Machining Science - Part I
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Lecture – 13

Hello and welcome to the 13th lecture of the Machining Science course. In the previous session, we were discussing the principles of measuring cutting forces. We have seen that for different processes like turning, milling, drilling or grinding, the forces are different and therefore, the measuring principle is also different. We have discussed the most basic element like axially loaded member, then we discussed the cantilever beam and then we discussed the ring type structure.

We have seen that in the ring type structure there are certain disadvantages like it is not very stable in the horizontal position, in the sense that it can actually roll under the action of the axial force. Therefore, the ring type structures are modified in the form of an octagon.

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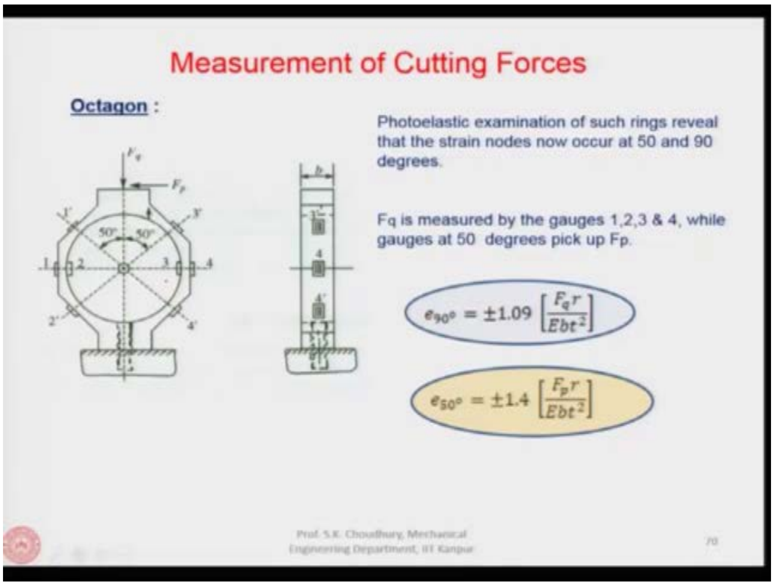

As you can see from the above slide that the left figure is an octagon which has the principle of the ring type dynamometer, but it is more rigid. And, another view of the ring type dynamometer is also shown from the side. Photoelastic examination of such rings reveals that the strain nodes occur at 50^o and 90^o. If you remember, in the ring type structure it was 39.6^o. The photo elastic examination of such octagon structures revealed that the maximum strain occurs at the nodes located at 50^o and 90^o .

So, at 90^o the sensors or the strain gauges will sense the thrust force like F_q as shown. The axial force or the tangential force F_p will be sensed by the sensors when they are placed at 50^o with respect to the vertical axis. Strain gauges placed at 1, 2, 3, 4 will sense the F_q and 1', 2', 3' and 4' will sense the tangential force F_p .

Now, at 90^o the magnitude of strength will be $\pm 1.09\left[\dfrac{F_q r}{Ebt^2}\right]$. This remains the same as in case of the ring type dynamometer or ring type structures. Whereas, at 50^o from the vertical axis, the strain will be $\pm 1.4\left[\dfrac{F_p r}{Ebt^2}\right]$, because these are the sensors which will sense the force, F_p .

Now, once again when the strain at 90^o is measured on the sensors 1, 2, 3, 4 there is no effect of the F_p , and vice versa, that is on 1', 2', 3' and 4' there is no effect of the F_q , they will only measure the force F_p. Now, based on the principles of cantilever beam or ring type structure or octagon, let us see the dynamometers that are designed and made to measure the cutting forces.

