Machining Science - Part I
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Lecture – 17

Hello and welcome to the 17th session of our discussion on Machining Science. In our previous session we discussed about the specific energy in grinding and we said the specific energy in grinding is very high. In fact, it is an order of magnitude higher than in case of similar or comparable single point cutting tool or single point machining. Now this is because that when the t_1 or the uncut thickness becomes less, U_c becomes very high, which was said to be as size effect.

Now, why it happens is that during the grinding process, the t_1 is normally very small and within that small thickness, thin layer there is almost no imperfection or in-homogeneity and the material behaves almost like an ideal material. In that case the shear stress required to create the plastic deformation in the material becomes very high and therefore, this power consumption becomes very high and the specific energy becomes very high.

Then we said that it is not only the size effect, but there are some other effects which occur in grinding, because of which the specific energy in grinding becomes very high, let us see these phenomena.

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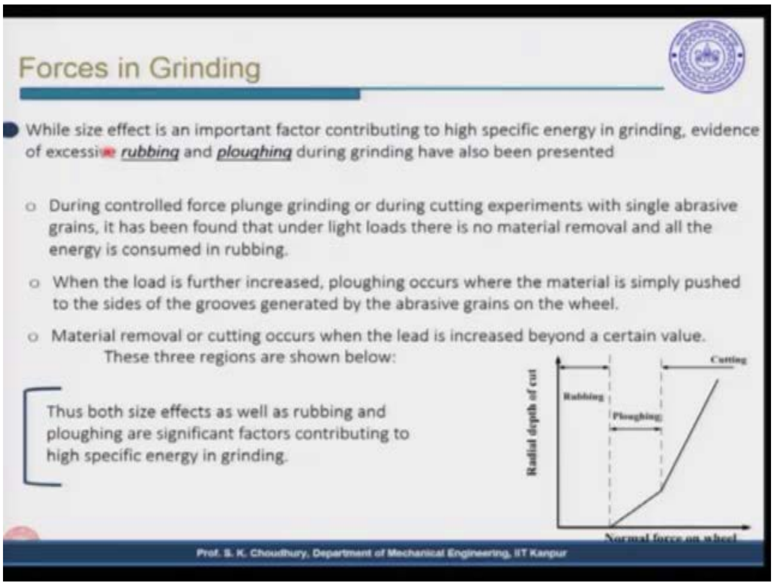

While size effect is an important factor contributing to high specific energy in grinding, there is excessive rubbing and ploughing during the grinding, they are also responsible along with the size effect for very high specific energy.

During controlled force plunge grinding or during the cutting experiments with single abrasive grains, it has been found that under light loads there is no material removal and all the energy is consumed in rubbing. Let us explain through the curve drawn for the radial depth of cut in the y-axis and the normal force acting on the wheel in the x-axis; then we will see that at the lower load when the normal load or the normal force is still low, then, there is no material removal and the grinding wheel or the grains rub against the workpiece without removing the material.

This zone is then termed as the rubbing zone and here the power consumption is very high, because it is rubbing and there is no material removal takes place. After further increase in the normal force, the radial depth of cut starts increasing; therefore, the material is being removed, but not as much as it is in the cutting process.

Because in this region there is more ploughing, this material is not segregated completely, but this is ploughed like we plough the land for cultivation. As the normal force further increases, the material is segregated in terms of small chips and the cutting takes place.

So, as you can understand that before the material removal actually takes place or before the cutting process actually takes place, there is ploughing and there is rubbing. And because of the rubbing and ploughing, lot of energy is spent without removal of material. Along with the size effect, this rubbing and ploughing are also responsible for the higher specific consumption in the grinding process. Now of course, the size effect is the main effect followed by the rubbing and the ploughing.

