape of the workpiece which we are kind of aware what this shape would result or what would be the final shape which is desirable. So, this is given by the design team for the component. And we also are aware that this workpiece is being fed towards the tool at a feed rate of f.



And this is automatically the shape of the tool which is generated by the requirement of this workpiece surface which is known to you. So, if we select the, you know in the 2 dimensional sense a point here on the workpiece surface. Let us say Pw which is again a function of xw and yw. And try to map a corresponding point on this particular surface, the tool surface Pt xt yt. We should be able to somehow find out the functional relationship that exists between this point and this point given the constraints or conditions of the ECM process like the feed, the direction of the feed so on so forth.

So, the feed as you know is in this direction meaning thereby that if you look at a tangent to this particular point it would assume to have moved at an angle theta with respect to the direction of the feed. So, we are already aware of the workpiece surface. So, let it be defined by a function y equal to phi x. So, there is a relationship between these 2 coordinates x and y. And it is a sort of non-parametric representation of the surface y equal to phi x.

And we want to determine what this would mean when it gets translated into the tool surface to provide the tool shape. So, a point on the workpiece let us say this xw yw point Pw and the point on the tool surface be given by a steady state equilibrium gap ge where ge has already been calculated before we know what ge is. It is function of many things like where the equilibrium gap is a function of many things as you know the atomic weight, the available voltage, which is there, the conductivity, the density of the workpiece which material may be iron or copper whatever is being removed or machined so on so forth. So, if you look at the positional relationship between these coordinates xw yw and xt yt. So, the xt is displaced forward displaced from the xw by an amount ge sin theta where ge is this gap here between Pw and Pt.

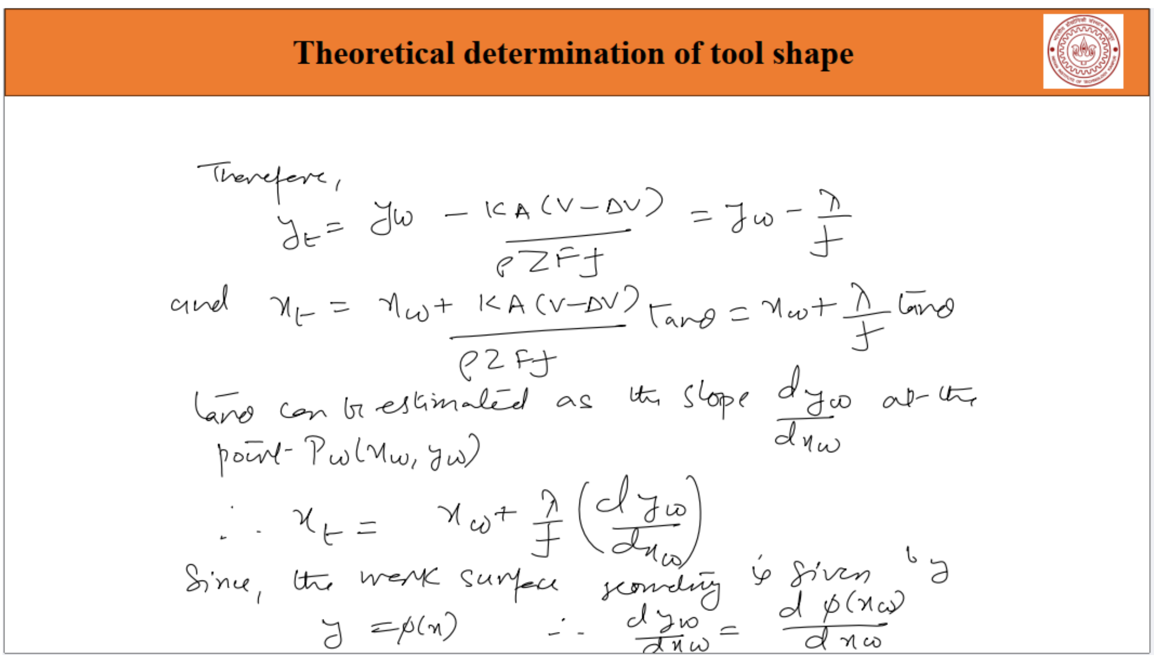


And if you compare the position coordinates yw and yt, the yw is forward displaced from the yt by a gap ge cos theta. Meaning thereby we have 2 equations here xt minus xw which is ge sin theta. Let us call it equation 1 and yt minus or yw minus yt which is ge cos theta let us call it equation 2. We already know the value of ge. ge is actually K A V minus delta V divided by rho