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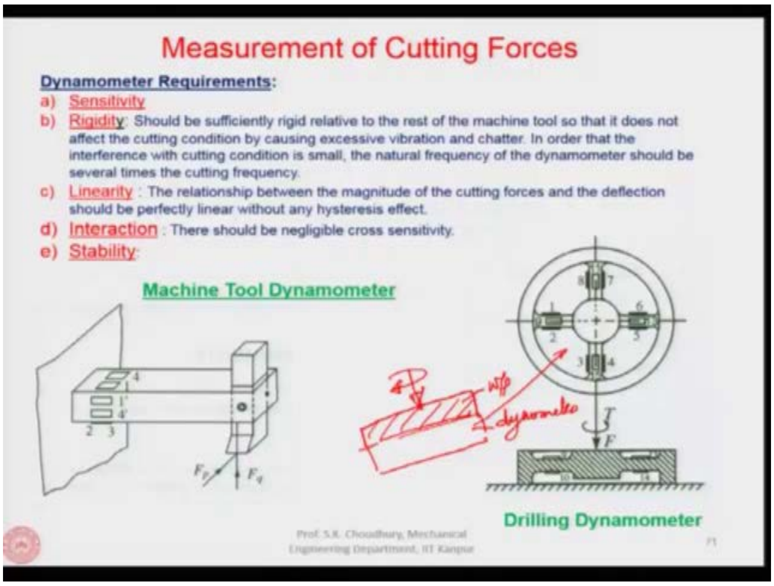

There are five requirements of a dynamometer. One is the sensitivity. The dynamometer has to be very sensitive, meaning that even a small force should be sensed by the sensors, which are present in the dynamometer. Second is the rigidity. It should be sufficiently rigid relative to the rest of the machine tool, so that it does not affect the cutting condition by causing excessive vibration and chatter. Chatter is the self excited vibration. In order that the interference with cutting condition is small, the natural frequency of the dynamometer should be several times the cutting frequency otherwise it will match the natural frequency of the dynamometer and it will be in the resonance mode and the vibration will be too high.

Third requirement is the linearity – the relationship between the magnitude of the cutting forces and the deflection should be perfectly linear without any hysteresis effect. This you understand that as it goes up it will come back along the same line. There should be no hysteresis so that the relationship between the magnitude of cutting forces and the deflection is linear. As the cutting forces increase, the deflection should increase and when the cutting forces are taken out, the deflection should come back to the initial position along the same lines without any hysteresis.

Fourth one is the interaction or cross sensitivity. There should be negligible cross sensitivity. By cross sensitivity we mean that one set of sensors should not sense the other force which they are not supposed to sense. Meaning that 1, 2, 3 and 4 will sense only F_q and the effect of F_p on 1, 2, 3 and 4 will be minimum or negligible. Therefore, interaction or cross sensitivity should be negligible. Finally, the dynamometer has to be stable enough so that the whole system is not affected by the stability of the dynamometer itself. Now, let us take some examples of design of machine tool dynamometers, their principle and how they are actually made.

Look at the design of the dynamometer which is based on the principle of a cantilever beam. Its structure has four sensors: 1 and 2, on one face and 3 and 4 at the surface opposite to it. On other surfaces which are 90^o to the previous ones, there are 1', 2', 3' and 4'. So, there are 8 strain gauges 1, 2, 3, 4 and 1', 2', 3', 4'.

So, 1, 2, 3, 4, as you understand like we have discussed in the case of the cantilever beam, will sense the vertical force F_q , which can be considered to be a thrust force. Perpendicular to that is the F_p which is cutting force, will be sensed by 1', 2', 3', 4' sensors. And, the effect of F_q will not be there on 1', 2', 3', 4' and vice versa that is the effect of F_p will not be on 1, 2, 3, 4 sensors. This is an example of the machine tool dynamometer which is used for the turning. Horizontal portion, which is a cantilever beam can be considered to be a tool post and the tool is protruding out which will cause the moment. We know the distance between the point of action of the force and where the sensors are located. Force into the length will be the moment and I have shown it to you earlier while discussing the cantilever beam that how from the moment we can find out the force. So, basically we will be measuring the strain, from the strain we can find out the moment and if we know the distance then we can find out the force because the force into distance is the moment.

Another example is the drilling dynamometer by which the thrust and the torque can be measured. It is on the principle of the ring type dynamometer, which have the arms or spokes. 1, 2, 3, 4, 5, 6, 7, 8 are on vertical surfaces of the spokes and 9, 10, 11, 12, 13, 14, 15, 16 are on horizontal surfaces of the spokes.

So, there are altogether 16 elements or 16 strain gauges or 16 sensors because as I said in the beginning that this can be either strain gauges or piezoelectric elements which will sense the force. 1, 2, 3, 4, 5, 6, 7, 8 sensors will measure the torque because if torque is provided, these arms will be deformed and along with the arms these sensors will be deformed and they will send the signal which will be equivalent to the force or the torque which is being applied.

