Production Technology: Theory and Practice
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Lecture - 12
Measurement of Cutting Forces

Hello and welcome back to the discussion sessions. Let me remind you in brief that last time we have discussed in details the structures that are used in machine tool dynamometer. These structures are cylindrical type, then we had the cantilever beam, the ring type structure, octagon and so on. And then I have shown what kind of machine tool dynamometer actual structures are used.

In case of turning, we can use the cantilever beam type structure. And by measuring the moment we can find out the force magnitude because the distance between the point of application of the force and the sensor will be known. Then there is a formula from the solid mechanics using which we can find out the strain and by measuring the strain we can indirectly find out the magnitude of force.

So, once again I would like to tell you that in case of turning particularly, the forces which can be measured are the F_c and the F_t normally. These are the 3 directions, 3 axes x, y and z. If you remember I showed you those forces in turning. Those were F_f in the feed direction, F_R in the radial direction and $F_z$or F_c in the vertical direction.

So, the modern dynamometers are the piezoelectric based dynamometers, they have the 3 axes, F_X, F_Y and F_Z these are the 3 components of the forces along the 3 axes and they are supposed to be the F_c, F_f and F_R. So, from F_f and F_R you can find out the thrust force, F_T. So, that is why we say that basically we can measure 2 forces which are thrust force and the cutting force F_T and the F_c.

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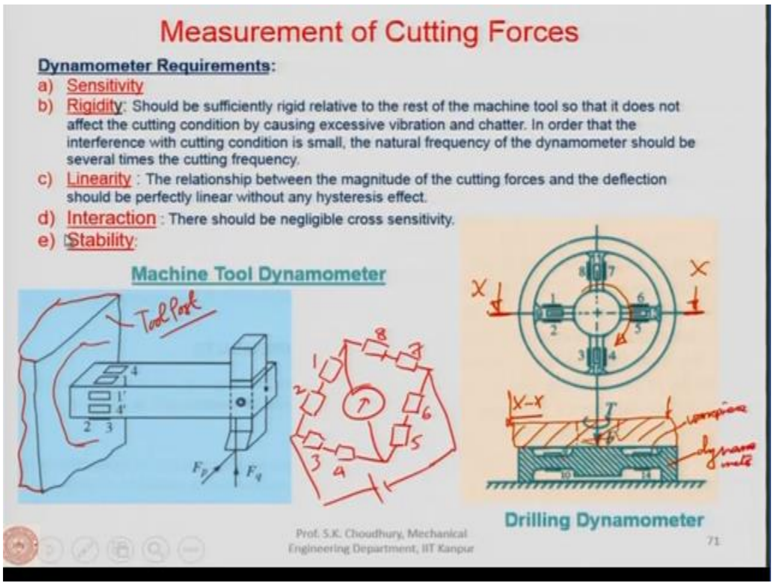

Then we said if you see here that the ring type dynamometers are modified into the structure like this for the drilling dynamometers and similarly the octagon structures are extended to be used in case of the milling or in case of the grinding. And I have mentioned some requirements that the dynamometers should have. They should be sensitive, there should be rigid, they should have linearity, they should have the good interaction and they should be stable these are the dynamometer requirements that we discussed.

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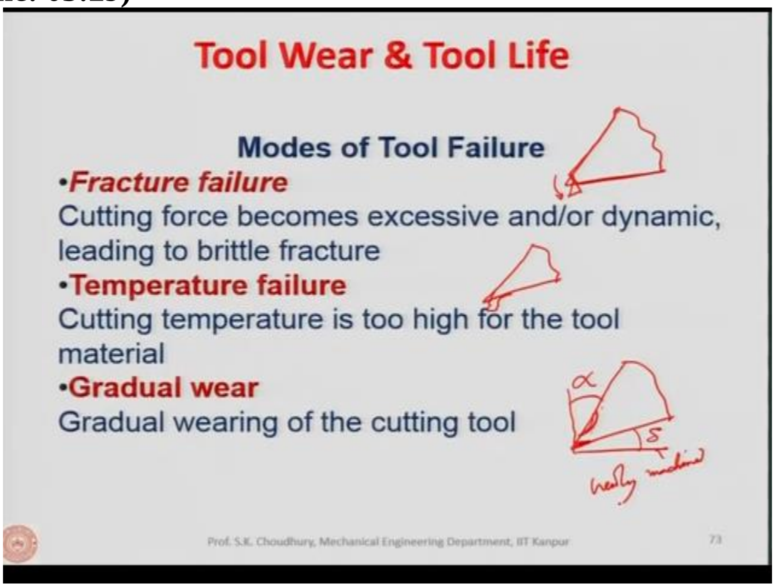

Now we will discuss our next topic which will be tool wear and tool life. Modes of tool failure: the tools during the machining process can fail, they can have fracture failure. So, excessive cutting force may lead to the brittle fracture of the tool. Temperature failure: cutting temperature is too high for the tool material. So, they get thermally deformed or the gradual wearing of the cutting tool takes place. To give you an example, let us say that we had a sharp tool.

