Machining Science - Part I
Prof. Sounak Kumar Choudhury
Department of Mechanical Engineering
Indian Institute of Technology Kanpur

Lecture - 07

Hello and welcome to the 7th lecture of the Machining Science course. In the last session we have discussed the selection of tool angles. Selection of particularly the rake angles, flank angle, cutting edge and tool cutting edge angles are extremely important because the cutting forces, surface finish, power consumption of the machining are all dependent on the proper selection of the rake angles.

We said that although the cutting force and power consumption reduce if we increase the rake angle, but the rake angle cannot be infinitely increased because in that case the cutting angle decreases and therefore, the tool becomes weaker and less material is available for the heat conduction.

So, during the machining because of the plastic deformation and because of the chip sliding over the rake face of the tool, a lot of heat is produced and part of it goes to the tool. If the temperature which is occurring during the machining is not conducted from the tool in that case there will be thermal deformation of the tool. Therefore, we cannot infinitely increase the value of the rake angle and there is an optimum value at which the tool will be neither very weak nor it will consume lot of power and lot of force.

Therefore, there is a range of rake angles particularly the side rake angle, orthogonal rake angle and the normal rake angle and the range given was about 5^o to 15^o. Although, we said that negative rake angle tools are also used for example, for the carbide tools, when we have to have the strong tool, because there are quite a lot of force involved in the high speed cutting and particularly the carbide tools are brittle. It cannot withstand the jerks or the sudden increase in the load. Therefore, the tool has to be strong. To make the tool stronger we have to have the more material and therefore, the cutting angle has to be large and the rake angle has to be less. Hence, the rake angle should be selected as less as possible, i.e, a negative rake angle can be selected.

It is very important to select the tool judiciously so that the power consumption and the surface finish, particularly, become desirable as per the requirement.

Now, the cutting forces in the machining and the Merchant's circle diagram will be discussed; this is the mechanistic model which explains the mechanics of metal cutting.

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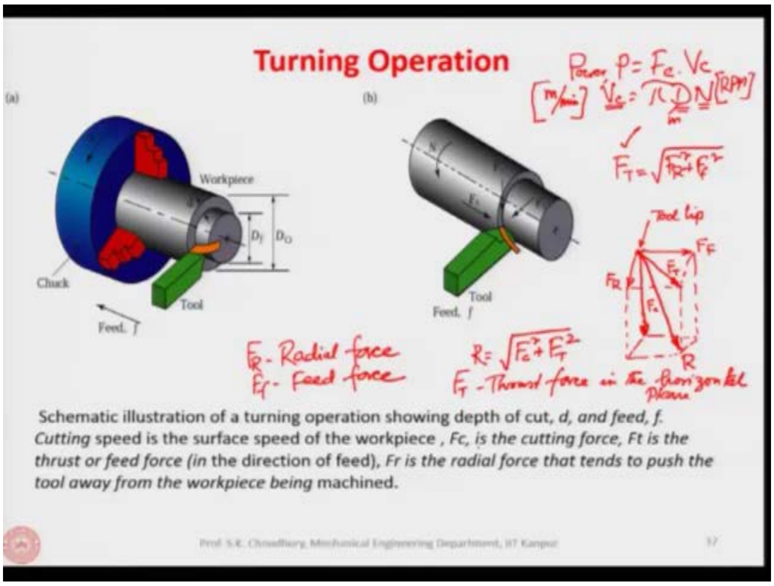

Let us consider the turning operation on the cylindrical work piece which is clamped with the help of the three jaw chuck. The three jaw chuck is used for automatic centering the workpiece. Although, four jaw chucks and collet chucks can also be used, but here only a three jaw chuck is shown which is used for mounting or clamping the workpiece.

During the machining, particularly three major forces are acting; one is the cutting force which is the major force and there is a thrust force which is the combination of the radial force and the feed force.

The direction of the feed force is along the direction of the feed and perpendicular to that is the radial force. Radial force is acting perpendicular to the feed direction. So, it will try to detract the tool from the workpiece. The cutting force is vertically located.

So, as shown in the slide, if it is the tool tip, so, this will be the direction of the feed force. So, this is the direction of the feed. Now, this is the tool tip; Now, if this is the feed direction, so then in the radial direction we have the force like this; so, this is the F_R. Resultant force in the horizontal plane, F_T is called the thrust force. So, the thrust force which becomes equal to $\sqrt{F_R^2 + F_f^2}$. F_R is the radial force and F_f is the feed force.

