Computer Numerical Control of Machine Tools and Processes
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Lecture 16
3D Machining Basic Conscepts

Welcome viewers to the 16th lecture in the open online course "Computer numerical control CNC of machine tools and processes". So this time we are going to deal with completely new topic, 3D machining Basic concepts. Till now we have discussed about CNC programming, interpolation, etc, now this is 3-D machining.

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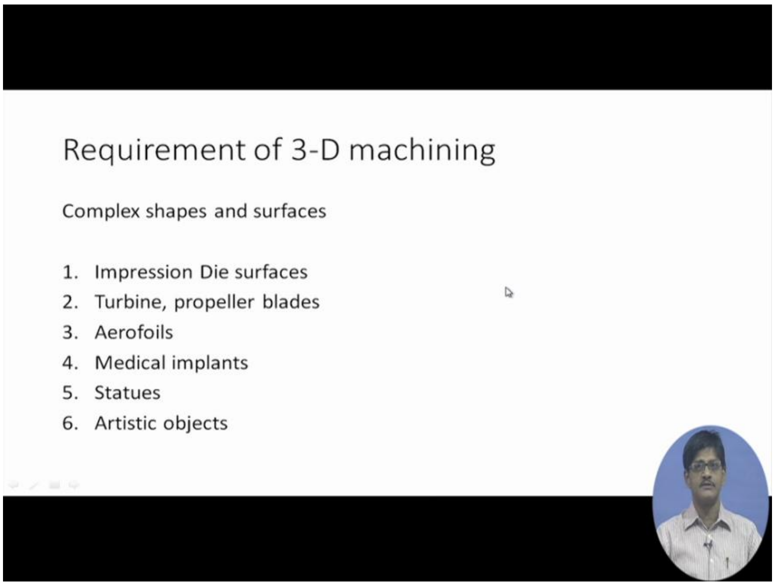

First of all why do we require 3-dimensional machining and what is 3-dimensional machining after all. 3-dimensional machining essentially involves 3-dimensional movement of the cutter okay. So it is not simply the cutter moving around in 2 dimensions and cutting out some two-dimensional profile out of some say plate like material, et cetera, no, it involves simultaneous 3 axis motion of the cutter. Some examples of some 3D machining applications, generally whenever we have some complex shapes and surfaces to be machined out, we resort to 3-dimensional machining.

For example, we might be having impression of Die surfaces okay, when two dies are coming together and pressing some material to a definite shape, we have impression dies. And in order to machine or in order to manufacture these impression dies, we might have to go for 3-dimensional machining, it is not the only way of getting these dies but this is definitely one of the ways. Then turbine, propeller blades which have complex shapes, these can be manufactured by 3-dimensional machining. Aerofoils that means of any type and medical implants which have irregular shapes, statues, artistic objects, these are just some of the examples where we might be having application of 3-dimensional machining.

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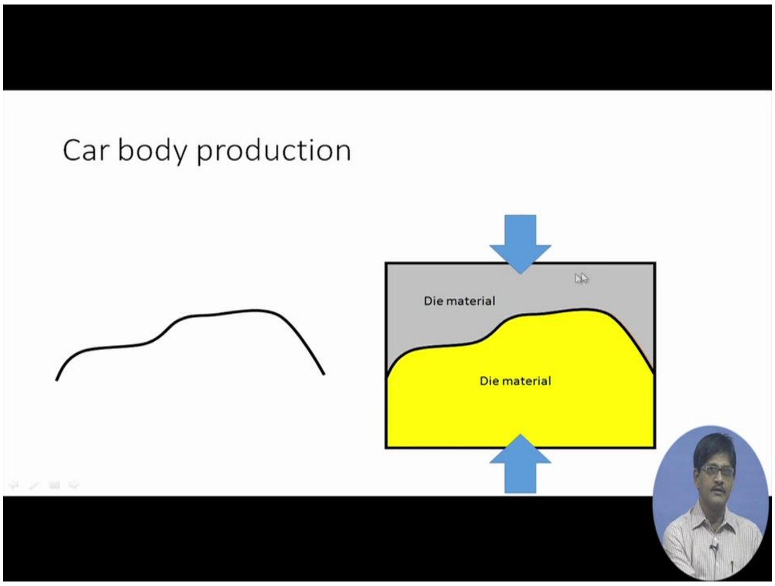

This is an example of a car body production; car body is generally made of sheet metal, deformed in a particular manner which fits some design requirements and also caters to our aesthetic sensors that means it has some aesthetic appeal as well apart from engineering requirements. So in this case there will be 2 dies coming from 2 sides pressing the sheet metal to the required shape and size that we want. These die materials of they can be very hard and the of high strength temperature resistant material and it will be difficult to remove material from a block and update these 2 die faces.

That means if we plan to make these dies with the help of 3-dimensional machining, it is no doubt possible but it will require a lot of expenditure because of tools, tooling expenditure will be high because we have to cut strong, tough materials, tool ware will be high and therefore, expenditure for tooling will be quite high.

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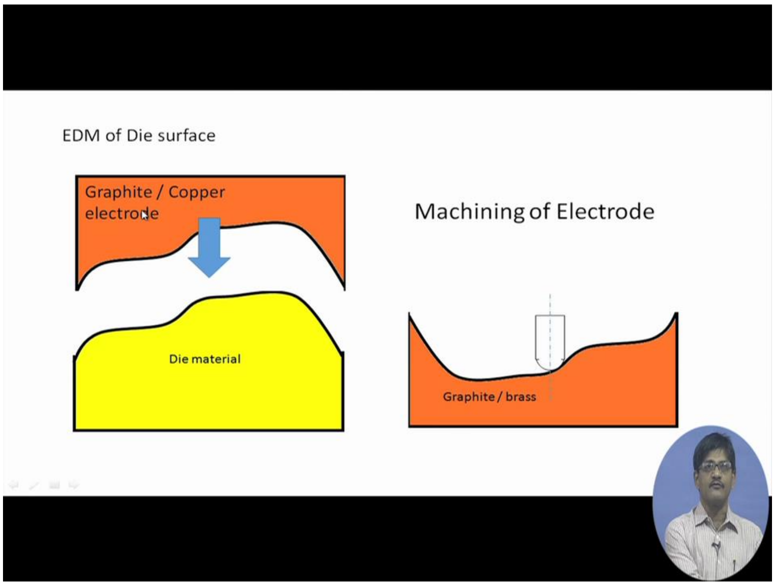