Whereas, the thrust will be sensed by 9, 10, 11, 12, 13, 14, 15, 16 because as the thrust is applied then the elements will be deformed in the vertical plane and then strain gauges 9, 10, 11, 12, 13, 14, 15, 16 will be affected and they will sense the thrust. In the sectional view, it can be seen that if you apply the torque then 9, 10, 13, 14 and all others up to 16 will be affected and the torque can be measured equivalent to the deformation of those strain gauges in these cases.

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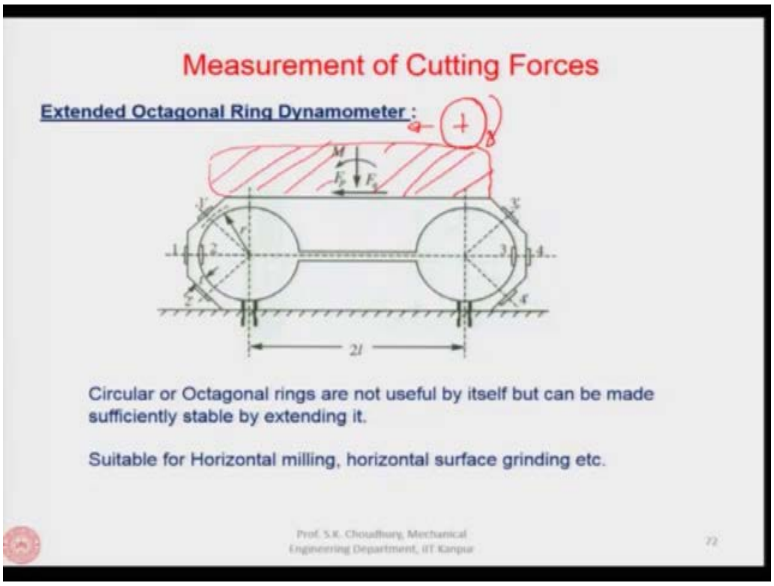

Next is the extended octagonal ring dynamometer; the octagonal structure that I have shown is an improvement of the ring type structure, which is still not enough to withstand the rigidity that is required for milling or grinding for example. So, these extended octagonal ring dynamometers are used for grinding or milling.

By the way I would like to clarify one thing that in the drilling dynamometer, the workpiece is placed on the top of the dynamometer. When a hole will be drilled in the workpiece, there will be a thrust and a torque imparted by the drill. In the dynamometer, with the principle explained earlier, the torque will be sensed by sensors 1 to 8 and the thrust will be sensed by 9 to 16. So, this is just to clarify how it works.

As the dynamometer is placed below the work piece, the dynamometer senses the torque and the thrust being imparted on the work piece by the drill. Similarly, in case of extended octagonal ring dynamometer also the work piece is placed on top of it. Let the work piece be placed over it and will be milled or will be ground. So, during the milling and the grinding, the forces that will be imparted on the work piece will be sensed by the dynamometer. It is either a thrust or a moment or a tangential force.

Here the design is the same as in case of the octagon. At 90^o and at 50^o with respect to the vertical axis, we have the 1, 2, 3, 4 sensors which will sense the thrust force F_p and 1’, 2’, 3’, 4’ sensors will sense the tangential force, let us say F_q.

So, this is the dynamometer which is extended octagonal ring because the rigidity is extended or increased. Circular or octagonal rings are not useful by itself, but can be made sufficiently stable by extending it. The rigidity and the stability have been increased by extending the octagonal structure. It is suitable for horizontal milling or horizontal surface grinding.

So, for example, when the milling cutter or the grinding wheel is working and the feed is given then the torque and the thrust will be sensed by the sensors 1, 2, 3, 4 and 1’, 2’, 3’, 4’ respectively.