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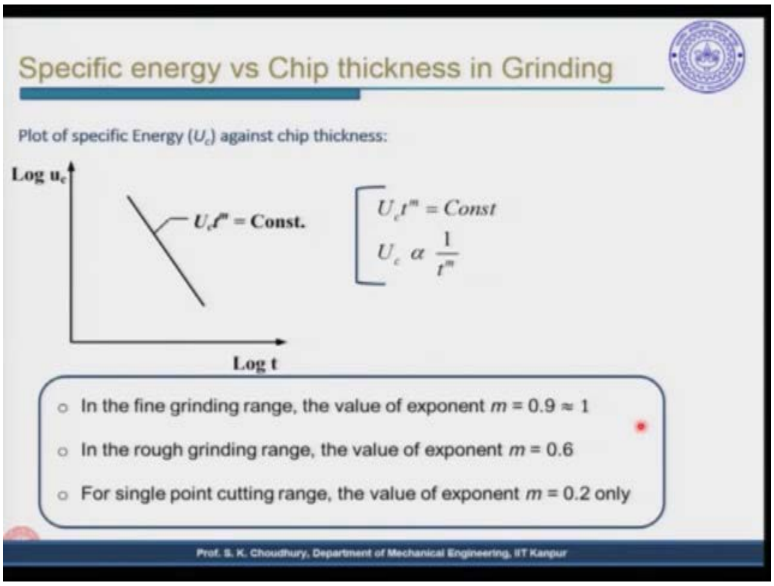

Now, let us see how in the grinding process this can be plotted; for example, if we plot the same curve in the log-log scale. Let us say here it is the log of the uncut thickness and here it is the log of the specific energy, then the curve will be a straight line like this. And, this straight line can be represented by the equation as the $U_c t^m = Const$ or $U_c \propto \frac{1}{t^m}$.

Here, the *m* is constant and this equation I wanted to show you because, then you will understand that what is the effect of this size effect in case of the grinding. For example, in case of the fine grinding range, the value of *m* is very high and it tends to close to 1. In that case, the layer or thickness is very small and there is no imperfection on that layer and the size effect works. So, the specific energy becomes very high.

In case of rough grinding where the t_1 is still relatively higher, in that case we have some imperfections and along with the shear force which is applied, the imperfections move and the total shear force required will be less, so the specific energy decreases. In that case the value of *m* will be about 0.6.

To compare with this, for example, in case of single point cutting range the value of exponent *m* will be about 0.2. Because there are a lot of imperfections and the specific energy is less, because the shear stress required to remove the material or to create the plastic deformation, creating the slip is less. This indicates that the specific energy in turning process will be less than in case of fine grinding.

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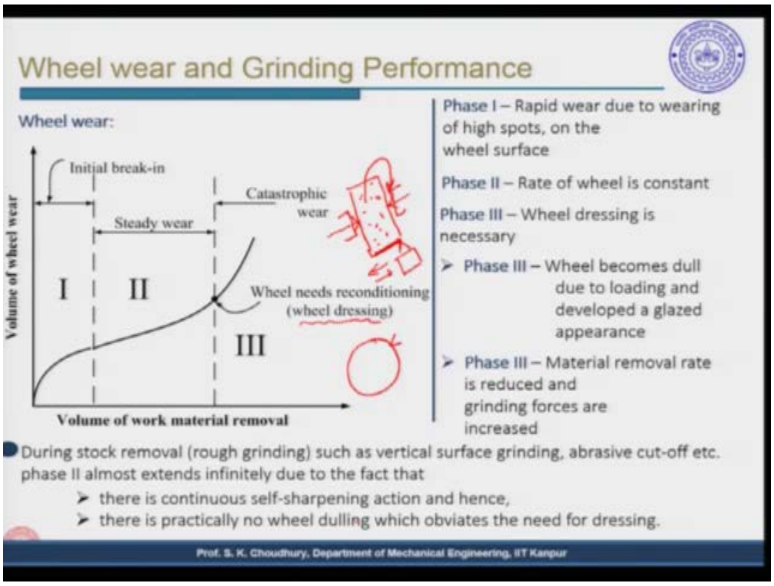

Now, let us see how the grinding wheel wears out. If you plot the volume of wheel wear along the y-axis and the volume of work material removal along the x-axis; you will find a curve of the wheel wear which will be more or less similar to the one that we have seen in case of the single point cutting tool.

