Machining Science - Part I
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Lecture – 04

Hello and welcome to the 4th lecture of the course on Machining Science. Let me remind you that in the last session, last lecture, we have discussed the typical lathe tool.

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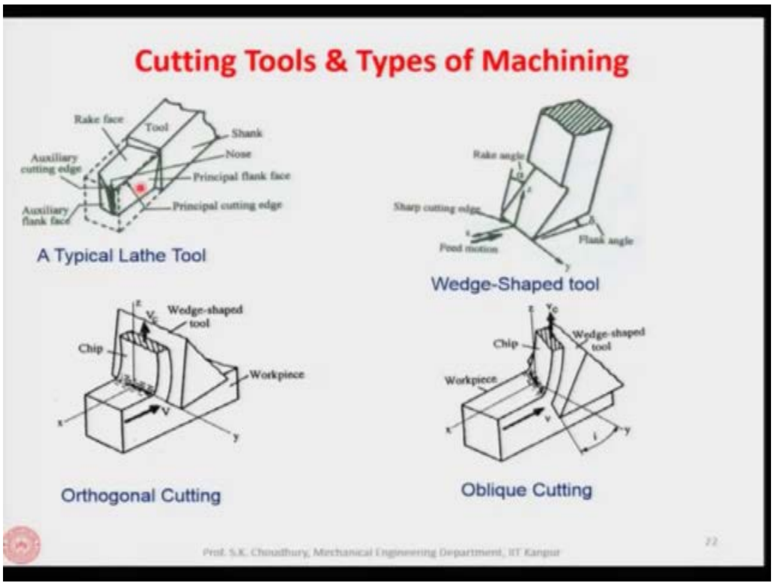

And we said that here basically there are two faces, one which is the rake face, and along the rake face always the chip flows, and there is a principal flank face. Apart from that there is an auxiliary flank face. And there are two edges, one is the principal cutting edge and another is the auxiliary cutting edge. Apart from that we have the shank, and the shank helps us to clamp the tool in the tool post.

Now, instead of showing the lathe tool in the analysis, it is easier to analyze the cutting process with the help of a wedge shaped tool, because here also we have the rake face, we have the flank face. And inclination of the rake face can be defined by the rake angle. And the rake angle as we said is the angle between the rake face and a line perpendicular to the cutting velocity vector.

This is not the straight line as sometimes people confuse. This line between which the rake angle is determined, this is the line which is perpendicular to the cutting velocity vector. Similarly, flank angle is given by the flank face and this is the already machined surface. So, the already machined surface makes an angle with the flank face which is called the flank angle. The rake face makes an angle with the line perpendicular to the cutting velocity vector is the rake angle. These concepts we have discussed.

Then we said that basically there are two types of cutting processes – one which is orthogonal type, and another which is the oblique cutting. Orthogonal cutting and oblique cutting, these two are normally practiced in the industries. Now, in the orthogonal cutting, the cutting velocity vector makes a 90^0 angle with the cutting edge of the tool. So, the angle between the tool edge and the cutting velocity vector is strictly 90^0.

If the tool is inclined, as it is shown here and tool is inclined with respect to the cutting velocity vector, then it will be oblique cutting. So, in orthogonal cutting since the velocity vector makes an angle of 90^0 with the cutting edge, the chip will be flowing strictly perpendicular to the cutting velocity vector in the z-axis, as it is shown here.

The forces which act here will be confined to the x and z-plane only, because the tool edge is perpendicular to the cutting velocity vector. There will be no side spread of the chip and the chip will be flowing exactly perpendicular to the cutting edge.

In case of oblique cutting, since there is an inclination angle, and by the way this tool inclination is defined by the tool inclination angle which is *i*, and this is also sometimes called the angle of obliquity because this is the oblique cutting. And since this is - there is an angle between the cutting edge and the cutting velocity vector which is not 90^0, therefore, the chip will be flowing at an angle from the perpendicular to the cutting velocity vector, meaning that it will not be flowing exactly along the z-axis, but it will be inclined to that.

The cutting forces will be confined not only to the x z plane, but now it will be on x, y, z, all three planes. This is the basic difference between the orthogonal cutting and oblique cutting. Therefore, orthogonal cutting is known as the two-dimensional case or two-dimensional cutting and oblique cutting is a three-dimensional cutting. Two-dimensional cutting because the forces are confined to the x z plane; and oblique cutting is a three-dimensional cutting, because the forces are confined to x, y, z plane.