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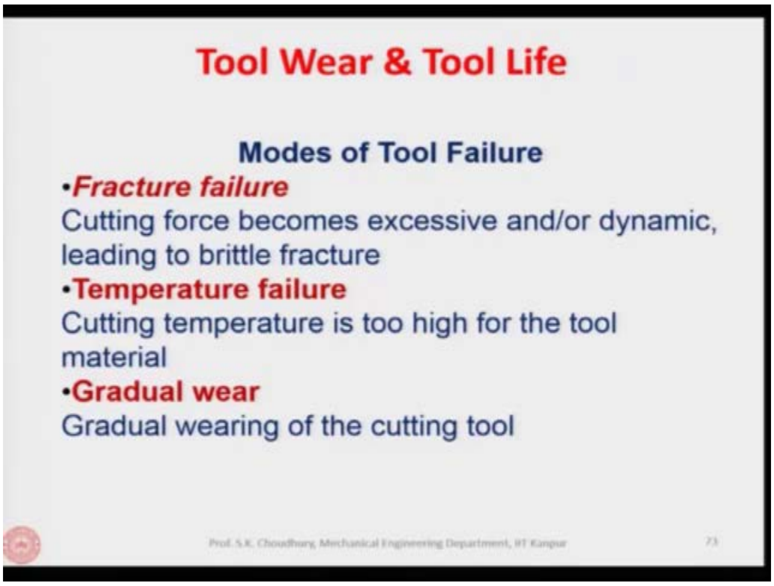

Next topic will be tool wear and tool life. Let me give you a preamble that this is a very important topic because the tool material is very expensive. The tool material is harder than the work piece material. Tool materials should have less wear.

All these properties will make the tool material very expensive and therefore, we cannot afford to have the tool wear very fast. If tool wears out very fast in that case we are bound to incur a lot of cost on the machining and the product that we will be producing will be very costly because the tool wears out making additional expenditure on the tool.

Modes of tool failure are several. For example, it can be fracture failure; tool can be failed by fracture. It can simply break. Cutting force becomes excessive leading to brittle fracture. In brittle fracture it simply breaks. The second factor could be the failure due to high temperature that is the thermal failure, i.e. when the cutting temperature is too high for the tool material. So, it will be thermally deformed and it will be failed. One of the reasons of the tool failure is the thermal failure.

Third is the gradual wear during the machining because it is in constant contact with the work piece. On the rake face, as the chip is moving continuously there is a friction. At the flank face, it is rubbing with the already machined surface of the work piece. These surfaces are in constant contact with the work piece at a high speed and therefore, there is gradual wearing of the cutting tool.

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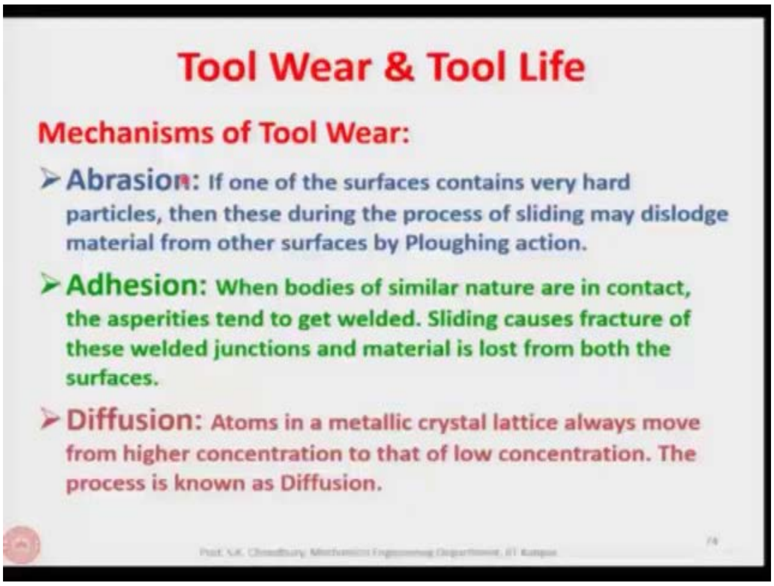

Now, the mechanism of tool wear can be either abrasion or adhesion or diffusion. It can be either one of them or a couple of them together. By mechanism we mean to say the factors which are responsible for the tool wear. What is abrasion? If one of the surfaces contains very hard particles, then during the process of sliding these may dislodge material from other surfaces by ploughing action.

If you write something with a chalk on the blackboard, you will see the chalk is wearing out because the blackboard has harder particles and it will abrade the chalk material; that is why it is called the abrasion. Second mechanism could be adhesion. This happens when the bodies of similar nature are in contact and the asperities tend to get welded. Sliding causes fracture of these welded junctions and material is lost from both the surfaces.