Initially, when the grinding wheel comes in contact with the work piece, grinding wheel surface having the sharp grains will get very quickly dulled; because of the rubbing, ploughing and because of the material removal from the workpiece. Initially, the wear is very high and this zone is called the initial break in; like in case of the single point cutting tool. If you remember we said that initially when the single point cutting tool comes in contact with the work piece, because of the single point there is a very high stress concentration and it gets blunted very quickly.

Same thing happens in case of the grinding wheel, that when the sharp grinding wheels with the sharp grains coming in contact with the work piece; initially, the wear is very high, because those grains will be dulled. After that as the grinding process goes on, there is a steady wear for a very long time. What happens is that when the grinding process goes on, there is a self sharpening phenomenon; that means, when the grains will be worn out, they will be dislodged and the sharp grains will be coming which are behind the worn out grains. And always, almost always there will be sharp grains on the grinding wheel surface, particularly in case of the rough grinding.

We say that this steady wear zone is very long, but after some time the wheel will be worn out so much that we need to have the reconditioning of the wheel. So, this is called the wheel dressing. When we take a diamond pin and with the help of a diamond pin we remove the outer layer of the grinding wheel. If you see the grinding wheel in this way, it is actually placed along the centers, the grinding wheel is rotated and then the diamond pin goes to and fro to remove the outer layer.

Because of the wheel glazing we have the worn out grains or because of the wheel loading we have the chips embedded in the space between the grains. So, this is the process which is called the wheel dressing. And wheel dressing will be required when the wear goes very high and the worn out grains have to be removed or the chips embedded have to be removed, otherwise this specific energy will be very high and the power consumption will be very high.

There are three phases; this is the rapid wear initially then the steady wear and the third phase is when the wheel dressing is necessary. Now, during the stock removal, I already told you, this is the rough grinding such as vertical surface grinding, abrasive cut off etcetera, phase II almost extends infinitely due to the fact that there is a continuous self sharpening action. Hence there is practically no wheel dulling, because behind the dull grains always there will be sharp grains and they will be coming out on the surface of the grinding wheel.

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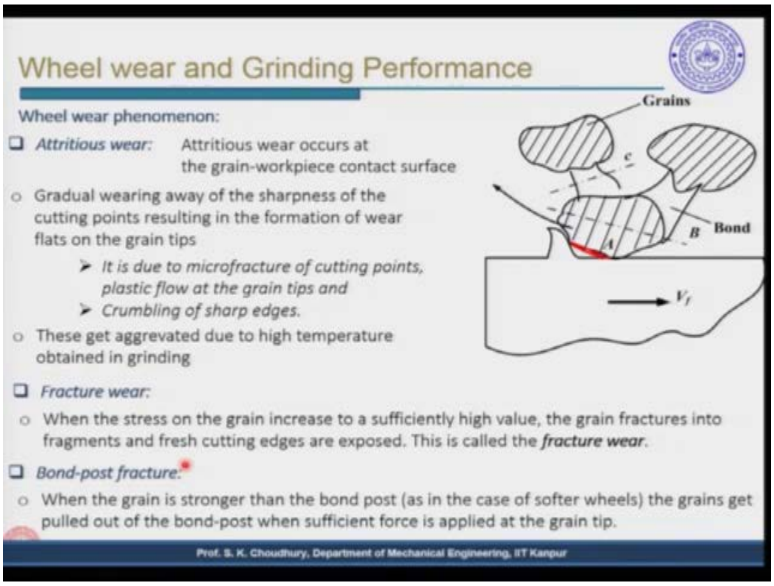

Now the wheel wear phenomena: when the wheel gets in contact with the work piece initially because of the wear due to the rubbing and ploughing, there is a flat created here, this is shown as A. This is the gradual wearing away of the sharpness of the cutting points, resulting in the formation of wear flats on the grain tips. So, this is due to the micro fracture of cutting points, it could be due to plastic flow at the grain tips and due to crumbling of the sharp edges.

These get aggravated due to high temperature obtained in the grinding; as we said earlier that because of the very high speed of the grinding wheel, the temperature which is occurring in the grinding zone is very high. After that if the forces become higher, in that case the grain strength will not be able to withstand that force and grain can break along B B and this is called the fracture wear.