Instead of that, we can have graphite or copper electrodes and we can apply electrical discharge machining in the die sinking mode to remove material and get the die surface I mean die shape provided the die is made of conductive material, which is most commonly so for metals and alloys. So instead of incurring heavy expenditure due to tooling cost in case of 3-dimensional machining by conventional machining. By conventional machining here I mean hard material removing material from a soft softer part with the help of a sharp edge. Instead of using that machining procedure, we are employing electrical discharge machining in the die sinking mode and getting the shape of on the die material with the help of copper or graphite electrodes.

But the problem remains, initially how do we produce this complex 3-dimensional shape on this time now on the electrodes? However, even though die material is very hard and tough and strong, etc, but graphite or copper they are not so. Graphite and copper can be machined very easily, of course there are other issues with these materials, but at least they are machineable without causing that kind of tool ware. So if this is the inverted electrode which was used previously, we can use a ball in the milling cutter on a 3-dimensional machining centre and cut it out, so here the application of 3-dimensional machining is very much required.

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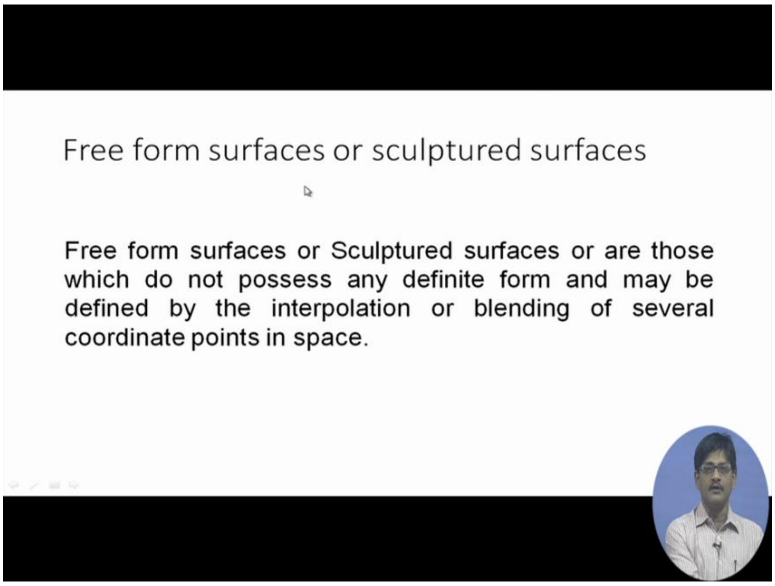

Now whenever we are having a complex surface, before starting to machine it we have to 1st get this complex surface machining planned in our cutting procedure, how are we going to cut it? In that case 1st of all we have to have this surface in some form at least in our minds and then into the computer memory and then afterwards realising it as a physical surface. So for that some free-form surface modeling methods are present, whatever free form surface? Free form surface does not possess any definite form and it may be defined by the interpolation or bending of several coordinate points in space. I have some points in space and by mixing up their coordinate values I can define a particular surface.

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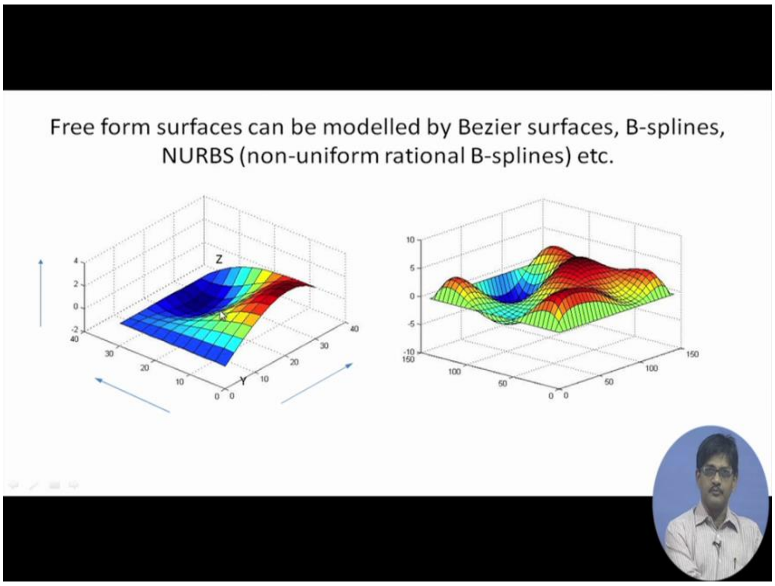

And I can place these coordinate points as I desire so that I can change or modify these shapes if so require these are also called sculptured surfaces, free-form surfaces, et cetera. These are 2 examples, by using MATLAB programming we have developed some examples of free-form surfaces and there are some surfaces available I mean some techniques of representing such surfaces available like Bezier surfaces, B-splines surface, non-uniform rational B-spline surfaces, et cetera. Whenever CAD model is developed and cutter paths are generated from that CAD model, ultimately all the surface elements of that CAD model are represented by NURBS (non-uniform rational B-splines) and then cutter paths are generated from that.