This we have discussed while discussing the sliding friction, that basically the two surfaces are meeting on the asperities and when the normal force is becoming higher, then those asperities will be welded and during the sliding the welded asperities will be sheared off. Because of that shearing of the welded asperities, small particles which will be broken will start abrading both the surfaces. This is called the adhesion mechanism and this is one of the factors responsible for the tool wear and that is why we call it as a mechanism of tool wear.

Third mechanism is diffusion. Atoms in a metallic crystal lattice always move from higher concentration to that of low concentration. The process is known as the diffusion. Therefore, we can explain why tools wear out, because tool material is harder and it has more atomic density. Therefore, during the cutting process when it is interacting with the work piece, the atoms from the tool which are at the higher density will move to the lower density of atomic structure which is the work piece material and therefore, the tool wears out. The diffusion is one of the mechanisms of tool wear.

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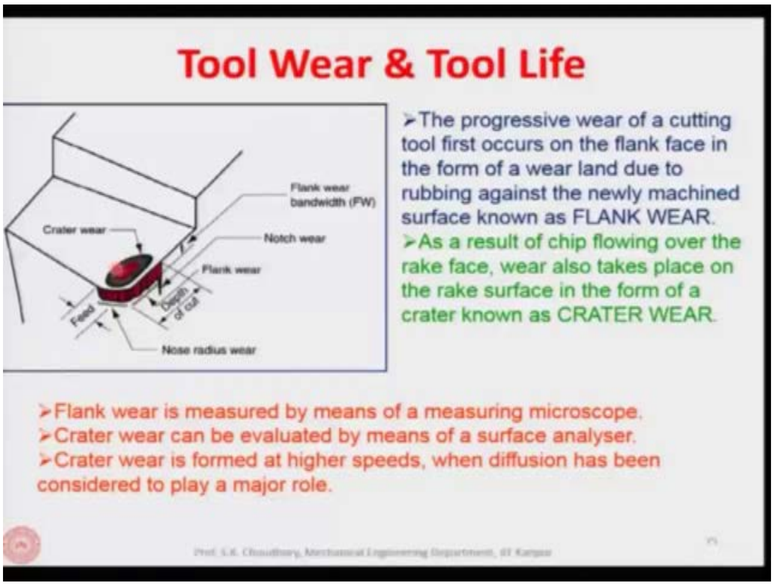

Now, how the tool wears out? As I said that chips are moving continuously over the rake face of the tool so that there is a wear at the rake face. The flank face is in continuous touch with the already machined surface, so there is also a wear.

The progressive wear of a cutting tool first occurs at the flank face, which is in contact with the work piece surface in the form of a wear land due to rubbing against the newly machined surface. This wear is known as the flank wear. Now as a result of chip flowing over the rake face, wear also takes place on the rake surface in the form of a crater which is known as a crater wear.

Flank wear can be measured by means of a measuring microscope. You must be familiar with the tool microscopes for example, that is used for measuring tool angles. Under the tool microscope you can find out the flank wear or the length or width of the flank wear. Crater wear can be evaluated by means of a surface analyzer because crater wear is something which is a deep on the rake face of the tool. If you have a surface analyzer, the surface analyzer can measure the depth of the crater.

Crater wear is formed at higher speeds when diffusion has been considered to play a major role. Normally as we said that as the machining starts, we have the flank wear and at higher and higher speed when the chip flows at higher speed over the rake face of the tool, the crater wear takes place.

So, for crater wear the responsible mechanism is the diffusion because it is at the higher speed and for diffusion what we need is the higher temperature and at higher speed the temperature becomes high. So, it actually facilitates the diffusion process. Therefore, at higher speed the crater occurs and at lower to medium speed the flank wear occurs.

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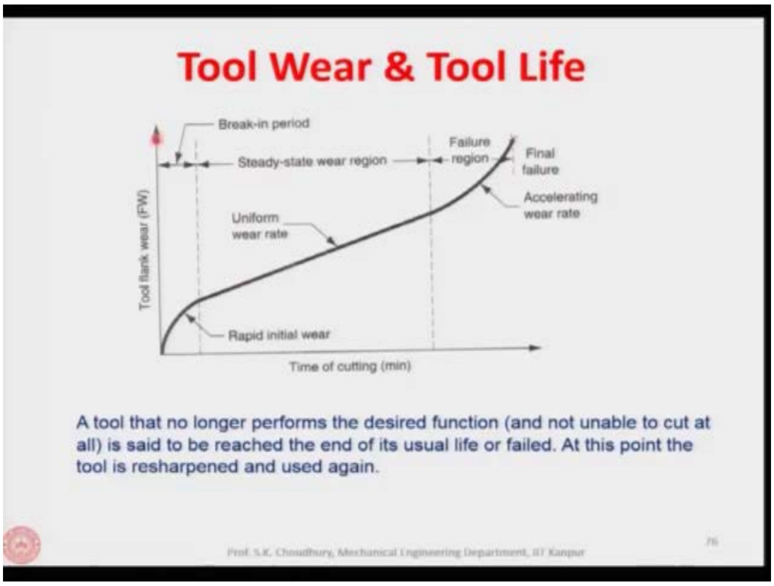