Now, in case the grain is stronger than the bonding material and the bond is weaker, in that case the grain can be pulled out from the bond and this is called the bond post fracture. That means instead of the grain breaking, the grain can be pulled out from the bond post and it is called the bond post fracture. Now as you can see that if the grain fractures along the B B, then there will be sharp grains again, because if the grain fractures out then this portion will have the sharp edges.

So, this is also as we discussed in the case of the steady wear, the grain breaks and the grains will be considered as sharp grains again, because it is broken here. As you you understand that the grain does not break along a straight line; it can break giving different edges and those edges will be the sharp edges and they will take part in the material removal process. So, these are the three wears; first is the A A which is called the attritious wear, B B is called the fracture wear and C C is the bond-post fracture; this is how the fracture in the grinding wheel takes place.

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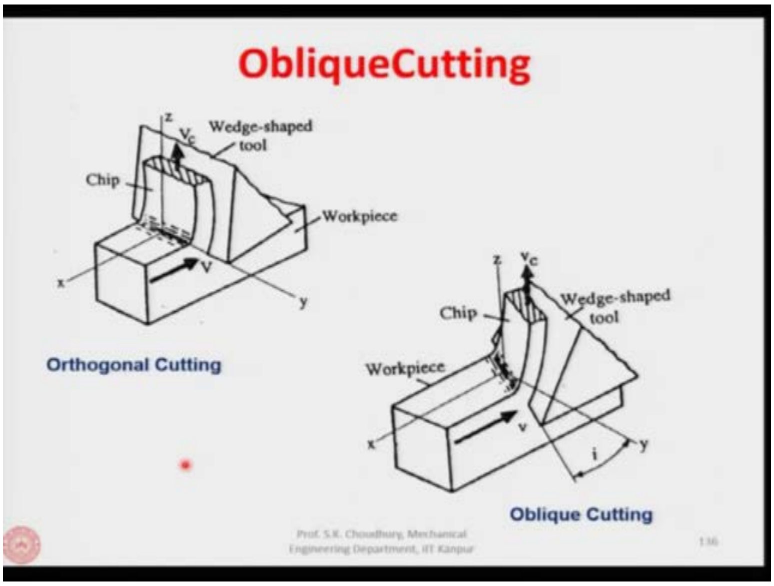

Next topic that we will be discussing after the grinding process is the oblique cutting. I would like to show you the diagrams which we have already seen earlier and compare the orthogonal cutting with the oblique cutting. We said that in case of orthogonal cutting, the tool edge is perfectly perpendicular to the direction of the cutting velocity vector.

In case of oblique cutting, the tool is inclined at an angle and it does not make a 90^o angle with the cutting velocity vector. This cutting edge is inclined with respect to the y-axis by an angle of *i* and this angle is called the angle of obliquity or the tool inclination angle.

Now, let us see that if we have the tool inclined, then what kind of forces are occurring with respect to the orthogonal cutting; Orthogonal cutting we have discussed while we have discussed the Merchant’s circle diagram.

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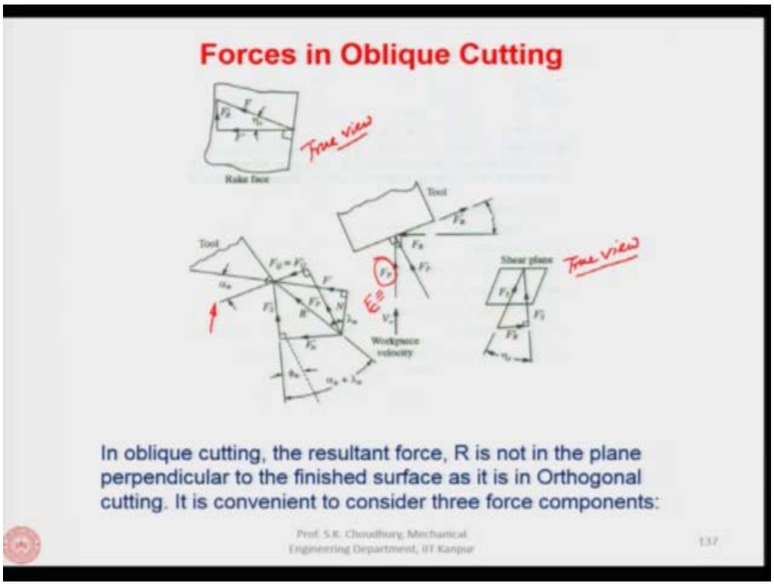

These are the forces in oblique cutting in the diagram shown. What is shown is that, this is the tool in the base plane and the tool is inclined. Inclined means this tool edge is making an angle of *i* with respect to the line perpendicular to the cutting velocity vector.