And because of the high forces which are acting the part of the tool can be broken from here. In that case the tool will have this kind of shape as shown in the slide. This is the fracture failure or the temperature failure because of the temperature failure, this sharp tool may be thermally deformed or gradually worn out.

The tool can be gradually worn out because the chip flows along this rake face and the flank face is rubbing with the already machined surface. Therefore, these are the kind of gradual wear that may happen, temperature failure or the failure that is the thermal effect and the high cutting forces or there can be dynamic cutting forces, meaning that when the cutting force fluctuates.

So, in that case either it can be fatigue failure or it can be that because of the high magnitude of forces, the tool is not able to withstand that force. Now, these are the modes of tool failure, this is how the tools can actually fail.

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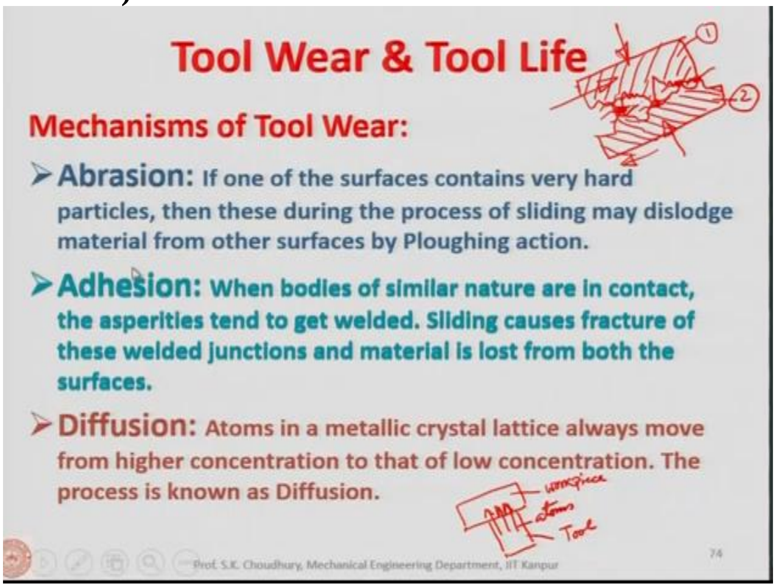

Mechanisms of tool wear: we have 3 main mechanisms. There are other mechanisms as well, but basic mechanisms of tool wear are the abrasion, adhesion and diffusion. Abrasion is when one of the surfaces contains very hard particles then these during the process of sliding may dislodge material from other surfaces by ploughing action. Let me give you an example. Suppose, you have a chalk which is with absolutely sharp edges and flat at the other end and you write something on the board.

So, you will see that the chalk wears out because the board material has the harder particles than the chalk material and those harder particles of the board will abrade the softer particles in the chalk. This is the mechanism which is called the abrasion. Second mechanism is adhesion. When bodies of similar nature are in contact, the asperities tend to get welded. Sliding causes fracture of these welded junctions and material is lost from both the surfaces.

I have shown it to you that two surfaces may sit on each other like this on the asperities. So, this is one surface, this is another surface and both surfaces have the asperities or the undulations, these are the undulations. These undulations are on both of those parts. Now both the parts have their own weight or a normal force may act on them.

These junctions will have the elastic deformation under the normal force and when the force increases, then it will have the plastic deformation and they will get welded. Now, if the parts are moving with respect to each other, in that case, these welded junctions break. Now, the broken particles will remain within the two surfaces.

So, due to adhesion when the welded asperities break, the material will be lost from both the parts. This mechanism is called the adhesion mechanism that when the asperities get welded and during the movement of these two parts, when they are sliding on each other those welded junctions get broken and the material is lost from both the parts. That is the mechanism which is known as adhesion.

Diffusion: atoms in a metallic crystal lattice always move from higher concentration to that of a lower concentration. The process is known as the diffusion. So, let’s say these are the two surfaces, this is the workpiece and this is tool, they are in contact with each other and tool is working on the workpiece. The tool will have the atomic density more than the workpiece because material is different, in case of tool this can be made of high speed steel or ceramics or diamond.