Now, draw a parallelepiped by using the forces F_R , F_f and F_c as shown in the above slide. The diagonal of the parallelepiped represents the resultant force $R = \sqrt{F_c^{\,2} + F_T^{\,2}}$. where F_c is the cutting force and F_T is the thrust force. Thrust force, F_T is in the horizontal plane and is given by $F_T = \sqrt{F_R^{\,2} + F_f^{\,2}}$ where F_R is the radial force and F_f is the feed force..

So, what we have is the radial force at the tool tip. The resultant of radial force and feed force is the thrust force, F_T which is in the horizontal plane. In the vertical plane we have the cutting force F_c which is actually responsible for the power consumption. We have seen in our earlier lectures that power is the product of F_c and the cutting velocity V_c. The cutting velocity, $V_c = \pi ND$ where D is the diameter of the workpiece, N is in revolution per minute (RPM). D will be in meter. So, V_c is given in m/min unit .

Now, the force F_c is responsible for the power consumption. Therefore, this is important that F_c consumed during the process should be as minimum as possible so that the power consumption remains minimum. What does minimum power consumption mean? suppose you are using a machine tool for removing the workpiece material from the job to give the final shape, size, finish, accuracy. If the power consumption is very high in that case the machine will be very bulky and expensive. Therefore, the cost per piece which you are making in that machine will be very high and you cannot afford to compete in the market.

So, we have already discussed in our last class that we should judiciously select the angles, particularly the rake angle of the tool so that the machining operation can be performed in an optimum way. So, that the shape size finish accuracy obtained with a minimum cost.

Finally, basic forces in the turning are the thrust force, F_T and the cutting force F_{C}. The resultant force is $\sqrt{F_c^2 + F_T^2}$. Let us see how these forces can be correlated together.

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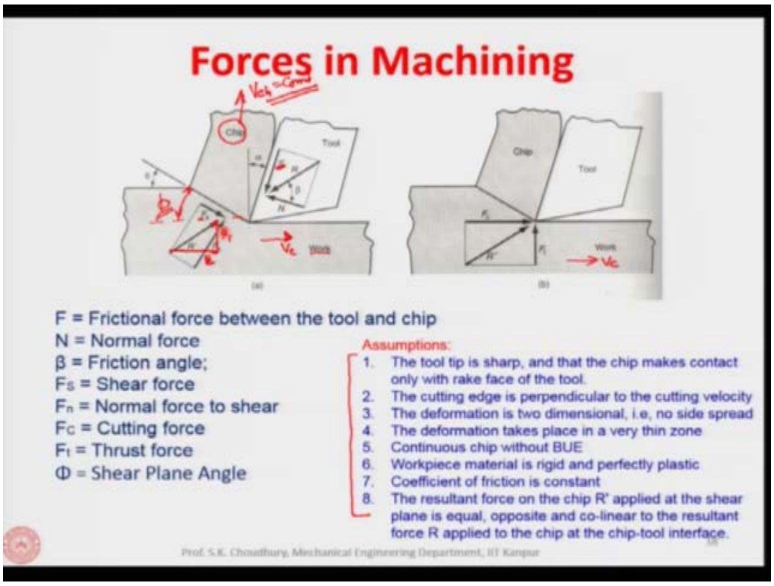

In the diagram shown here, we have the workpiece, tool and a chip flowing along the rake face of the tool. The tool has a rake angle of α. Shear plane is shown here which is the plane along which the maximum plastic deformation occurs. Shear plane angle ϕ is the angle between the shear plane and the line drawn parallel to the velocity vector, V_c.

Now, assume that the chip flowing over the rake face of the tool is a lumped homogeneous body and flowing at a constant velocity over the rake face of the tool. Then the resultant of the forces acting on the chip from the tool side through the rake face of the tool, and the resultant force acting on the chip from the workpiece which is the reaction force acting through the shear plane, the summation of them will be equal to zero.

In other words, resultant of the forces acting on the chip from the tool side and the resultant of the force acting on the chip from the work piece side have to be equal, opposite and collinear. Then only the chip, as a lump body can be moving at a constant velocity over the rake face of the tool.

Once again, I will repeat that here we have a resultant force which is acting on the chip and this is the resultant force acting on the chip from the workpiece side. Now, the resultant force R' is acting on the chip through the shear plane and the resultant force R acting on the chip from the tool through the rake face of the tool. So, they have to be equal, opposite and collinear. So, that their summation will be equal to zero; Then the chip moves at a constant velocity. So, let say V_{ch} is the chip velocity which is constant. The chip is moving at a constant velocity over the rake face of the tool.