Now this tool can be represented in a plane normal to this cutting edge. So, this is the rake face and this is the flank face of the tool. These forces or this tool can also be represented in the shear plane. This is called the true view of the shear plane.

Meaning, that if you look at the shear plane perpendicularly, this is the true view; then you will see that what is the true view of the shear plane, and this is the true view of the rake plane. By true view we mean that if you look at the rake face exactly perpendicular to the rake face, you will see a view like this which is called the true view.

In oblique cutting, the resultant force *R* is not in the plane perpendicular to the finished surface as in case of the orthogonal cutting. It is convenient to consider three force components in the case of the oblique cutting; because the *R* resultant force is not in the plane perpendicular to the finished surface.

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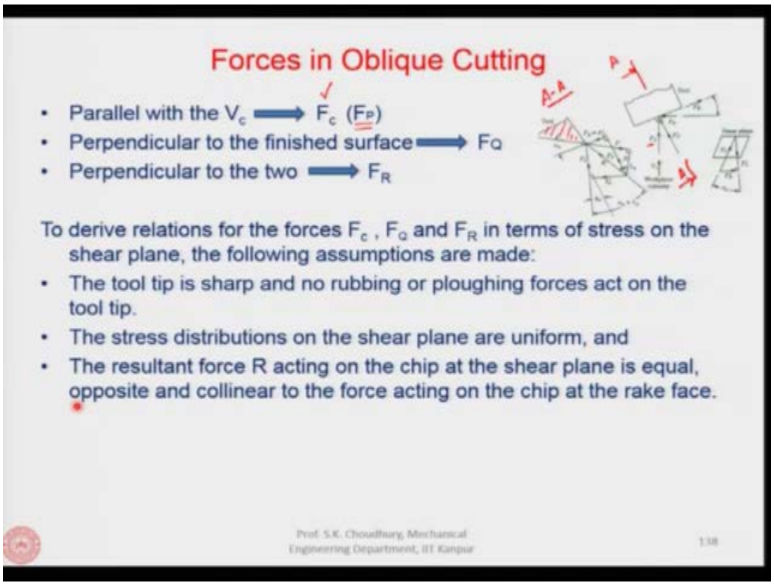

These forces are parallel with the cutting velocity which we will call as the F_c. Here by the way this is given as the F_P probably; if you can see that this is the F_P, this is equivalent to what we have said earlier as the F_c or the cutting force.

So, this is the F_c cutting force, in this case I have written here in bracket that this is shown as the F_P this is the cutting force, another force is perpendicular to the finished surface - this is F_Q. So, this F_Q is perpendicular to the finished surface; this is shown here, because this view is made perpendicular to the cutting edge.

So, if you see this plane, for example, let us say this is A-A. I am not writing this as a sectional view, because it is not sections, but for you to understand that if you take this section the sectional view will be like this, in that case of course, the tool will be hatched like this. But right now it is not hatched because it is not a sectional view; it is the view from the side.

Third force, component of the force is perpendicular to the two; perpendicular to cutting force and this F_Q, and this F_R is given here, this is the F_R. So, we have three forces F_c here or the F_P as it is shown here, F_R and F_Q. Once again, F_c or F_P it is parallel to the cutting velocity vector which is here, this is perpendicular to the finished surface. And to both of them F_c or F_P and the F_Q, another force is the F_R. F_R is perpendicular to F_P as well as F_Q, because F_Q will be perpendicular to the finished surface.