So, the atoms located here, I mean atoms in the atomic structure of the tool will be more in density and therefore the atoms will try to penetrate from higher density to the lower density of work material and the tool wears out. This is the mechanism that these atoms migrate from the higher density to the lower density, this mechanism is called the diffusion. Now, the diffusion, you might be knowing from the physics in your class 10, 11 courses that diffusion is facilitated by the temperature, more the temperature more will be the diffusion.

Therefore, during the machining process, as the temperature goes up, it facilitates the diffusion process. Now, for the wearing action, more than one mechanism can be responsible. We cannot say that a particular type of wear is because of the abrasion only or because of the adhesion only. Let me give you an example.

When these asperities, welded junctions are broken, we said that due to this wear mechanism material is lost from both the surfaces. We said that this is the mechanism which is adhesion, but see this wearing action that is taking place after these hard particles are sheared off, these particles will remain here within the two machined surfaces. So, these particles are also very hard because they are strain hardened material because they are welded junctions.

So, those small particles will also have the wearing action of both the surfaces. Those particles will also wear the softer particles because those particles are harder. Therefore that mechanism is the abrasion mechanism. So, in that case we will say that if adhesion happens, the abrasion also can happen along with that, they can take place parallelly.

But because diffusion happens at a higher temperature so, normally during the machining, the temperature goes up but more temperature will be for high speed machining. So, when the machining speed is very high normally it is the diffusion which is responsible. .

When the cutting speed is not very high, it is low to medium, then normally the abrasion and the adhesion mechanism are responsible for the wear normally. So, you must have heard about hard turning. Hard turning is a turning which is a high speed turning where the cutting speed is very high. So, during the hard turning the temperature goes very high. In that case we can expect that the diffusion wear is predominant.

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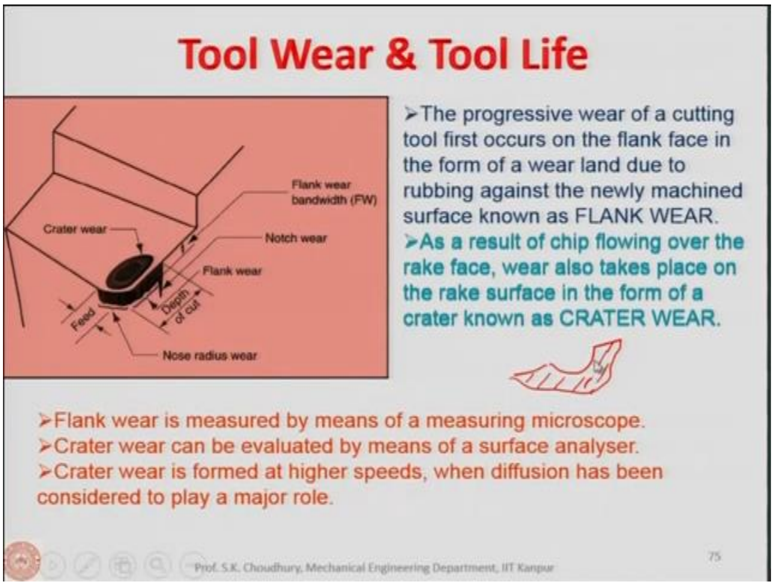

Now, the progressive wear of a cutting tool occurs on the flank face as I said here earlier that this is the flank face of the tool and the tool wear at the flank face takes place progressively in the form of wear land because flank face rubs against the already machined surface., Tthis is the wear land that is formed due to rubbing against the newly machined surface known as the flank wear. So, this is the flank wear which happens at the flank face of the tool because the flank face rubs against the already machined surface or newly machined surface.

As a result of chip flowing over the rake face, the rake face of the tool gradually wears out in the form of a crater.

This crater is known as the crater wear. So, on the rake face of the tool a crater is formed. Flank wear is measured by means of measuring microscope, flank wear is a land. So, in microscope you can enlarge it and you can find out what is the value. It is normally measured in millimetre because this is the land and the width of the land or the length of the wear land we are bothered about.

So, normally it is the width of the wear land which is measured and this is the measure of the flank wear. Normally crater wear is evaluated by means of a surface analyser that measures the surface roughness. So, there a stylus which is moved along the surface so, those asperities which are on the surface, will be sensed by the stylus.

The stylus will move along the surface covering peaks and valleys of the undualations on the surface. This movement of the stylus will generate electrical signal which will be amplified and measured in a device and this can give you what will be the surface roughness either in R_a or R_z . Those parameters we have discussed during our discussion on materials and properties.

The concepts of R_a and R_z we will again discuss in the metrology section once again in more details. Now the crater depth can be evaluated by the surface analyser. So, this is the crater depth, which can be identified by the surface analyser. Crater wear is formed at higher speeds when diffusion has been considered to play a major role.