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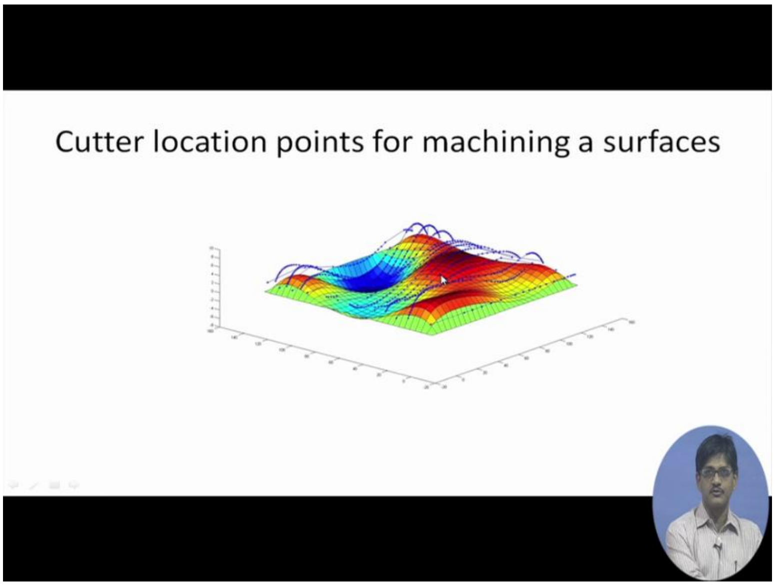

Here we have shown a surface and you can see some small red or rather blue dotted lines just over that particular surface, these are cutter paths that mean the centre point of a ball ended cutter path with these locus point as the centre points of the ball end okay, we will have an example later also in order to understand this.

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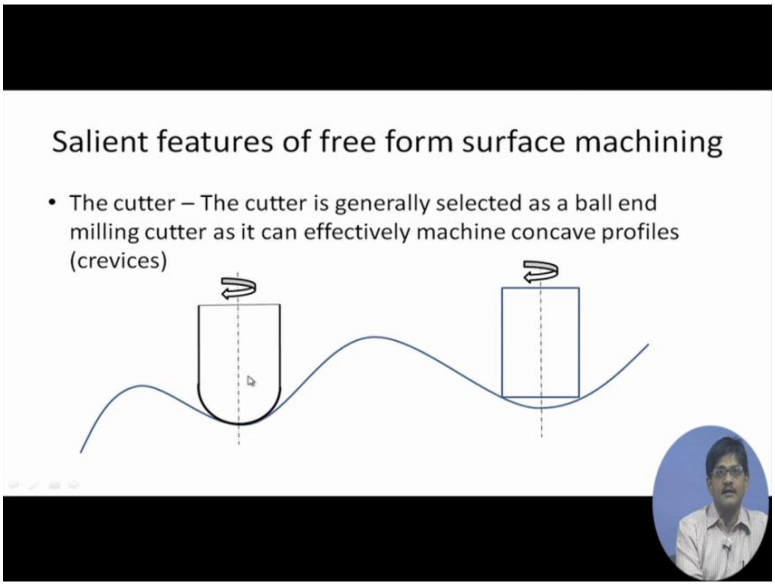

So 1st of all why are we talking about a ball ended cutter? In free-form surface machining, suppose this particular cutter which is rotating about a vertical axis and having a cylindrical shape ending in the shape of a sphere, this sort of a cutter is preferred for 3-axis machining and this is a typical free-form surface which has been shown which will be machined. Now why do we choose specifically a ball ended cutter instead of a flat ended milling cutter. This is also a milling cutter, this is a flat ended milling cutter okay, it is rotating about a vertical axis, this is not preferred for 3 axis machining, but this one is preferred and the reason has been made obvious by the very figure.

This cannot machine this part because it cannot rotate about a horizontal axis and take up any configuration, but this does not need to do so provided the radius of curvature of crave is okay provided the radius of curvature of a concave portion of crave is is larger than this particular radius of curvature as the end of this cutter, this can access any such concave portion and machine it, while this cannot, so this will be preferred and this will not.

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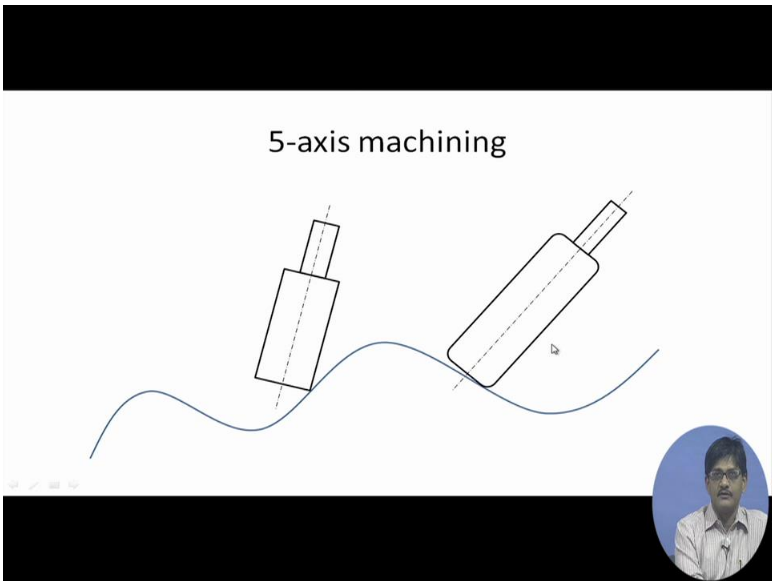

However, this is not always the case if you have a more sophisticated machine. If you have a 5 axis machine where the cutter can be rotated about horizontal axis, once this way and once the other way okay, once along this axis and another time along the axis coming out of the plane of the paper. If it can be rotated about these 2 axis, then even a flat ended milling cutter can be made to machine this particular surface because it will be now able to go right up to end, cutting by its edge. So 5 axis machine makes it possible to use a flat ended milling cutter to cut a 3-dimensional surface and incidentally it can achieve a higher surface finish compared to the ball ended milling cutter.