Now, to derive relations for the forces F_c, F_Q and F_R in terms of stress on the shear plane, the following assumptions are made that the tool tip is sharp, no rubbing or ploughing forces act on the tool tip. Next assumption is that the stress distributions on the shear plane are uniform and the resultant force R acting on the chip at the shear plane is equal, opposite and collinear to the force acting on the chip at the rake face. So, these three are the assumptions that have been taken for correlating F_c, F_Q and F_R in terms of stress in the shear plane. Let us see how they can be correlated.

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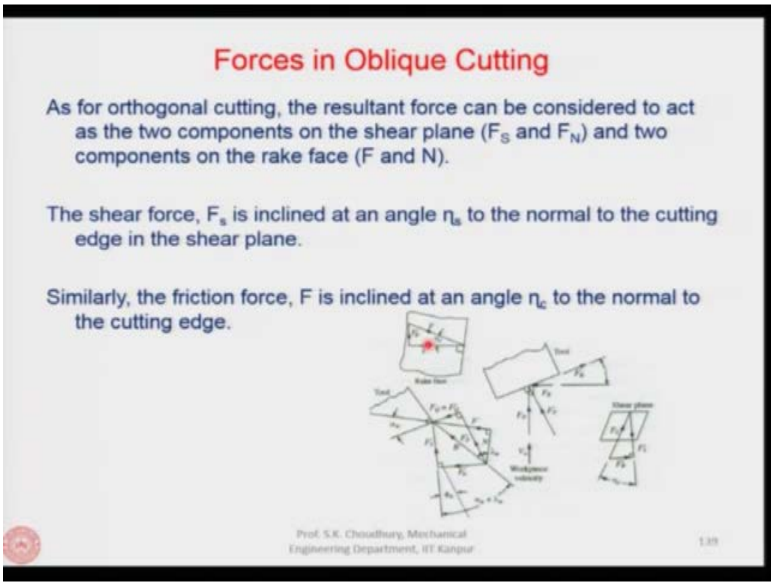

We need to refer to this diagram. Therefore, this diagram I have repeated on each of the slides. Now, as for orthogonal cutting, the resultant force can be considered to act as two components on the shear plane. So, we have the F_S, F_N that is along the shear plane and perpendicular to the shear plane and two components on the rake face *F* and *N*; *F* is parallel to the rake face and *N* is perpendicular to the rake face. So, this is like we have done in case of the orthogonal cutting when we have discussed the Merchant's circle diagram.

The shear force, F_S is inclined at an angle nu s to the normal to the cutting edge in the shear plane. If you see the true view of the shear plane, what we are saying is that the F_S is inclined to the cutting edge of the shear plane at an angle of nu s, to the normal to the cutting edge of the shear plane.

This is normal to the cutting edge of the shear plane and to the normal this F_S is making an $\angle \eta_s$. Similarly, the friction force, F is inclined at an angle nu c to the normal to the cutting edge. This is the normal to the cutting edge shown in the true view of the rake face. And to the normal to the cutting edge F which is parallel to the rake face is making an $\angle \eta_c$.

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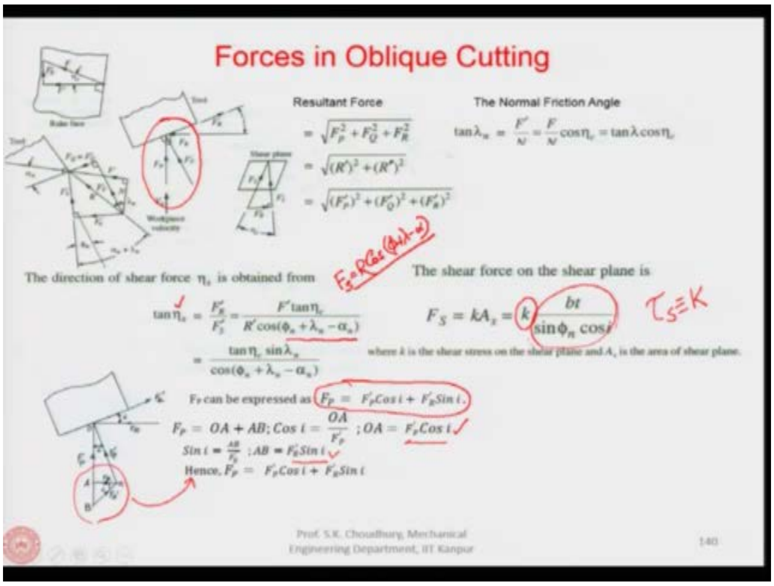