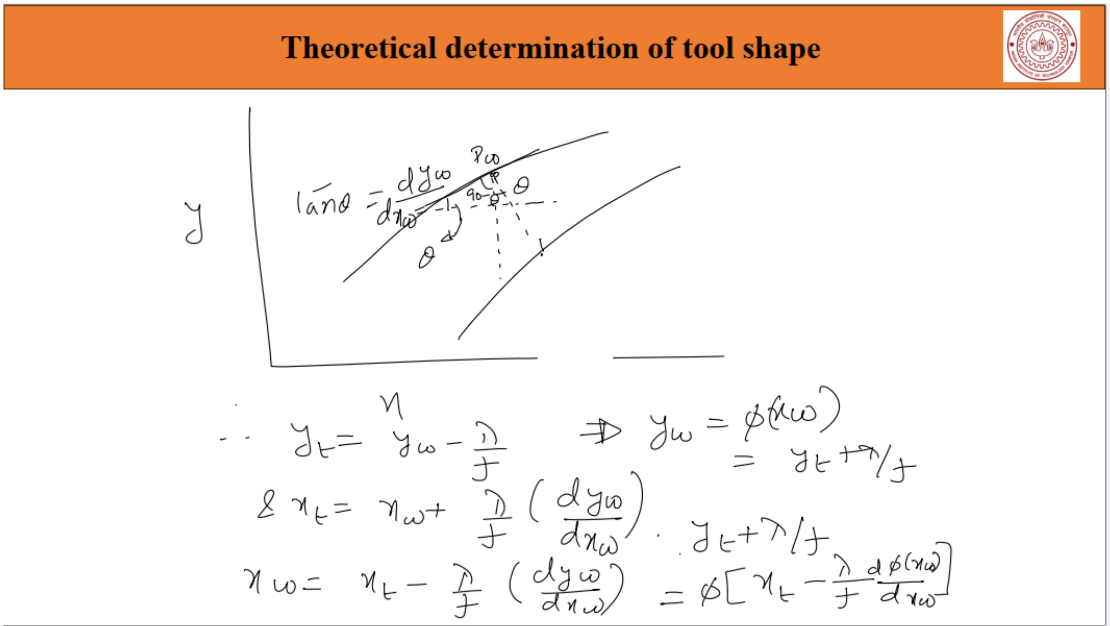
Z F f cos theta where we assume that the surface is moving along this line Pw Pt towards the tool surface at an angle theta.

So, these are very generic form of a surface of a certain functional shape to be replicated in terms of the tool surface. So, we are mapping from the workpiece surface to the tool surface by using simple mathematics. So, here let us say if we wanted to just write everything in terms of the new value of ge that we had obtained. So, yt becomes equal to yw minus K A V minus delta-V by rho Z F times of small f the cos theta goes away which is actually nothing but yw minus lambda by f. If you may remember this term here was actually equivalent to the lambda when we did the kinematics and dynamics of the ECM process.

And the xt here can be related to the xw by the term K A V minus delta V divided by rho Z F times of f times of tan theta right because this was cos theta and then the xw was displaced the xw was displaced backwards from the xt by the term g sin theta. So, therefore, if you just convert everything here in terms of lambda you can get xw plus lambda by f tan theta. So, we make this equation 3 and this equation 4. So, you already know that there is a functional relationship between the xw and the yw which exists. So, yw is function phi of xw in the workpiece side and tan theta can be estimated as the slope dyw by d xw at the point Pw xw yw where xt equals xw plus lambda by f times of tan theta which is dyw by d xw.