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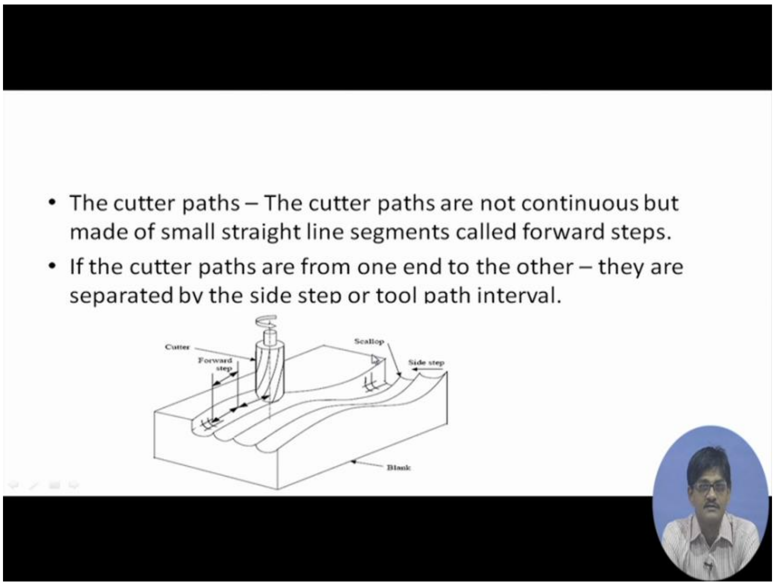

Now let us look at 3 axis machining in a little more detail. I have drawn some cutter paths, you can see that it is cutting out this material from a block, the 3 the what you call it, the free-form surface is gradually taking shape but very prominently the cutter paths are existing, they can be seen on top of the surface and they are creating minor deviations minor deviations from the design surface. The designer definitely must not have had these small scallops or appraised portions all along the surface, yes this was definitely not designed and this was definitely not part of the design surface but still you cannot avoid it because the cutter while moving through will definitely produce these grooves.

So since we cannot avoid it, we put some nomenclature for that and identify the ways in which we can reduce these undesirable features on the surface. For example, this one is called the forward step, what is this; it represents those straight-line segments by which the cutter approximates the curvilinear path. The cutter while moving from the side to that side does not exactly move along a continuous curve, rather it moves in small straight-line segments just as we discussed in case of curvilinear interpolator. In case of curvilinear interpolators, we breakup curve paths into shot straight-line segments and these are called the forward steps.

Forward steps make the cutter path deviate from the actual path actual curved path and some form tolerances defined which restricts the length of these forward step segments, we will have more detailed discussion on that. So the cutter is shown, it is taking forward steps and moving along, but once the complete path is finished at the other end, it takes a sidestep which has been shown here, sidestep or tool path interval, a sidestep is taken and it resumes its journey along another path the other side of the work piece and these appraised portions are called scalars.

So these appraised portions in their turn, just like the forward steps are creating deviation from the design surface and they are tolerated through formed tolerance, here the side steps are creating surface roughness and we will have a tolerable value of these appraised portions so that all these appraised portions will either have to remain within the tolerance value or preferably all of them should be of equal height everywhere, which is much more difficult to attain okay. We do not like these appraised portions called scallops existing, but at this moment it appears that we cannot do away with them completely and therefore, we define a tolerable value of this edge or roughness which is the result from these to and fro motions.

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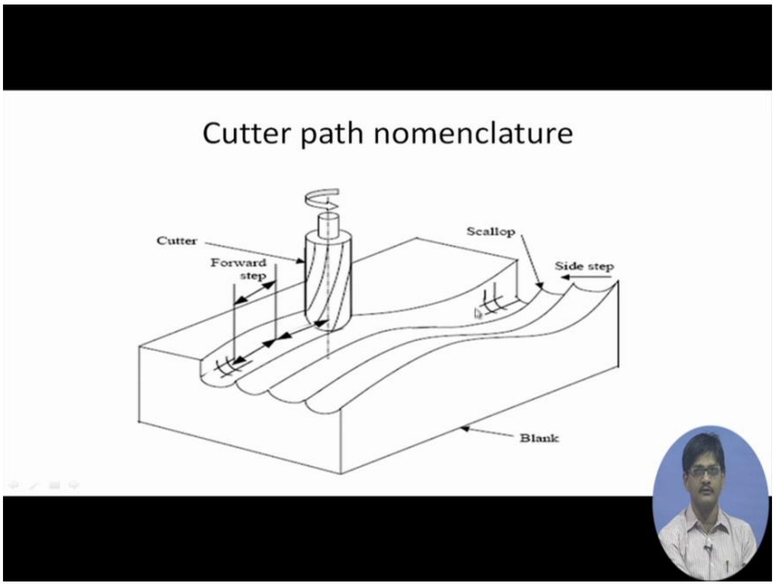

This is the same figure in a little more magnified form sorry same figure, so I am skipping this for a moment.

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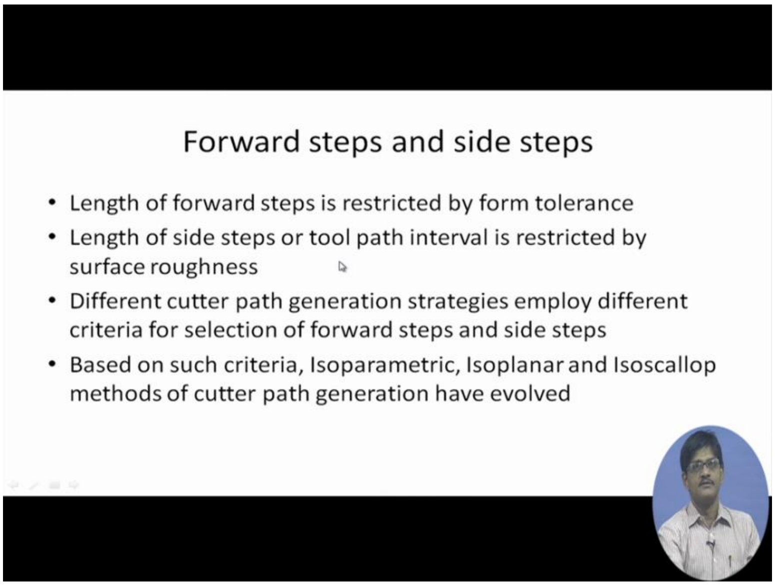

So forward steps and side steps, we have already discussed this. To summarize, length of forward step is restricted by form tolerance, length of sidestep is restricted by surface roughness. And different cutter path generation strategy employed different criteria for selection of forward steps and side steps. Based on such criteria there are 3 methods of cutter path generation which are known as Isoparamatric, Isoplanar and Isoscallop method, these are the main others also exist. Now some discussion about some geometric features connected with smooth surfaces.