Mostly in practice it is the oblique cutting that is practiced, because in oblique cutting the tool strength is more because the tool is not grabbing the work piece at a time like in the case of the orthogonal cutting. So, the tool life is less in orthogonal cutting, and tool life will be or tool strength rather will be more in the oblique cutting.

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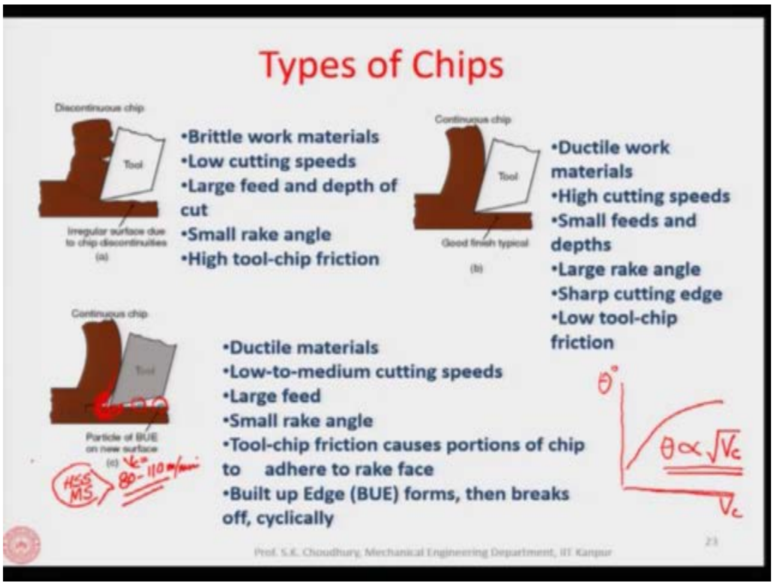

Now, let us see the types of chips which is very important because depending on the types of chips or depending on the workpiece material and the properties or the machining parameters, we can have different types of chips. For example, we can have the continuous chip. If the material is ductile, for example, if it is a mild steel, in that case the chip which will be formed will be continuous.

Now, the other parameters which are responsible for the formation of continuous chip are the high cutting speeds, small feeds and depth of cut. Rake angle has to be large for the formation of the continuous chip; cutting edge is sharp, and the low tool-chip friction, that means, the coefficient of friction between the rake face of the tool and the chip should be low. So, all these parameters have to be satisfied, all these conditions have to be satisfied, so that we can get the continuous chip.

Apart from that there is discontinuous chip, and in case the material is brittle for example, if it is a cast iron kind of material which is brittle, then the chips will be broken, because as I have discussed it while discussing the tensile test that the tensile test shown is valid only for the mild steel or only for the ductile material. In case of brittle material, it cannot go beyond the proportional limit, because it is brittle material and it will break.

So, the chip that is formed during the machining of the brittle materials is discontinuous. And because of the discontinuous chip, the surface finish is not good or surface finish in comparison to the continuous chip is worse in the sense that as the chip is breaking there is a peak or there is a fluctuation in the forces each time the chip breaks and that gives bad surface finish or low or the high value of the surface roughness.

Now, the other conditions for which the discontinuous chip is formed is low cutting speed, large feed and depth of cut, small rake angle, and the high tool chip friction. So, as you can see that these conditions are just opposite to the conditions which we have applied for the formation of the continuous chip. So, we have basically the discontinuous and the continuous chip.

Once again, continuous chip is formed when basically the workpiece material is ductile, and the cutting speed is high, small feed, large rake angle and the coefficient of friction between the chip and the rake face is low. And opposite conditions will be for the discontinuous chip and particularly when the material is brittle.

Now, in between these two types of chips, under certain condition of temperature and pressure and as you understand that as the velocity goes higher, the temperature rises, and you may be knowing that the temperature rises in the following way, suppose this is the temperature curve and this is the cutting velocity, so, this will be non-linear. And the temperature actually varies non-linearly and it is $\sqrt{V_c}$.