Since the work surface geometry is given by this relationship the dyw by xw actually equals to d phi xw by d xw. So, little bit looking at a little more fundamental way if this is the surface that we are trying to interrogate which is actually the workpiece surface and this is the point Pw that we are trying to use to find the or trying to map into the tool surface. At this particular point, the tangent which happens here is really in this direction right. This is the tangent at this point and we already know that the way that the surface would move is at an angle of theta with respect to the vertical direction. So, if I were to just find out whether tan theta is d w by dyw by d xw here you see if this is theta this becomes 90 minus theta and this becomes theta.

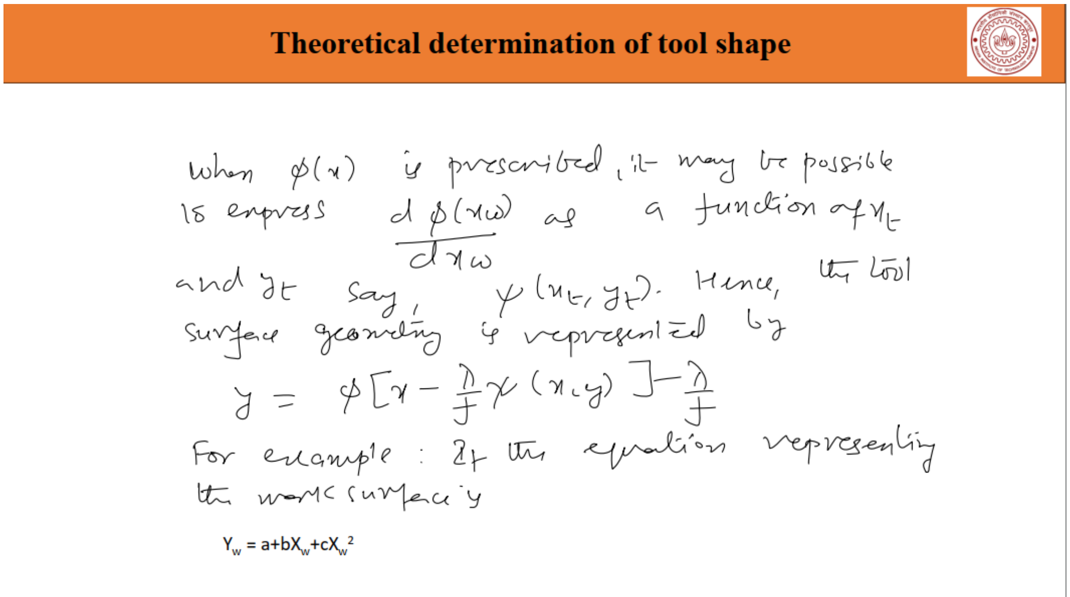


So, this tan theta is actually dyw by d xw right. And so, therefore, we can safely assume that g tan theta can be expressed as xt equal to xw plus lambda by f dyw by d xw right tan theta this is the g tan theta. Similarly, we already have the equation 3 as plotted earlier where we are trying to say yw is a function of xw is nothing but yt plus lambda by f. So, if this functional relationship exists between the yw and the xw and we have a relationship of yw with yt and xt with xw. We can actually write down that yw which is yt plus lambda by f is functionally connected in the same manner to xw value here which is xt minus lambda by f times of dyw by d xw.

So, if you really know the slope here then it should not be a problem to map the xw yw to xt yt as available here in this functional relationship. So, therefore, the whole essence that is involved in all this is to somehow be able to write this dyw by d xw meaning thereby this is d phi xw by d xw in terms of xt and yt. So, then this whole equation can be converted into all xt's and yt's and the function there in which would be plotted would be a map of xw into yw, xw yw into xt yt. So, therefore, the overall representation of a tool surface provided we already have a functional relationship between the workpiece surfaces yw is phi of xw is given by phi x minus lambda by f some function in terms of xt and yt of xy these are all tool sides minus lambda by f. So, this is the whole mapping equation from the workpiece surface to the tool surface.