Now, the resultant force therefore will be $\sqrt{F_P^2 + F_Q^2 + F_R^2}$, because this is how we are taking the components of the resultant force. Or, we can have it as $\sqrt{R^{'2} + R^{''2}}$, or let us say this will be $\sqrt{(F_P^{'})^2 + (F_Q^{'})^2 + (F_R^{'})^2}$. Now, we are saying that F_Q and $F_Q^{'}$ will be the same, because this is acting at the plane normal to the cutting edge. So, F_Q and $F_Q^{'}$ are the same.

F_P and F_R is making an angle of i with the $F_P^{'}$ and $F_R^{'}$. So, F_P and the F_R can be assumed to be equal to $F_P^{'}$ and the $F_R^{'}$. If you see the diagram, F_R and the F_P they are both making an angle of *i* with this $F_R^{'}$ and the $F_P^{'}$. Therefore, $\sqrt{F_P^2 + F_Q^2 + F_R^2}$ can be written as $\sqrt{(F_P^{'})^2 + (F_Q^{'})^2 + (F_R^{'})^2}$; $F_R^{'}$ is making an angle of *i* with the F_R.

Now the direction of the shear force, η_s is obtained from $\tan\eta_s = \frac{F_R^{'}}{F_S^{'}}$. So, $\tan\eta_s$ from here, if you can find out from this triangle, this will be $\frac{F_R^{'}}{F_S^{'}}$. $F_R^{'} = F^{'} \tan\eta_c$, from this triangle you can find out. And, like we said in the Merchant's diagram that $F_S = R\cos(\phi + \lambda - \alpha)$, $F_S^{'}$ can be expressed similarly.

We have resolved the *R'* into those six components like in the Merchant's diagram; therefore, the $F_S^{'} = R^{'} \cos(\phi_n + \lambda_n - \alpha_n)$. I will remind you that F_S in case of Merchant's we have written as $R\cos(\phi + \lambda - \alpha)$.

This is same here only in the normal plane. All these are in the normal plane, these angles are in the normal plane; this is the F_N, this is the λ_n and this is the $\alpha_n + \lambda_n$. So, you can find out these angles and the $\tan\eta_s$ can be written as $\frac{\tan\eta_c \sin\lambda_n}{\cos(\phi_n + \lambda_n - \alpha_n)}$. The shear force F_S on the shear plane is the *k*, some constant that is the shear stress on the shear plane and A_S is the area of the shear plane.

So, area of the shear plane is $\frac{bt}{\sin\phi_n \cos i}$ and this is the shear stress on the shear plane. Earlier, we represented that as τ_s, so this is let us say equivalent to the *K* here. So, this is the stress into area and the area is A_S, stress is the k.

Now, F_P can be expressed as $F_P^{'} \cos i + F_R^{'} \sin i$, this you can find out from this curve or for this diagram. If you extend this view or extend this part, so let us say at this the F_P is acting like that; $F_P^{'}$ is making an angle of *i* with the F_P and F_R is making an angle of *i* with the $F_R^{'}$. Now, if you rearrange that, in that case F_P can be represented as $OA + AB$ and the $\cos i = \frac{OA}{FP^{'}}$ from here and $OA = F_P^{'} \cos i$.

Now, $\sin i = \frac{AB}{F_R^{'}}$ from ΔABC. Hence, $F_P = F_P^{'} \cos i + F_R^{'} \sin i$, this is what we have written here, that F_P can be written as $F_P^{'} \cos i$ which is $OA + F_R^{'} \sin i$ which is *AB*, and $OA + AB$ can be assumed to be equal to F_P.