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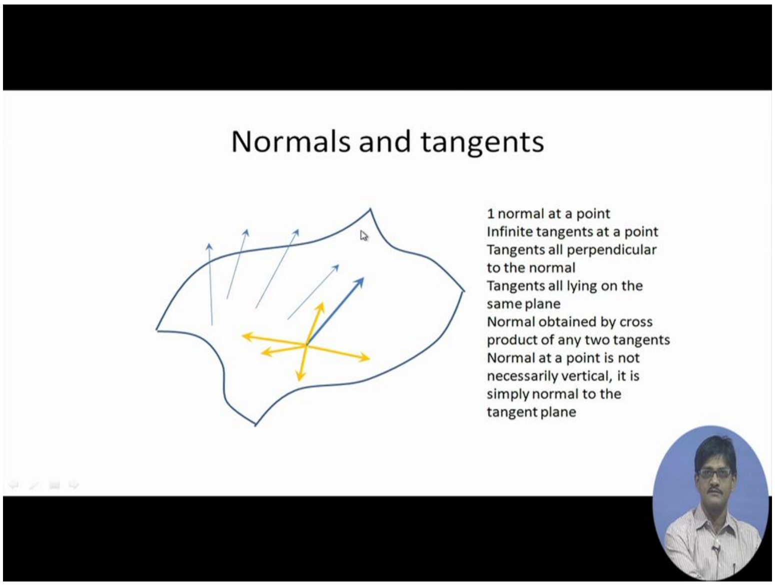

Suppose there is a smooth surface here and at different points I am interested to find out the normal, so I have drawn some straight-lines emanating from that surface at different points and I am calling them the normal, what is the normal? Is there more than one number at a particular point on the surface? At a particular point on the surface, there might be infinite number of tangents in different directions at a particular point on the surface but there is only one normal coming out. How this is normal defined? The normal happens to be perpendicular to all these tangents which are present here at the surface I mean to the surface at this point.

Which means the normal can easily be computed by the cross product of any 2 tangents, so if you are interested to find out the normal at a particular point you can simply find out 2 2 tangents to that particular point on the surface and find out the cross product between them which will yield the vector in the direction of the normal, so all these are normals and all these orange lines are tangents at this particular point to the surface. And of course this is of interest to us, are these normals vertical? The answer is, no they are not necessarily vertical but they can be contained in vertical planes.

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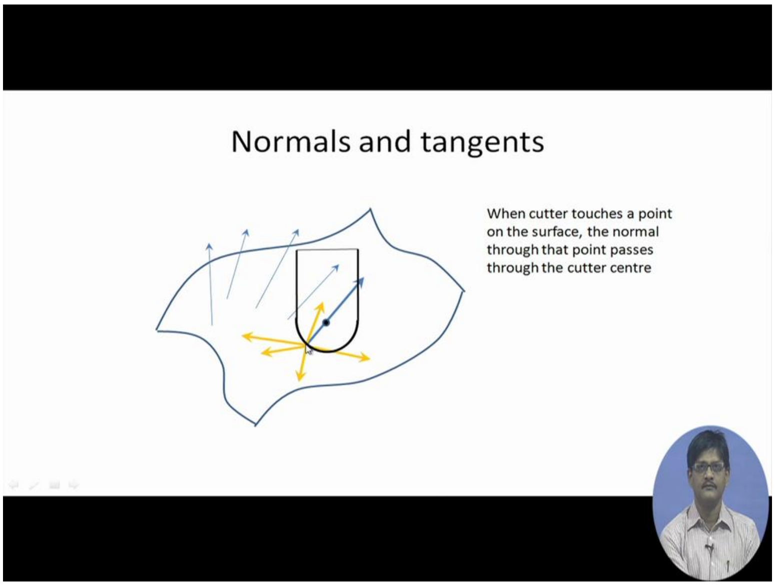

So this is the cutter, when the cutter is touching the surface at this point the normal to the surface will essentially contain the centre of the cutter okay. So the normal to the surface will essentially contain the centre of this spherical end of the cutter, so we understand that this normal which is emanating out at this point of the surface it is passing through this centre which is shown, so we make use of this… This figure will make it clear.

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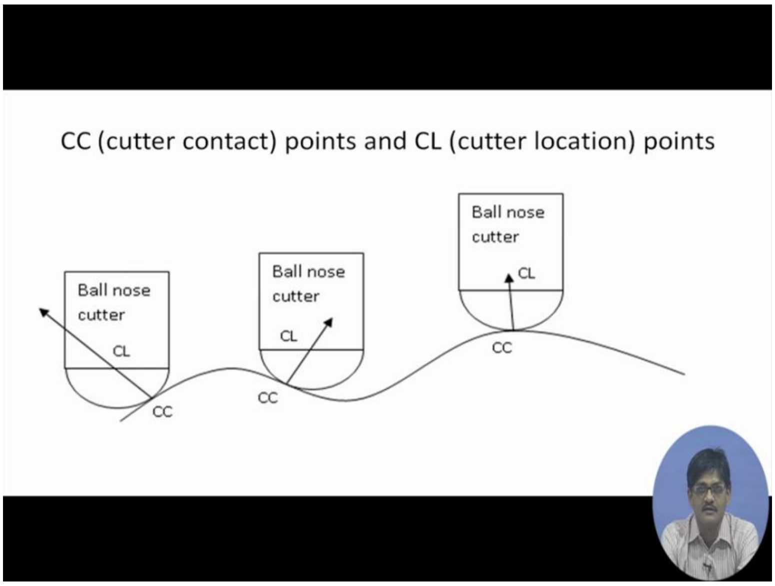

First of all, we are differentiating between 2 types of points in connection with 3 axis machining that is, if we have a ball ended milling cutter in connection with the surface, the point at which it connects to the surface the point of touch or contact, it is called cutter contact point CC point. So this is one cutter contact point, this is another cutter contact point and a 3rd cutter contact point, which shows clearly cutter contact points are not one steady constant point with respect to the cutter geometry, cutter content point might be anywhere. So if we identify a cutter, the cutter contact point is not uniquely positioned.