Now, supposing if we assume a functional relationship of the time y equal to let us say a plus bx plus cx square for the workpiece surface and we want to find out what is the mapping into the tool surface. As we already know the map is provided by yt equal to phi xt minus lambda by f some function of xt yt which is nothing, but the slope dyw by d xw minus of lambda by f. So, let us try to determine this and try to find out how this is related to some function of xt and yt. So, we already know that dyw by d xw is actually equal to b plus cxw right and we are aware that the xw or xt actually is equal to xw plus lambda by f times of dyw by d xw which means it is equal to xw plus lambda by f times of b plus cxw. So, therefore, we can either substitute the value of xw in this equation to find out what xt would be in terms or what this would be in terms of xt standalone.

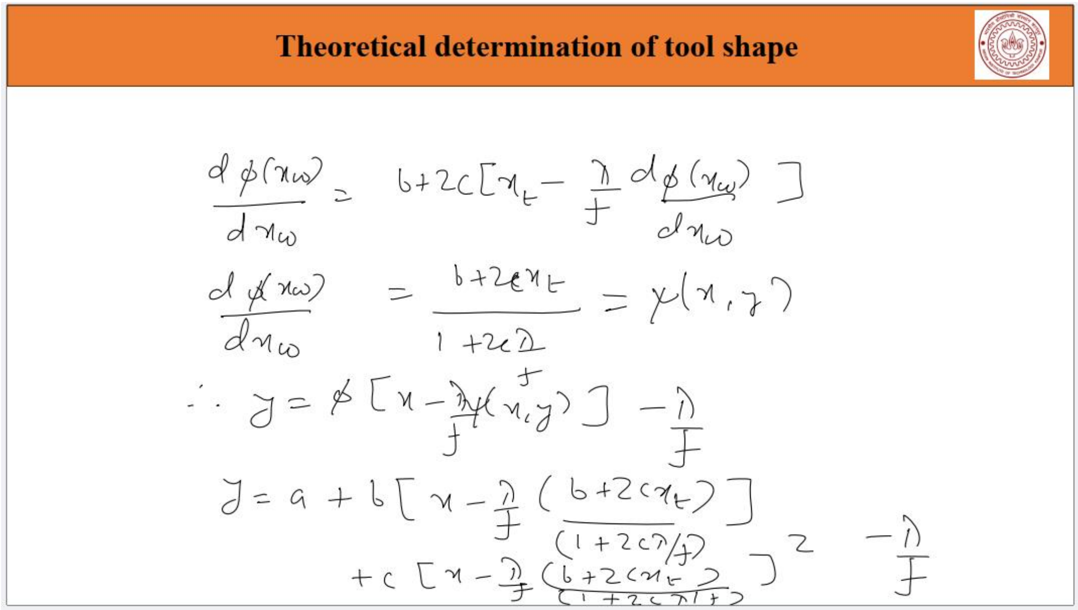
So, let us suppose that there is a function y on the workpiece surface which is related to x on the tool surface by the quadratic equation a plus b xw plus cxw square. Now, we want to find out how to map it from the tool from the workpiece surface into the tool surface. So, we first find out what dyw by d xw is let this be equal to some value I right and this is actually can be represented as b plus twice cxw. We already from our previous formulation for xt and xw are very well aware that xt is related to xw by the relation xt equal to xw plus lambda by f times of dyw by d xw. So, the whole effort somehow should be to actually convert this whole thing in terms of tools I mean tool side coordinates xt and yt.