Now, let us see how the flank wear progresses with the time of cutting. The shape of the curve is shown in the above slide. This is a popular curve and this curve is explained in the following way that initially the tool is sharp; there is a lot of stress concentration around the sharp tool. Therefore, initially as it comes in contact with the work piece, there is an initial break in. So, the first short region is called the break in period. After that there is a steady wear because of the rubbing of the flank face with the already machined surface and the sliding of the chips over the rake face of the tool. In the steady state region, the wear rate will be uniform whereas, in the first stage the rapid initial wear will be there. Then after some time the flank wear flat will be so high that the tool can fail any time after this point.

Third region is called the failure region or sometimes it is also called the catastrophic failure. In this region, the wear rate is accelerating. Wear rate will be very steeply accelerated because the wear flat has increased. The temperature becomes more and forces become more because of the flat which is being created on the flank face of the tool and more crater on the rake face of the tool.

A tool that no longer performs the desired function, but not that it is unable to cut at all, it is said to have reached the end of its usual life and failed. At this point the tool is resharpened and used again. So, when we say the tool life, definition of tool life is very difficult. When you can say that the tool life is over? Overall, we say that when the tool is not performing as per our requirement, its life is over and then we have to resharpen the tool, so that the previously made geometry of the tool is again established.

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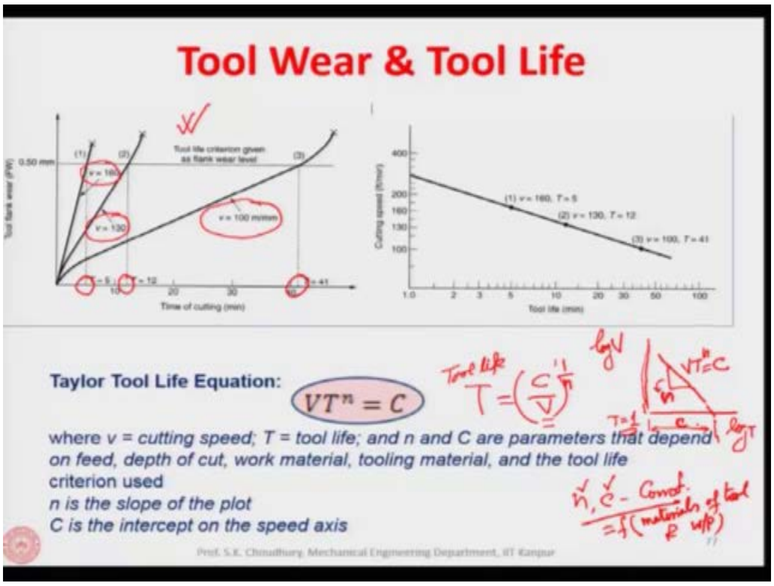

The curves for the tool flank wear are drawn against the time of cutting. The curves are drawn for different cutting speeds. Usually at higher cutting speed, the flank wear will be more. At lower speed the flank wear is less or the less steep curve, but at a higher speed the flank wear is more, this is very obvious.

Now, we draw these curves for different velocities and then we draw a line beyond which we should not allow the flank wear to grow. In practice it is usually 0.3 millimeter. So, within that 0.3 millimeter if the line is drawn, in that case will be knowing that what is the life for each of these velocities because then the time of cutting can be assumed to be the tool life.

For example, at V=160 m/min, when it has reached the criteria of the flank wear and we do not want the flank wear to grow beyond this point so, the tool life will be least. For V=130 m/min the tool life will be longer and for V=100 m/min, tool life will be longest.