So, as the cutting velocity increases, the temperature increases. At a certain condition of temperature and pressure, instead of chip flowing along the rake face smoothly, there will be a very thin layer which will be ruptured from the chip surface because the high pressure and high temperature. Because of this condition also a very thin layer from the rake face of the tool will be ruptured. So, now the rake face and the chip will have the nascent surfaces, that means, a very thin layer of chip will be removed from the chip surface, and a very thin layer will be removed from the tool rake face. So, these two nascent surfaces will have the affinity to each other, and they will get welded. As the welding takes place, there will be resistance to the flow of the chip and the chip will not be able to flow smoothly, and it will get resisted. So, it will pile up against the tool tip. This piling will grow as the cutting process progresses.

Now, once the piling happens, it will create more resistance to the flow of the chip and the pile will grow more and more and finally, it will be unstable and the pile will break. But still this high pressure and high temperature condition persists, so, again the piling starts because of the formation of nascent surfaces of the chip and the rake face that will get welded, it will create more resistance to the flow of the chip and the piling starts again.

This piling in front of the tool tip is called the built-up edge. So, built-up edge forms not every time, but at a certain condition of temperature and pressure, for example, in case of HSS - high speed steel, mild steel as a material this is the about 80 to 110 m/min, this is the V_c, cutting speed at which, actually this condition happens, there is a high temperature and pressure particularly for a combination of mild steel as a workpiece and high speed steel as tool material.

As the cutting process progresses, the temperature rises further. And when the temperature goes beyond the temperature of recrystallization, then the built-up edge formation stops, it ceases. For example, in case of a combination of mild steel and high speed steel, as the cutting velocity goes beyond 110, the temperature goes beyond the temperature of recrystallization and the built-up edge stops forming and then the cutting process goes on.

Now, the built-up edge, as you understand, is not desirable because as the built-up edge is formed, the tool geometry changes. And again this is a dynamic process, because the built-up edge grows and then it breaks because it becomes unstable. So, at any instant of time, the value of the rake angle is different, and therefore, the cutting process changes because as we know and further I will discuss it that on the rake angle, the cutting force, the cutting power, power consumption - all depend.

So, it is not desirable to have the built-up edge formation, and we have to avoid the formation of the built-up edge. Now, the built-up edge is probably only useful when a tool with a built-up edge can be used for the rough turning. For example, if we have a very hard surface on the top of the workpiece and that has to be removed before the normal machining process happens, then a tool with a built-up edge can be used because this built-up edge material is strain hardened material and it is very hard material.

It is harder than the tool material, and therefore, the tool life will be high and the tool will not wear out fast if such a tool with the built-up edge can be used for the rough turning. This is probably the only advantage, but otherwise as far as possible the built-up edge should be avoided.

Now, another reason why it is not desirable is that when the built-up edge breaks, then the part of the built-up edge remains embedded on the workpiece surface, already machined surface as you can see here, here and here, and part of it will be remaining on the chip when it breaks.

So, keep apart the chip because it goes away anyway, but the already machined surface will be spoiled, because the part of the built-up edge or the particles will be embedded in the already machined surface. So, this is another reason why we should avoid the built-up edge formation.

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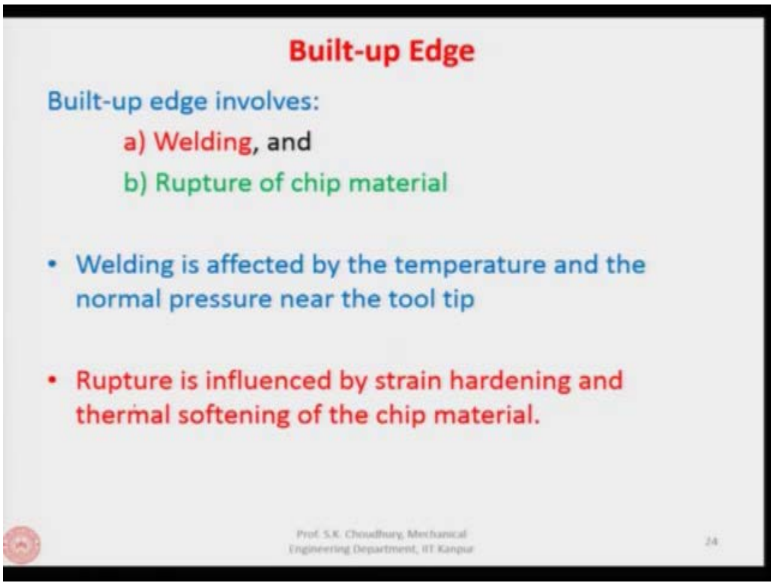

Now, built-up edge happens at a high pressure and high temperature therefore, the mechanisms responsible for the built-up edge are the welding and the rupture of the chip material. Now, the welding is affected by the temperature and the normal pressure near the tool tip meaning that if the temperature is higher, normal pressure is high, so the welding will happen because as I said a very thin layer will be ruptured from the chip surface as well as from the tool rake face, and they will have the affinity; they will get welded.