Now, the resultant force R can be resolved into two components; one component is F which is along the rake face of the tool, and another which is perpendicular to the rake face of the tool let us say N.

The force F, which is parallel to the rake face of the tool or acting along the rake face of the tool, can be considered as the frictional force, and this friction force is appearing because of the normal force acting on the chip from the tool side. So, the friction force F is because of the normal force N. β is the friction angle between the resultant force R and the normal force N which is acting on the chip.

Similarly, the resultant force R' acting on the chip from the workpiece side through the shear plane, also can be resolved into two components; one which is parallel to the shear plane F_S and another which is perpendicular to the shear plane which is F_n. Since F_S is parallel to the shear plane, therefore, F_S is considered to be the shear force and normal to that is the F_n .

Now, we have four components of forces: F friction force, N normal force, F_S shear force and F_n normal to the shear force. During the machining when ϕ is altered and α is altered, the directions of F_S , F_n , F and N will be changed. Therefore, during the machining the power consumption can fluctuate.

Particularly the shear plane angle ϕ can change a bit and if the shear plane angle changes in that case direction of the F_S , F_n , F and N will be changed. Therefore, we do not have constant direction of F_S , F_n , F and N .

Now, R' can also be resolved into two more components. One is F_c which is parallel to the cutting velocity V_C, and second is F_t which is perpendicular to the cutting velocity.

Suppose F_t is the thrust force and F_c is cutting force. Since F_c is parallel to the cutting velocity vector therefore it is called the cutting force because this is responsible for the power consumption as the product of F_c and the V_C is the power. F_c which is parallel to V_C is the cutting force and perpendicular to F_c is the thrust force.

We have six force components; friction force, normal force, shear force, normal to shear force, cutting force and thrust force. Any change in the shear plane angle ϕ will not change F_c and F_t , they will remain constant. They have an identical or a particular constant direction whatever happens with the shear plane angle that is why R' is also resolved into F_c and F_t. The six components can be correlated which was done by Merchant and Ernst in about 1944. That is considered to be the first model which explains the mechanics of metal cutting.

Explanation of mechanics of metal cutting helped us greatly because we tried to understand the machining process. We have gone deeper into the machining process with the help of the merchants diagram which is of course very basic. But nevertheless, this is the first treatment given to the mechanics of machining and therefore, it is important for the analysis of the machining process. The forces are correlated with the angles. There are eight assumptions which have been considered by them.

First assumption is that the tool tip is sharp. So, tool cannot have any nose radius and that the chip makes contact only with the rake face of the tool, because the tool is sharp. Second assumption is the cutting edge is perpendicular to the cutting velocity and if you remember this is the condition for the orthogonal cutting. They are assuming that this is a two-dimensional cutting or the orthogonal cutting.

The third assumption they made is that the deformation is two-dimensional, therefore there will be no side spread. Meaning of side spread was explained during the discussion of the orthogonal and the oblique cutting. In the orthogonal cutting, the cutting edge makes a perfect 90^o angle with the cutting velocity vector. The chip flows exactly perpendicular to the cutting edge of the tool and there is no side spread. It does not become inclined to normal to the cutting edge. So, there is no side spread of the chip while flowing along the rake face of the tool.

Fourth assumption is the deformation takes place in a very thin zone. This assumption had to be taken because the plastic deformation actually does not happen along a plane but it happens along an area. So, actually the shear plane is much thicker. They have assumed that the deformation is taking place in a very thin zone.

We will discuss it at a later stage that when the cutting speed increases the deformation zone becomes thinner and thinner. It can be assumed at a very high speed that the plastic deformation is occurring in a plane. So, here they are assuming that this is the plane and not the zone.

Fifth assumption is the continuous chip without the built up edge formation. If it is not continuous chip in that case of course, this model will not be valid. Sixth assumption is the workpiece material is rigid and perfectly plastic. If it can be assumed to be a perfectly plastic and rigid body and moving at a constant velocity then only the R and R' will be opposite, collinear and equal.

Seventh assumption is the coefficient of friction is constant. Coefficient of friction along the chip tool contact length μ has to be constant. And finally, they have assumed that the resultant force on the chip R' applied at the shear plane is equal, opposite and collinear to the resultant force R which is applied at the chip tool interface. So, R and R' have to be collinear, equal and opposite. With these 8 assumptions they have correlated, these forces along with the angles.

If we draw a circle with a diameter of R or R' then all the tips of the components F_n, F_C and F_t have to lie at the periphery of that circle. Because all these forces are the components of resultant forces R or R' which are equal.