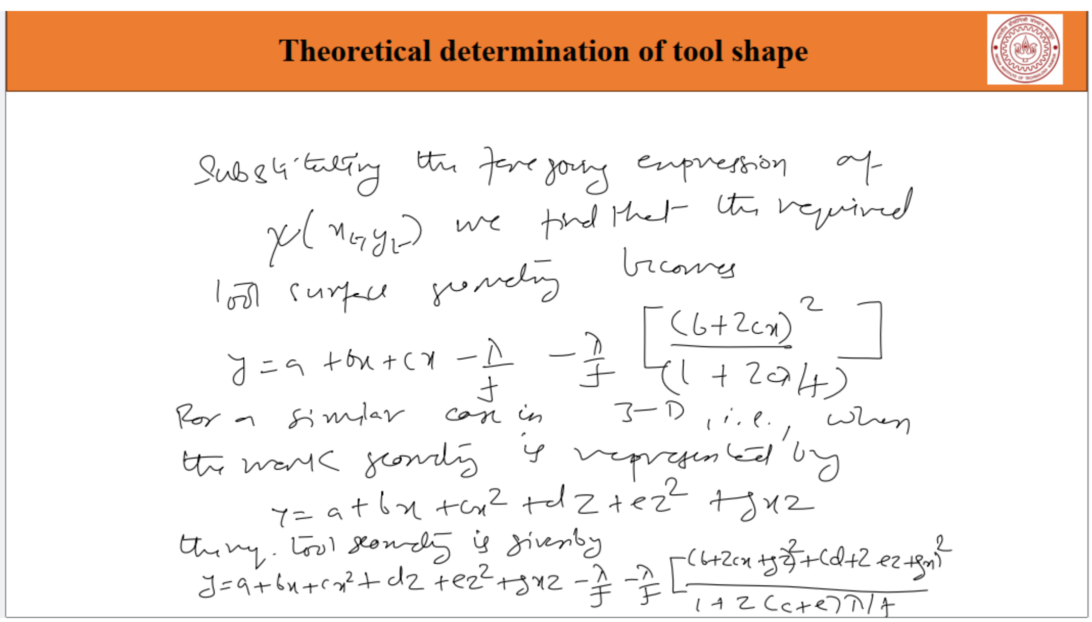
So, we can write this as xw plus lambda by f times of I. Remember we have taken this d w dyw by d xw as I and so very easily we can see here that if supposing we write xw in terms of I it becomes twice cxw is I minus b or xw becomes equal to I by 2c minus b by 2c right. And if we put this value here we get the value of xt as xt equal to I by 2c minus b by 2c plus lambda by f times of I. Obviously, this would mean that if we multiply the whole thing by 2c we have 2c xt equals I minus b plus lambda by f times of 2c times of I or the value of I in terms of all xt comes out to be b plus twice cx t divided by 1 plus twice c lambda by f.

So, that is how you can formulate d xw by dyw by d xw. So, if I were to represent this I back into the formulation for y you already know that yt in this particular case is related to the xt as yt equal to phi function phi of xt minus lambda by f times of I minus lambda by f. And this really means that this coefficient xt becomes equal to xt minus lambda by f times of the I value that has been deciphered before as b plus twice cx t divided by 1 plus twice c lambda by f. So, minus lambda by f. And then of course, you already know that yt therefore, is written as a function of phi here which means it is a plus b times of this argument which has been formulated. So, we are mapping now the function plus c times of xt minus lambda by f b plus twice cx t divided by 1 plus twice c lambda by f square minus lambda by f.

In other words, if you simplify this expression here this would be coming out as a plus b xt plus cx t minus lambda by f minus lambda by f times of b plus twice cx t square divided by 1 plus twice



c lambda by f. So, that is how you can map a quadratic function on the workpiece surface to a tool surface. So, in this is just a generic representation of if suppose the surface is defined by a function what would happen. Now, if you look at the theory that is associated with the CAD designing process. The CAD designing also looks into local functions like this and tries to fit some of the formulations like Bezier curve or let us say you know spline fits between either 2 points or many points.