Now, the rupture is influenced by the strain hardening and thermal softening of the chip material that is how the built-up edge gets ruptured. So, these are the two mechanisms of the built-up edge formation which is welding and the rupture. Welding is affected by the temperature and pressure, and the rupture is influenced by the strain hardening and the thermal softening of the chip material.

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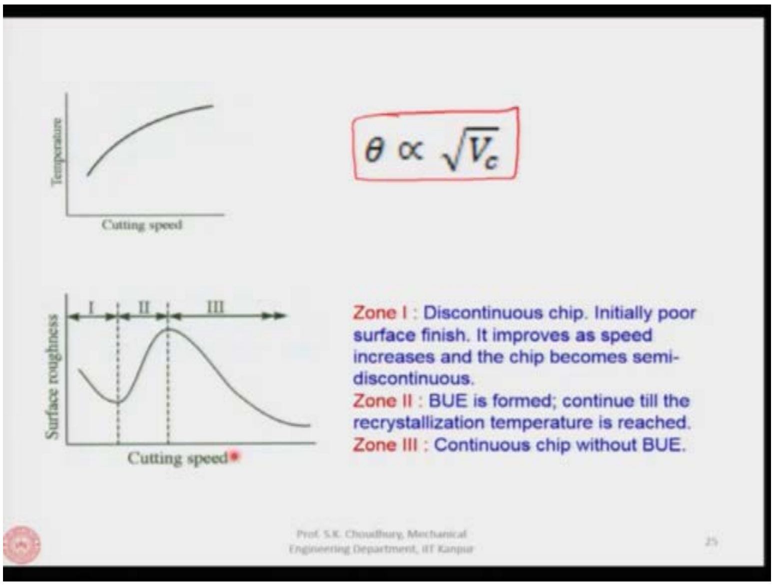

Here as I said that with the cutting increase in the cutting speed, the temperature increases nonlinearly, and the temperature is proportional to the root over of the cutting velocity. So, as the cutting process goes on, as the cutting speed increases, the temperature increases and therefore, it comes into the built-up edge formation zone and the built-up edge gets formed.

Now we know that there are discontinuous chips, there are continuous chips, there are chips with the built-up edge formation. So, here is what happens as the cutting process progresses, as the cutting speed increases with the surface roughness or the surface finish.

At a very low speed as the cutting process starts, then the surface roughness is high, because as we have said that the low speed, at the low speed the chips are discontinuous. And when the discontinuous chip happens, I have already explained that the surface finish is not good. So, surface roughness values will be higher meaning the surface finish is bad. As the cutting process progresses, as the cutting speed is increased, so the discontinuous chip becomes continuous with the increase in the cutting speed, and the surface finish becomes better meaning the surface roughness values reduce.

With further increase in the cutting speed, this goes into the zone of built-up edge formation. And as the built-up edge is formed, the surface finish becomes worse because of many reasons, two basic reasons are: one is that particles are embedded on the already machined surface, and the rake angle is fluctuating, rake angle changes.

And of course, the entire geometry of the cutting tool is changed because of the formation of the built-up edge. So, the surface finish is bad, surface roughness values increase. And as it reaches to this point, with further increase in the cutting speed, the temperature goes up and it becomes more than the temperature of recrystallization, then the built-up edge stops being formed and the surface finish becoming better and better, so that surface roughness values decrease.

So, in zone 1, discontinuous chip is formed resulting in poor surface finish initially. It improves as the speed increases and the chip becomes semi discontinuous. So, it is not really continuous exactly, but it is relatively more continuous, and the surface finish becomes better.

In the zone 2, the built-up edge is formed; continue till the recrystallization temperature up to this. And then after this the third zone is the continuous chip without the built-up edge formation, so the surface finish becomes better and the values of the surface roughness reduce. So, this is what happens with the surface roughness as the cutting speed increases.