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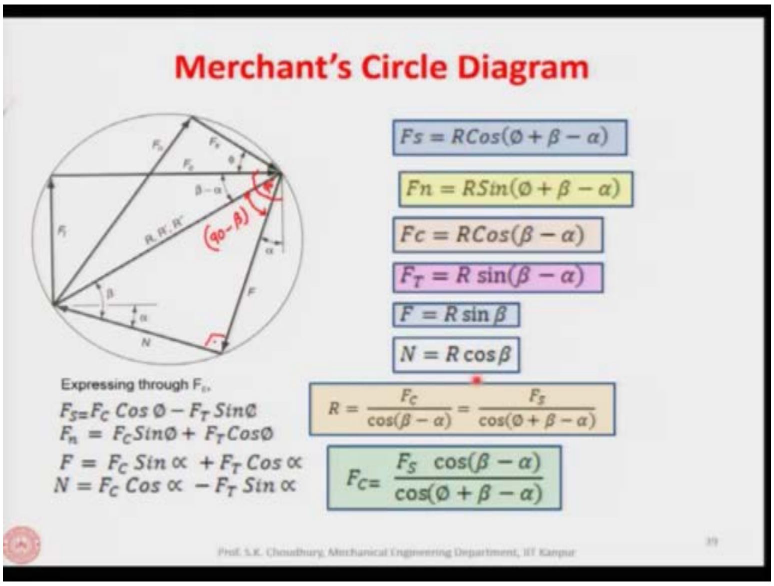

So, in the circle of diameter R or R', F_c will be the cutting force which is parallel to the cutting velocity vector and perpendicular to that is the thrust force F_T. Now, F_S is the the shear force which is parallel to the shear plane while perpendicular to F_S is the F_n. And there are two more forces; one is the F which is parallel to the rake face of the tool and perpendicular to the rake face of the tool is N which is normal force.

You can see the tips of all these components are lying at the periphery of the circle with a diameter of R or R'. The circle is called the Merchant's circle diagram and this circle explains the mechanics of machining in the following way.

Now, between the F_S and the F_c the angle is the ϕ which is called the shear plane angle. F_S is parallel to shear plane and F_c is parallel to the V_C.

Now, F is the friction force which is along the rake face of the tool and F_t is perpendicular to V_C. α is the rake angle of the tool. α is the rake angle which is between the F and the line parallel to F_t . So, you can assume that α is between the F_t and the F.

Now, we have seen that between the N and the resultant force, the angle is called the friction angle β. The angle between the line perpendicular to F_t and perpendicular to F which is N is also α which is the rake angle. Therefore, if angle between the F_S and the F_c is ϕ and angle which is between the F and the line parallel to F_t is α, then the angle between R and F_c will be the $\beta-\alpha$ because angle between F and N is actually the 90^o, therefore, the angle between R and F is $90-\beta$. Again the angle between F_c and a line parallel to F_t is 90^o therefore, you can see that the angle between F_c and R will be $\beta-\alpha$. β is the friction angle and α is the rake angle of the tool.

Now, if we have this geometry then from here we can find out the force components from the triangles. For example, F_S with respect to the R or R' will be the R multiplied by the angle between F_S and R i.e. $F_S = R\cos(\phi+\beta-\alpha)$. F_n which is perpendicular to F_S will be $R\sin(\phi+\beta-\alpha)$, because it is perpendicular to that and the angle will be the same $(\phi+\beta-\alpha)$.

So, we have determined F_S and F_n analytically; that means, if R is known and these three angles are known then F_S can be found out. Similarly F_c will be $R\cos(\beta-\alpha)$. F_t which is perpendicular to that will be $R\sin(\beta-\alpha)$. And finally, we have the two forces which is friction force F which will be $R\cos(90-\beta)$ which is $R\sin(\beta)$.

Now, this is the friction force $R\sin(\beta)$ therefore, the N which is perpendicular to the friction force F this will be equal to $R\cos(\beta)$. So, all 6 components we found out from the Merchant's circle diagram through the angles. ϕ, β, α are the 3 angles. Particularly α is the rake angle which defines the inclination of the rake face. It is the angle between the rake face and line perpendicular to the cutting velocity vector .

Second is the friction angle, β. Friction angle is between the resultant force and the normal force or the normal component of the resultant force which is perpendicular to the rake face of the tool. And the third is the shear plane angle ϕ which defines the inclination of the shear plane and which is the angle between the shear plane and the direction of the cutting velocity vector.

So, these three angles are important, they relate all the components with the resultant force. How we can find out analytically the cutting force and other components that I will discuss in the next lecture.

Thank you for your attention.