And this somehow has to be topologically mapped into the corresponding negative workpiece surface. So, the best way to do it is to keep in mind the equilibrium gap, keep in mind that the surface is going at a certain angle to this you know tool surface. And topologically map it by a function mapping from of the xy on the workpiece surface to the tool surface. For a certain simple equation like a quadratic equation, it has been demonstrated here. But then if there is a complex function which is used for fitting contours, or you know complex contours or topologies that function can also be mapped.

So, the idea is that the whole design that is there of the workpiece as per the requirement of the workpiece have to be designed in bits and pieces. And this each can be represented by either a group of functions or just a function or some of them are just linear. And then you simply map those points on to the corresponding tool surface and obtain that way the tool surface. So, the tool design can be arrived at theoretically. So, that is a pretty good aspect of the ECM process that you can actually develop a tool surface exact negative of what is there on a complex design of the requirement of the workpiece.

Numerical problem

The geometry of a work-piece surface with single curvature is given by the equation, $y = 10 + 0.3x - 0.05x^2$, where x and y are in cm. The process data are Applied potential = 15V, Overvoltage = 0.67 V, Feed velocity = 0.75 mm/ min. (given to the work in the –y direction), work material = copper, electrolyte conductivity = 0.2 Ω^{-1} cm $^{-1}$. Determine the equation of the required tool surface geometry.

We find that for copper Z=1, A = 63.57, and ρ = 8.96 g/cm^3. The value of F is 96,500 coulombs.

Feed velocity f = 0.00125 cm/sec.

We find λ as

$$\lambda = \frac{KA(V - \Delta V)}{\rho Z F} = \frac{0.2 \times 63.57 \times (15 - 0.67)}{8.96 \times 1 \times 96{,}500} \text{ cm}^2/\text{s}$$

$$= 2.11 \times 10^{-4} \text{ cm}^2/\text{sec}.$$

Thus,

$$\frac{D}{f} = \frac{2.11 \times 10^{-4}}{125 \times 10^{-4}} \text{ cm} = 0.169 \text{ cm}$$

So, with this in mind we just try to do a numerical problem, try to solve the numerical problem here as you see here the geometry of a workpiece with single curvature is given. And this geometry is given by the equation y plus 10, y is equal to 10 plus 0.3 x minus 0.05 x square. You know that these are values in centimetres and the process data is that the applied potential is 15 volts over voltage which is needed is 0.67 volts. The feed velocity of 0.75 millimetres per minute and is given in typically the minus y direction. And the work material is copper electrolyte conductivity is about 0.2 ohm inverse centimetre inverse and we have to determine the equation of the required tool surface geometry. So, once again I would like for the sake of repetition to reiterate this point that a CAD geometry is a complex system which is created out of many such functions which are standard functions either representing, represented by non-parametric or parametric equations. Some linear connections between the many complex functions and then some fits.

The fits are because sometimes you need to really express very closely a complex topology and there is no other choice, but to force fit a sort of function like maybe the Bezier function or the B-spline function or just a normal cubic Hermitian function polynomial to in a manner that by knowing just by slopes on both ends or the different or maybe 1 or 2 points or maybe all the points you can try to develop a fit that way. So, that fit then the standard functions which are already there representing the surface and the linear functions may very safely be mapped topologically to develop the exact negative replica. So, the purpose of all these theoretical analysis is to ultimately arrive at a tool surface given a split up CAD model of a workpiece surface. So, let us look at this, this is a very simplistic case you have already defined the single curvature of the equation given by this quadratic form and we want to find out that for copper we assume let us say a monovalent state which is coming out. So, we are assuming Z to be plus 1 the atomic weight of copper the work material is 3.757 grams and the rho here the density function here is actually 8.96 grams per centimetre cube and the value of F here is 96500 coulombs. And we want to find out provided the feed is given to be 0.75 millimetres per minute or in other words 0.00125 centimetres per second. We want to find out what the g value is which is lambda by f and lambda can be represented as K A V minus delta V divided by rho Z F where these terms are all as you have done many times meaning their own you know they are encompassing their own definitions.