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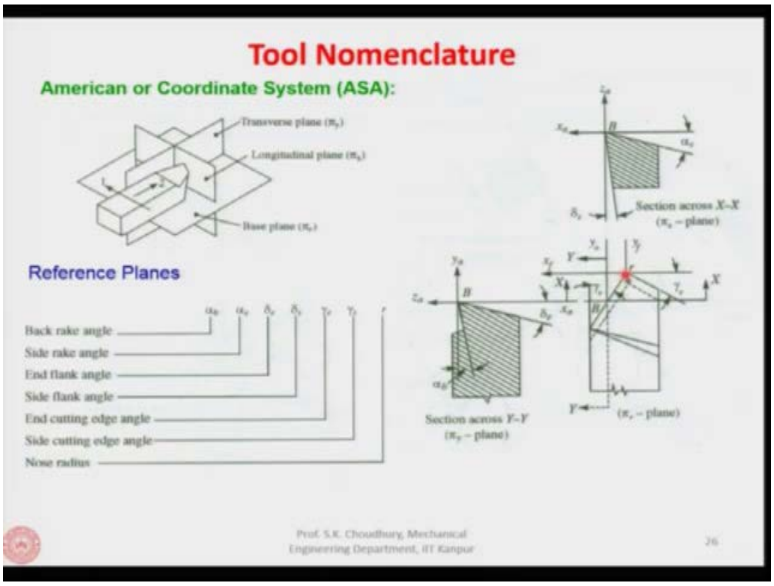

The next topic that we would like to discuss here is the tool nomenclature, that means how the tool angles are defined. By the way the tool nomenclature, when the tool angles are defined, different countries adopt different nomenclatures.

For example, one of the nomenclatures is called the coordinate system or the ASA, this is the American system because it is used mostly in United States. Here this plane is the base plane. Base plane is a plane on which the tool is resting. Perpendicular to the base plane there are two more planes, one is called the longitudinal plane and another is the transverse plane.

The longitudinal plane is along the longitudinal feed, that is the feed given to the tool, and the transverse plane is along the transverse feed given to the tool. So, this plane is parallel to the transverse feed, and this plane is parallel to the longitudinal feed. These are the three mutually perpendicular planes by which the tool angles are defined in the coordinate system or the American system. So, let us see how it is defined.

Suppose you have the tool here in the base plane. Now, at any point here on the cutting edge, one of the cutting edges, so this is the principal cutting edge, you take two sections - one is y-y and another is x-x. So, x-x view we will put at the top and y-y view we will put at the left. So, in these views we can see the rake and the flank faces.

So, the inclination of the rake face with respect to the line perpendicular to the cutting velocity vector, this is the line in the x-x view. So, this makes an angle which will be called the rake angle. Similarly, in this y-y view the rake angle will be between the rake face and the line perpendicular to the cutting velocity vector here. Now, mind it in these two planes, both are rake angles, but the values of the rake angle will be different, because these are the two different planes, because there are different inclinations given to the tool.

Now, apart from this there are two more angles, one is with respect to the principal cutting edge, and another with respect to the auxiliary cutting edge. So, now we have two rake angles, two flank angles, and two cutting edge angles because we have the principal cutting edge and the auxiliary cutting edge. These are the 6 angles by which the tool is defined or the nomenclature is given. The sequence is the following that first this angle is defined that is called the back rake angle. Second is the side rake angle it is in here in the x-x section.

Next is the end flank angle, and the end flank angle is here in the y-y section. And next is the side flank angle, side flank angle is here in the x-x section. And the two of the cutting edge angles, one is the end cutting edge angle, and here is the side cutting edge angle. Side cutting edge angle, by the way, is between the principal cutting edge, and this line which is making the angle, which is called the side cutting edge angle. And end cutting edge angle is between the x-axis and the auxiliary cutting edge. So, this is the end cutting edge angle.

Now, these six angles and in this sequence will be given in the tool nomenclature. Once again: the back rake angle, side rake angle, end flank angle, side flank angle, end cutting edge angle, side cutting edge angle. And another factor which is important here is the nose radius. Now, each tool will have a certain curvature on the nose and that curvature is required for the cutting process to go smoothly that we will discuss later. This is the tool nose radius.

So, apart from the six angles that we have, that is, one set of rake angles, one set of flank angles, one set of cutting edge angles, and apart from that we have the tool nose radius. All these seven factors are given in the tool nomenclature. Particularly in this coordinate system this is the way that is given here, and this is used only as I said in the United

States, and it is called the ASA system or the coordinate system, because it is the simple coordinates x y coordinates or the transverse and the longitudinal planes are used.