Taylor's tool life equation describes how the cutting velocity affects the tool life. Particularly in the formula it is shown that $VT^n = \text{Constant}$ and this is popularly known as the Taylor's tool life equation, which actually gives the tool life as $T = \left(\frac{C}{V}\right)^{1/n}$.

It is showing that how the cutting velocity affects the tool life, *T*. We actually define that flank wear should not go beyond 0.3 millimeter. From the point at which the curve intersects the horizontal line drawn at 0.3 mm, draw a vertical line which intersects the x-axis at the tool life.

If you draw the tool life versus the speed in a log scale, with logV along the X axis and log T along the Y axis, then it will be a straight line as shown in the slide and the line can be represented as $VT^n = \text{Constant}$ which is known as the Taylor's tool life equation. log$T$ vs log$V$ is drawn from the experiments performed to draw the curve for tool life verses flank wear. For example, values of tool life for V=100 m/min and V=130 m/min are put in the log scale and plotted against the speed. X-intercept of the curve gives the value of C because at this place, T=1. Slope of the curve gives the value of n. V is the cutting velocity, T is the tool life, n and C are constants.

The constants C and n actually depend on the combination of the materials of tool and the work piece which are normally given in the material handbook. Again, n is the slope of the plot and C is the intercept on the speed axis.

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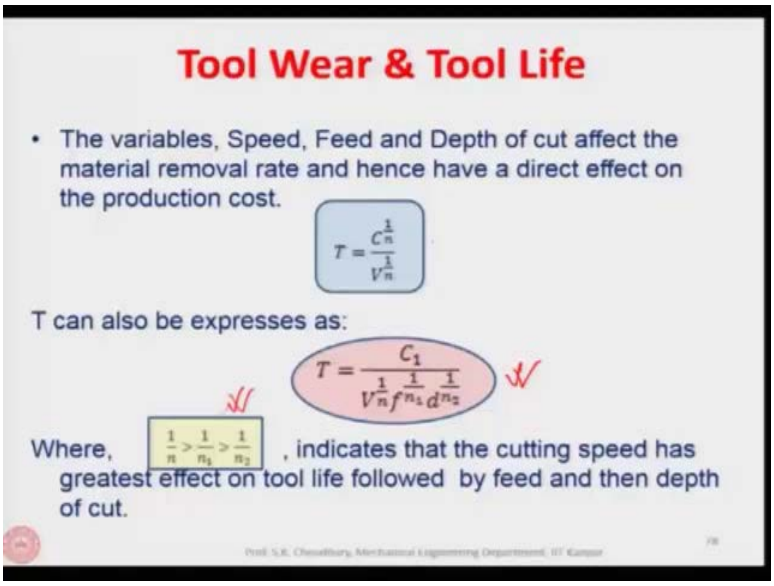

Now, we will discuss the variables of the tool life equation. I said that $T = \left(\frac{C}{V}\right)^{1/n}$. Now, the T can also be expressed as dependent not only on cutting velocity, but the feed and the depth of cut as well. F. W. Taylor has shown that T is dependent on the cutting velocity, but apart from the cutting velocity, the tool life also depends on the feed and the depth of cut in the following way as it is shown here.

After Taylor's tool life equation was invented, in further research with the help of taking the feed and the depth of cut as the variable parameters, experiments were made and $T = \dfrac{C}{V^{\frac{1}{n}} f^{\frac{1}{n_1}} d^{\frac{1}{n_2}}}$ is the result which have been found out. It has been seen that $\dfrac{1}{n}$ is more than the power of f and which is more than $\dfrac{1}{n_2}$. This actually shows that the effect of velocity which has power of $\dfrac{1}{n}$ has more effect than the feed, than the depth of cut having power of $\dfrac{1}{n_2}$. It indicates that the cutting speed has greatest effect on the tool life followed by feed and then the depth of cut. So, this is an important formula which also sometimes called the extended Taylor's tool life equation where it relates the tool life to cutting velocity, feed and the depth of cut.

Whereas, the Taylor's tool life equation relates the tool life with the cutting velocity only, because Taylor has performed the experiments long time ago when he did not have the computer facilities and the proper experimental facilities that we are having right now. Afterwards, the extended Taylor's tool life equation has related the tool life with the cutting velocity, feed and the depth of cut.

The rest of it we will discuss in our next lecture. Thank you for your attention.