So, the K is the conductivity is given to be for the electrolyte 0.2 ohm inverse centimetre inverse. So, we have 0.2 times of the atomic weight of copper 63.57 times of the total potential which is available minus the overvoltage which is 15 minus 0.67 divided by the rho value which in this particular case is about 8.96 it is copper times of monovalent state. So, plus 1 times of 96500 coulombs. So, that is how the lambda is and this would come out to be about 2.11 into 10 to the power of minus 4 centimetre square per second.

Of course, the lambda by f can be 2.11 into 10 to the power minus 4 by 12.5 into 10 to the power minus 4 centimetres. This 0.169 centimetre then comes out to be the equilibrium gap ye or ge whatever you may think appropriate, and this gives us a basis of plotting this functional relationship between yw and xw into yt and xt. So, that let us now have a look at the final formulation. So, for the workpiece side you know that phi xw is related to the yw by the equation 10 plus 0.3 xw minus 0.05 xw square and we know that the final tool surface geometry as we have already derived before for a quadratic equation can be represented as yt equal to 10 plus 0.3 times of x minus 0.169 times of 0.3 times of 0.1 x divided by 1 minus 0.1 times of 0.169 minus of 0.05

Contd., Theoretical determination of tool shape

Now, $\phi(x) = 10 + 0.3x - 0.05x^2$

Finally, the equation of the tool surface geometry is found by using equation

$$y = 10 + 0.3\left[x - 0.169\,\frac{(0.3 - 0.1x)}{1 - 0.1\times 0.169}\right] - 0.05\left[x - 0.169\,\frac{(0.3 - 0.1x)}{1 - 0.1\times 0.169}\right]^2 - 0.169$$

Simplifying this equation we get

$$y = 9.8154 + 0.3157x - 0.0517x^2$$

where both x & y in cm.

times of square of this argument. So, this is that argument value if you may remember which was including the slope and which was you know including the slope in terms of the xt and the yt value this minus 0.05 into the same argument 0.169 into 0.3 minus 0.1 x divided by 1 minus 0.1 times of 0.169 square of that value minus 0.169 which is the lambda by f or the equilibrium gap term in this expression. And so, if you solve all this you get a relationship between the xt and the yt as x yt is a 9.815 times plus 0.315 xt minus 0.051 xt square where both xt and yt are in centimetres. So, basically this is a very good methodology of giving a sort of optimum tool shape for a single curvature which is already given by a quadratic equation for the workpiece shape. So, I think today we are kind of at the end of the lecture we have learnt how to derive some of the very fundamental aspects of velocity of the electrolyte while moving through the gap. And we have also learnt that how critical it is because you know it will essentially be related to the pressure which would be a determinant of the maximum level of the velocity. And on the minimum level of the velocity would be determined by the temperature requirements which would ensure that there is no boiling action. We tried to apply this fundamental problem to see what are the surface finish-related defects which come in an ECM process.

Thereby, we learnt a lot of you know different corollaries of the ECM process which happens like for example, sporadic breakdown of the anodic film or for example, the flow separation of the eddies or the hydrogen gas generation which changes local conductivities and is always a problem with the ECM because the local roughness would tend to change and the local current densities because of that would be higher. And you can have selective dissolution which creates further problems by coiling the electric fields. You can have a case where more hydrogen is generated because of which the conductivity goes up or the flow separation of the eddies thereby meaning the local precipitates can deposited at different places where the local conductivity changes would result in more or less current densities. So, these are some of the very prominent problems which are available with the ECM system and the prominence goes high as you do microsystem fabrication with such ECM processes. We also tried to determine the tool shape where we investigated how you can topologically map one tool surface to other.

The other aspect of tool is the electrolyte flow design which will of course, try to complete in the next lecture because the way that you insulate the tools edges, the way that you create a conduit for the flow of the electrolyte from the tool on to the workpiece zone decides a lot of machining parameters for the electrochemical processes such. And so, I would like to investigate these one by one in the next lecture. Thank you.