If we identify a cutter contact point on the surface, the cutter cannot be uniquely positioned there, what do we mean by that? Different points on the cutter might be in contact with that. If we take this cutter contact point, it is touching the tool on the on its right-hand side, it is touching the tool on the left-hand side, it is touching the tool at its end point something like that. So if I give you a number of cutter contact points, you cannot straightaway put the say the lower most of the cutter in contact with all those cutter contact points and say that these must be the tool positions, no.

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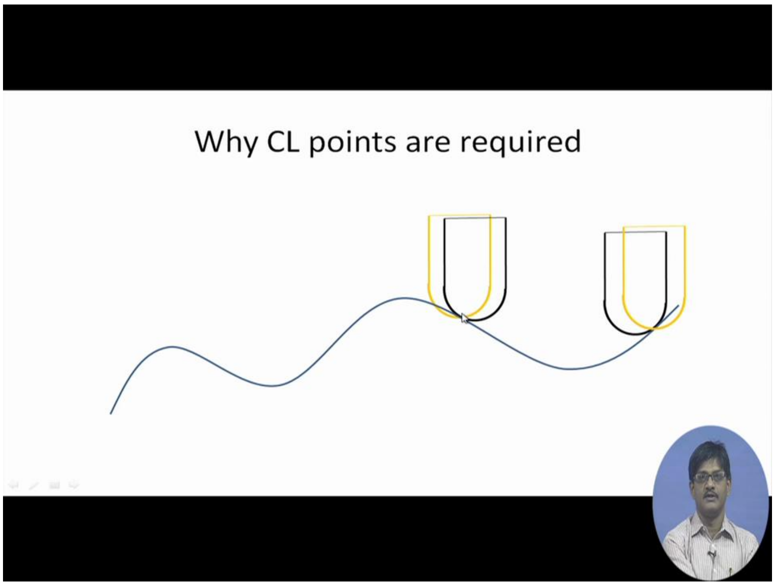

This is an example, say this is one cutter contact point, this is one cutter contact point. If I ask you, find out the corresponding tool positions. The yellow position marks arbitrarily I have put always the bottommost point of the tool through these points, this is wrong, why? Because obviously it is clearly visible that part of the tool is inside and quite a large portion of the tool or the cutter is inside the surface, which means that if I use this position, part of the job will be machined out. So the cutter position has to be such that it should be tangential to the surface and the cutter contact point.

So if we have to position that cutter tangentially, this is the only possible position; a circle tangent touching to this particular point on the surface. So having accepted that we can uniquely place it in what way, we will we will draw the normal emanating out of the surface at this point and radius away from the surface, we will select the centre of the cutter spherical end. So this way if we if we draw the normal, this will be the point, let us have a quick drawing here.

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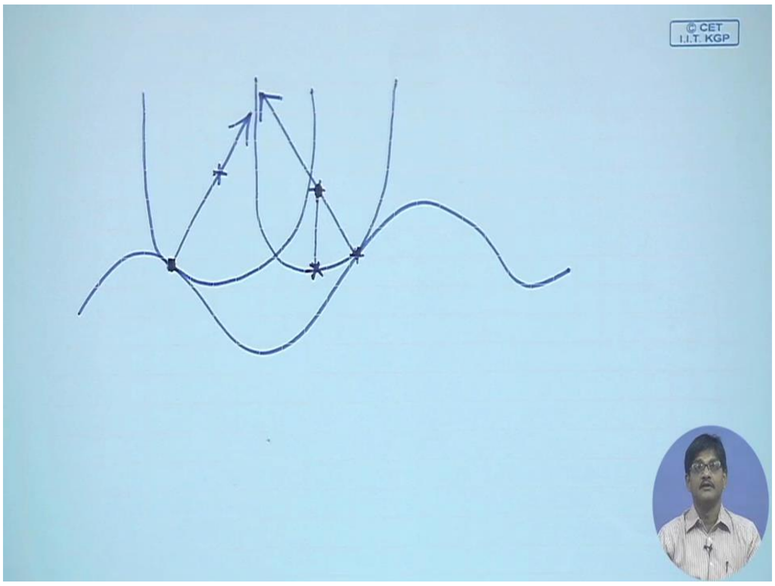

We have a surface of this type here, I take this point, how can I find out the centre point of the cutter here? So I draw the normal, this Suppose is the radius of the tool, so I can draw a circle and this is my cutter position. So I can find out, this is a fixed point on the cutter, once I know this is the cutter is defined in position. I could have given this point also, this point is just move along the Z axis by radius, you will get this point. So that way if I have this point as the cutter contact point, I can draw the normal, I can move by the radius, I can say this is the centre of the spherical end of the cutter this is the cutter position that is it, so I can draw the cutter uniquely once I have defined the position of some constant point on the cutter.