Once again, the base plane, longitudinal plane and the transverse plane, they are three mutually perpendicular planes. And in these three mutual perpendicular planes the angles are defined. So, this is one way of defining the tool angles.

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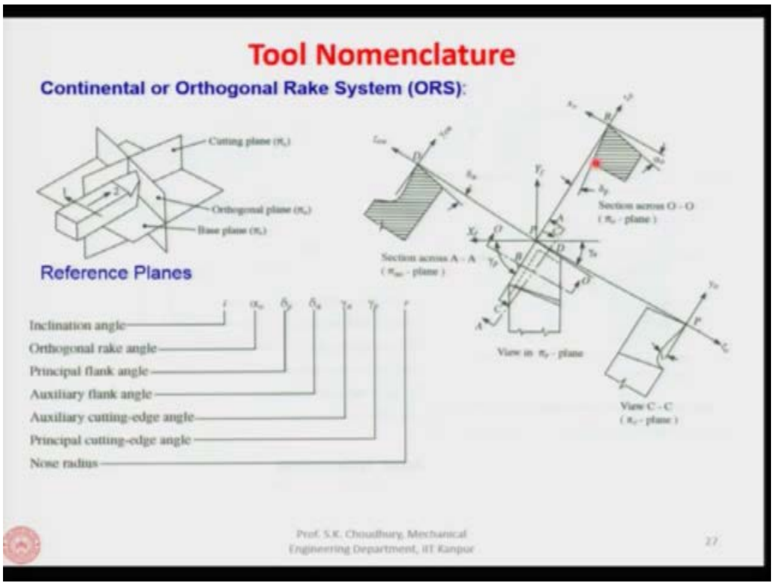

Second is the continental or the orthogonal rake system, by the way this kind of a tool nomenclature is used in India. So, this is also called the continental. And the system is orthogonal rake system. Here the planes that are used are different than the one that are used in the ASA system. Here we have the base plane, this is the same as in case of the coordinate system on which the tool is resting.

And the two more planes, one is called the cutting plane, cutting plane will contain the cutting edge - that is the plane which is called the cutting plane. And perpendicular to the cutting plane and perpendicular to the base plane is the plane which is called the orthogonal plane.

So, you have three planes - base plane, cutting plane and the orthogonal plane. Once again, cutting plane will contain the cutting edge; orthogonal plane is perpendicular to the cutting edge. They are also mutually perpendicular planes. Within these three planes the angles are defined in the ORS system. ORS stands for the Orthogonal Rake System.

Here we have the tool as it is shown in the base plane like in the case of the ASA system. We will take the sections in different planes. The cutting plane - cutting plane contains the cutting edge, so this is the principal cutting edge. So, the C-C this is the cutting plane containing the cutting edge. Another plane which we will take as orthogonal plane is perpendicular to this and perpendicular to the base plane; so, this is the O-O plane which is perpendicular to this, perpendicular to the cutting edge here.

We will take another plane which we will call as the auxiliary plane. This is A-A which is perpendicular to the auxiliary cutting edge - this is the auxiliary cutting edge, and this plane is perpendicular to the auxiliary cutting edge. So, if we see the orthogonal plane for example, in the sense that we will cut it off and then we will see it like this. So, you will see that the rake face is here, flank face is here. Similarly, in the case of the cutting edge since it is not a section, so this is not hatched and it is not a sectional view and the view is like this. So, here we will have the rake face; here is the flank face.

If we look at the sectional view A-A which is perpendicular to the auxiliary cutting edge, we will see the view like this where this is the rake face and this is the flank face. Accordingly, now that we have defined that the rake face and the flank face in each of these sections, we can find out the angles. The angles will be different than the angles that we have determined in case of the ASA because these planes are different.

For example, here this is the orthogonal plane, and this is the angle between the rake face and a line perpendicular to the cutting velocity vector. So, this will be called as a rake angle, but this is the orthogonal rake angle. So, this is different than for example, the back rake angle in ASA or the side rake angle in the ASA. Another rake angle that we can find out is this. Here this is the rake face, and this is the line perpendicular to the cutting velocity vector.

This angle is called the *i* which is the tool inclination angle. The details about all other angles we will discuss in the next lecture.

Thank you.