I already told you when we were discussing the diffusion that in case of diffusion atoms move from the higher concentration to the lower concentration and since tool is the harder material than the workpiece, so, the atoms are denser, that is the density of atom is more than in case of workpiece. Therefore, the atoms will migrate from the tool to the workpiece at a higher temperature so, temperature is a factor.

Therefore, the responsible mechanism for the crater wear is the diffusion whereas, for the flank wear it is normally the abrasion or the adhesion because flank wear takes place at a lower or medium speed.

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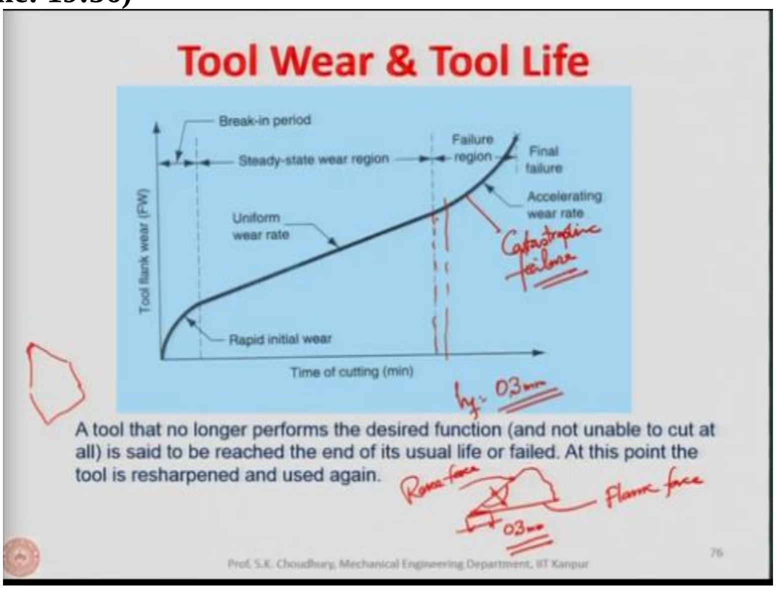

This is the tool flank wear and as the time of cutting progresses, the tool flank wear progresses in the way as shown in the curve. This curve will have 3 distinct zones - one zone is this which is called the break-in period or it is also called initial break-in. Here, it is a rapid initial wear, after that it will be very steady and the uniform wear.

The wear rate will be uniform in this section and this section is called the steady state wear region. After this there will be a failure region and after sometimes it will be catastrophic failure. So, the tool can be destroyed here. Now, initial break in period is because the tool is sharp.

As I said that it may have the sharpness or it may have a little round of the nose radius but as soon as the tool comes in contact with the workpiece initially, it gets worn out particularly when the tool tip is sharp; either it breaks or it gets a little radius because of the rubbing and the flank wear goes very high. So, this is the initial break-in period and then as the time progresses the wear happens uniformly, it is not rapid and it goes uniformly as the cutting process goes on.

But after some time, the flank wear flat becomes more . So, the temperature increases more and more because the flat is increasing which is the flank wear. And at a certain point this flat goes so high that the temperature becomes very high and the tool may fail any time after this and that is called the catastrophic failure.

So, here somewhere at this region it is popularly known as catastrophic failure, and here it is the uniform wear rate. So, the wear rate is very steady in this region. A tool that no longer performs the desired function, but not that it is unable to cut at all is said to be reached the end of its usual life or it is failed.

Now, when we say that tool life is over then we mean that the tool is no more able to perform with the desired level of accuracy. The tool that no longer performs the desired function, desired function is particularly the dimensions and the surface roughness. But it still can cut but it will not be accurate it will not be precise, is said to be reached the end of its usual life or failed.

At this point the tool is resharpened and used again and tool is resharpened in a grinding machine. I will show you the tool resharpening, how the resharpening of the rake face of a tool can be done in a tool grinder.

So, this is the region where the tool may fail somewhere here or the tool may fail somewhere here. Different tools may behave in a different way depending on the cutting process, depending on what kind of cutting parameters you are using and so on.