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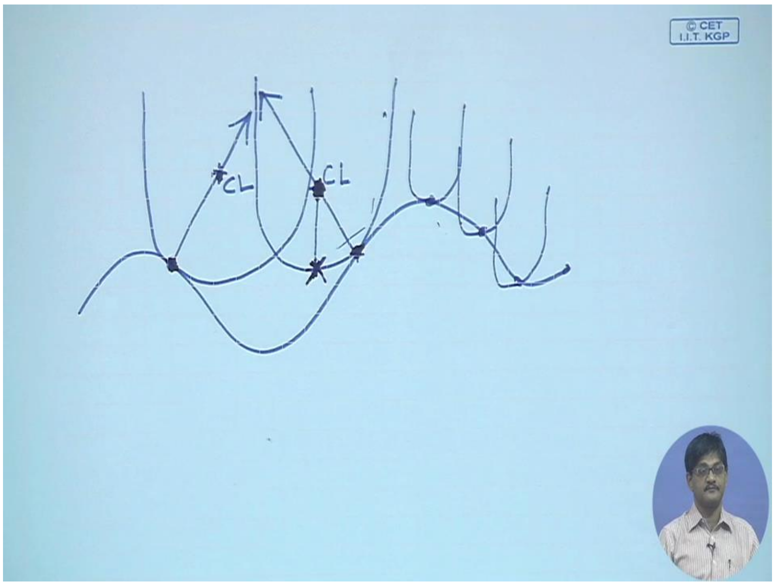

Just giving CC point is not enough, if I give you a series of CC points, and you draw okay this is the cutter, this is the cutter, this is the cutter, no all these would be wrong, part of them are inside, it should be in the touching condition. So we define certain points on the cutter which are specific points say the centre of the spherical portion and then we say it is a cutter location point, which locates the cutter exactly in space. There can be no 2 positions, it is not a it is completely in contact with the surface at the cutter contact point and this is this is the location of its central position of the spherical end to fix it in space.

So cutter location points are the ones which should be given to the machine control, it will immediately understand yes this is the position to which I have to bring the centre of the spherical end. So as per the convention of the machine we have to give a specific point on the cutter for each and every cutter contact point and call it the cutter location point, this can be cutter location, this can be cutter location, like that so that is why we call serial data cutter location data.

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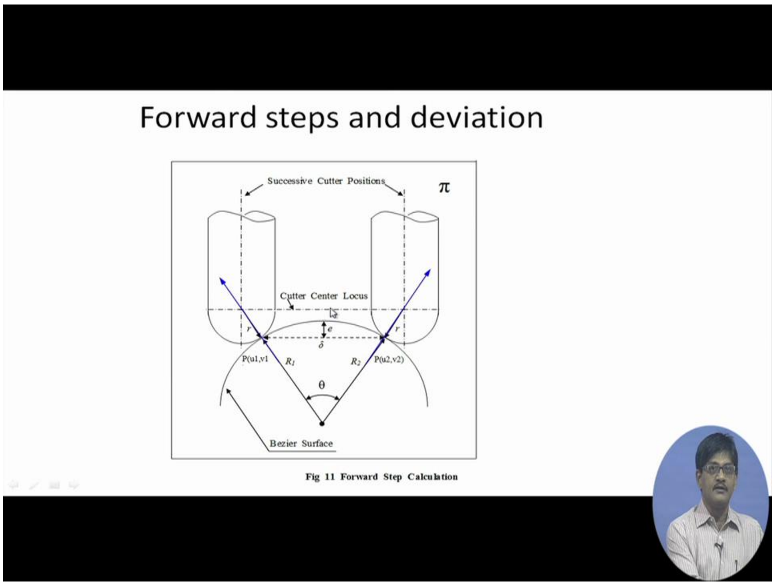

This one is in more detail shows the calculations which are involved to find out the forward step positions along a surface. This is a Bezier surface, on the Bezier surface we have selected two points and in between these 2 points this segment represents the forward step. If this is the forward step, machining will be done and this portion will be cut off actually a little more of the material will be cut off due to some effect called external gouging, but we will come to that later on, at this moment we will understand that this part is cutoff and this is known as this we try to equate to a value called Form tolerance.

Suppose we can tolerate a maximum deviation of 50 microns from the design surface, so we will equate this to 50 microns and sorry we will equate this to 50 microns and that way ultimately calculate what should be this particular forward step length, so we will do this calculation in more detail in our subsequent lectures, let us all to have a look at the Bezier curve and surface that we have been talking about, what is a Bezier curve for a Bezier surface?

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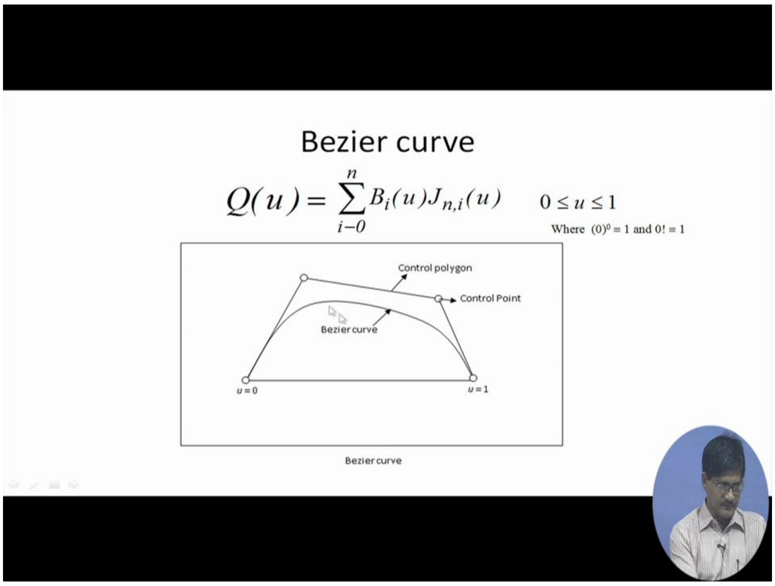

It is referred to as a parametric curve which means that even if we are dealing with the Cartesian coordinate space in X, Y, Z, we are going to express the Cartesian position of a particular point in terms of a variable other than X, Y or Z. In this case we are taking help of a variable U, how is U varying? If this is the final Bezier curve which we are attempting to define, this is the Bezier curve, U is a variable which is supposed to take a value of 0 at this point and it is gradually increasing proportionate to the length pass and at the end of the curve, it takes up a value U = 1, U = 0 and steadily increasing to U = 1 that is good, but how are we 1st of all defining this shape?