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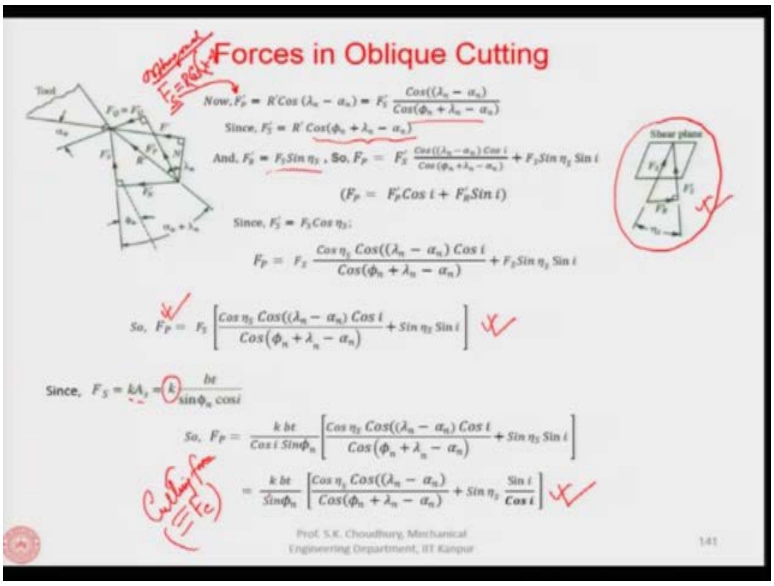

Once it is this in, this case, we can find out that the $F_P^{'} = R^{'} \cos(\lambda_n - \alpha_n)$. So, $F_P^{'}$ we can find out from here. So, this is actually similar to F_c in case of the Merchant's. I will remind you that there we wrote, F_c which is actually $R\cos(\lambda - \alpha)$, that is orthogonal case by the way.

In orthogonal case, in Merchant's we have written that $F_c = R\cos(\lambda - \alpha)$. So, F_P and F_c , this is here it is F_P; now the $F_P^{'}$ is in the normal plane. Therefore, it can be written as $F_P^{'} = R^{'} \cos(\lambda_n - \alpha_n) = \frac{F_S^{'} \cos(\lambda_n - \alpha_n)}{\cos(\phi_n + \lambda_n - \alpha_n)}$.

Now $R^{'} = \frac{F_S^{'}}{\cos(\phi_n + \lambda_n - \alpha_n)}$. And the $F_R^{'} = F_s \sin \eta_S$ that you can find out from the diagram. So, the $F_P = \frac{F_S^{'} \cos(\lambda_n - \alpha_n)}{\cos(\phi_n + \lambda_n - \alpha_n)} + F_S \sin \eta_s \sin i$, because the $F_P = F_P^{'} \cos i + F_R^{'} \sin i$.

Now, since $F_S^{'} = F_S \cos\eta_S$, $F_P = F_S \dfrac{\cos\eta_S \cos(\lambda_n - \alpha_n)\cos i}{\cos(\phi_n + \lambda_n - \alpha_n)} + F_S \sin\eta_S \sin i$. All together what you can find out the expression which you have taken that F_S common and this expression will be the expression for the F_p.

Now the F_S, that is the shear force, this is equal to we said earlier, that the stress and the area of the shear plane which is equal to $\dfrac{bt}{\sin\phi_n \cos i}$ which is the area and k is the shear stress. So, F_S can be replaced by this value and then if you simplify, this will give you the expression as shown. So, this is the expression for the F_P which is the cutting force, and this is equivalent to F_C in the case of the orthogonal cutting that we have discussed.

Now, if we consider the orthogonal case, go back to the orthogonal case and find out how we have determined analytically the value of the F_C. You will find that there is a similarity; except that there are components which are coming in the normal plane because the tool is inclined and the cutting forces are not anymore remaining in the x z plane, it will be in all x y z plane.

Therefore, the resultant force R does not remain perpendicular to the workpiece surface. As we said that initially, the R is not in the plane perpendicular to the finished surface, so because of that all these problems come that, all these components we have to consider. But there is a similarity between the oblique cutting and the orthogonal cutting except the forces coming in the other planes like the normal to the cutting edge, and parallel to the cutting edge. Rest of the things we will discuss in our next session.

Thank you for your attention.