Before going for a mathematical formal definition, we understand that this curve is going to be controlled by the positions or locations of certain points in Cartesian space, which are called controlled points. So it basically means that if I shift this control point outwards okay, if it shifts, then the curve will also follow through that means the curve will also start getting shifted in that particular direction. So the points which are making up this controlled point network, the 1st control point and the curve they are coincident, the last control point and curve they are also coincident. In between the curves might or might not pass through these control points okay and the curve can be having different shapes in between.

But it is always affected by the location of these control points; now let us have a look at this particular curve formula. The curve any point on the curve Q is defined to be a submission of certain terms and each term represents a control point coordinate, so what is this control point coordinate? B i okay so how do we represent this on the formula? It can be X, it can be Y, it can be Z, if it is X, we will find out the coordinate value for particular point I mean we will find out the X coordinate value of a particular point on the curve. If it is Y, it will be Y coordinate, if it is Z it will be Z coordinate.

But it seems to be multiplied with a coefficient, is called a Bernstein polynomial and it is basically a function of that U parameter which was varying along the curve, so it is simply a a what you call it a function of this particular U parameter, so it basically means I have a control point, this is one control point for example. This will be multiplied with a particular function of the U parameter so that ultimately each and every point gets some contribution from this point, get some contribution from this point, get some contribution from all the points that way. What about the 1st point; 1st point gets contribution from the first point fully and from the other points 0.

In between the points, share the contribution of the different control points. And the last point of the curve, contribution of the last control point is maximum because of which they are coincident and the affect of other control point is 0, let us have a look at this particular polynomial, how it looks like.

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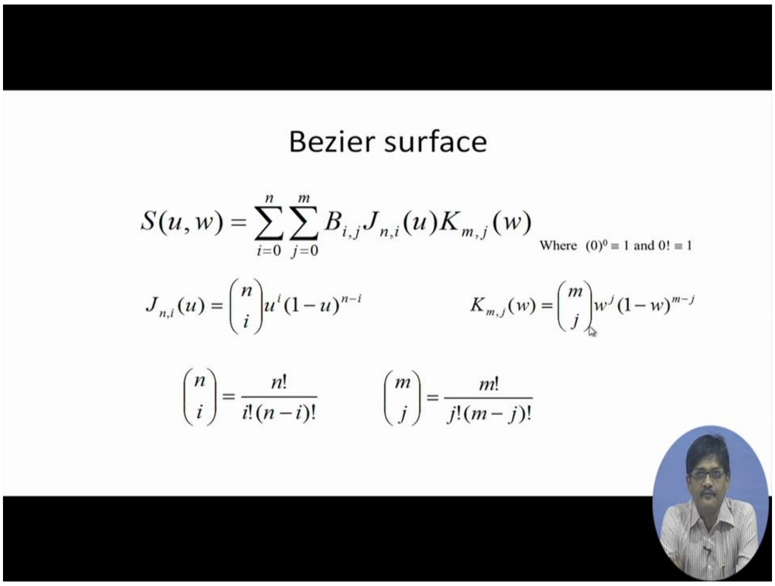

So this is the equation of the Bezier surface, we will be taking up in more detail, this is the particular Bernstein polynomial and let us have a quick look what it looks like. So this U what you call it Bernstein polynomial this weight function multiplied with all the control point coordinates, it is equal to n c i u to the power i multiplied by 1 - u n - i. What is n? n is the total number of control points counted from 0 that means if there are 4 control points, n will be 3, i is that particular term in that submission that we are talking about, u is the variable value, it takes up different values at different points on the curve starting from 0 and ending in 1.

U to the power i, i is the particular term that we are talking about in that submission and 1 - u to the power n - i, so this way this value is completely, it can be completely determine and multiplied with the weight function and multiplied with the control point coordinate.

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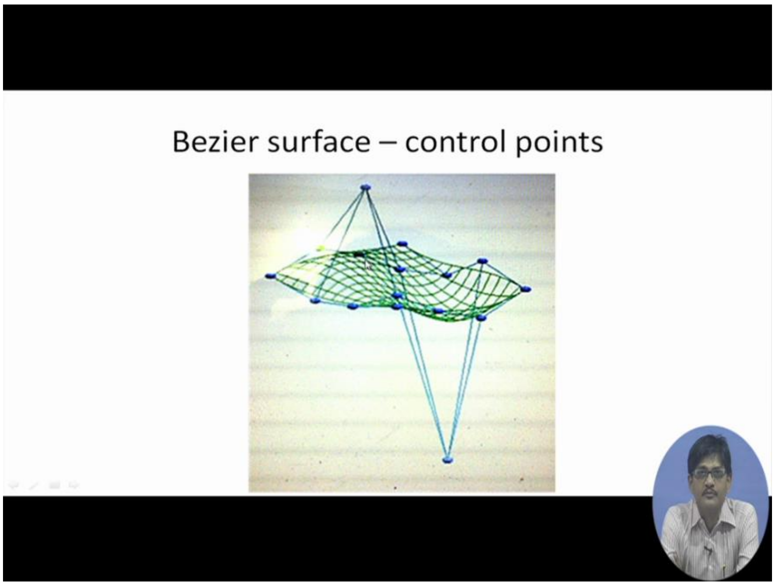

This is a pictorial representation of how a surface can be controlled by the position of the control points, this is one control point, this is one control point, all the other control points are quite near to the surface, just shifting to points will make the surface slightly undulated. In detailed discussions about how Bezier surfaces can be drawn, how the control point locations can affect the Bezier surface, how to calculate the derivatives that means the tangent vectors to the Bezier surface and from that how to find out the normal, from the normal how to locate the cutter, etc, thank you very much.