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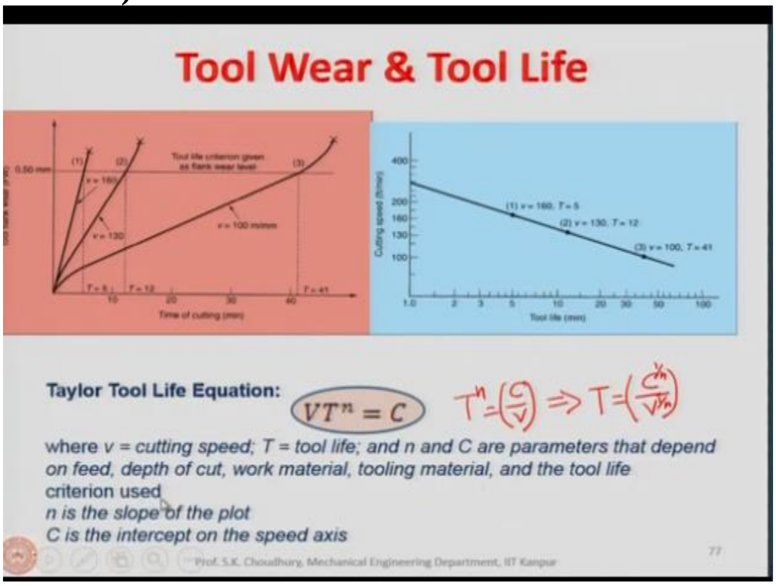

So, in practice therefore, tool life is taken in a different way. Let us say that the tool flank wear is taken in the y axis and time of cutting is taken in the x axis like in case of this. So, then for different velocities at 100 m/min and 130 m/min and 160 m/min, if we conduct the experiments, then the curve will be like this.

When I say that we are increasing the velocity, please understand that for a certain process, when the process is going on, you cannot increase or decrease the speed. So, the process will continue for some time, then you change the speed and then you cut the material again with the increased speed. So, that is what it has been done here for different speeds 100, 130 and 160 m/min. The process has been carried over for along this that is 40 to maybe 60 minutes.

And these are the curves which have been obtained. So, as you understand from here, from the curves and experimental results that higher the velocities rapid will be the flank wear more the speed more will be the flank wear that is one conclusion that you can draw. And then as I was telling, in this curve that making sure that the tool has to be taken out for resharpening exactly at which point is very difficult.

So, normally what is done is that when the flank wear grows up to 0.3 millimetre, then it is taken out, let us say this h_f. What is h_f is that if you take the tool like this, this is the crater wear, this is the rake face, let us say that this is the flank face and this is the wear flat, so, when this flank wear reaches 0.3 millimetre then the tool has to taken out for resharpening, this is the depth of the crater. So, once again, this can be measured by the microscope. and as soon as it reaches 0.3 millimetre, the tool is taken out for resharpening.

Here it is given as 0.5 mm it can be also 0.3 mm. This point is normally 0.3 millimetre. So, at 0.3 mm we are drawing a line saying that we do not allow the tool flank rate to grow beyond 0.3 mm, because beyond 0.3 mm tool will not be functioning at a desired accuracy or the way that we want the tool to be functioned, to give us the proper dimensional accuracy, proper tolerances and the proper surface finish.

So, this is the line which we define as the tool life. Then at this velocity at 100 m/min, this is the tool life at 130 m/min this is the tool life and at 160 m/min, this is the tool life. So, you can find out the tool life at different speeds. And then to draw the curve, let us say that we will put the cutting velocity here.

This is the tool life. So, this will be a straight line let say we will put it in logarithmic scale. So, this will be a straight line and this straight line is represented by a formula $VT^n = C$ and this is called the Taylor's tool life equation. So, here the intersection of this with the velocity cutting speed axis this is actually this C and the slope of the curve is the n. Both n and C are constants.

Once again, if you take these values, these are the speeds of 100, 130, 160 m/min and you take the corresponding tool life. Here you take the log of these values, log of the speed, put it here and log of these values you put it along the y axis. Then it will be a curve like this, a straight line like this, which can be represented as $VT^n = C$ V is the cutting speed or cutting velocity.

T is the tool life, n and C are constants, n and C depend on the tool and the work material combination, n is the slope of the plot, C is the intercept on the speed axis. So, we have to have the velocity along this axis and that intercept is the C because you understand that here it is $t = 1$ because we have taken as a log, so, $log\ T$ is 0 and therefore, if you put the $T = 1$ then $V = C$.

The slope of this curve of this line will be the n which is a constant. C and n are constants. So, from this equation, we can find out is that $T^n = \left(\frac{C}{V}\right)$. Therefore, the tool life is equal to

$$T = \left(\frac{C}{V}\right)^{\frac{1}{n}}.$$

Now, here as I said that the C and n these are constants and V is the cutting velocity, T is the tool life, n and C are the parameters that depend on the feed, depth of cut, work material, tooling material and the tool life criteria used. Now, here as you can see that the tool life has been shown by Taylor's equation is dependent on the cutting velocity only, because in this equation $T = \left(\frac{C}{V}\right)^{\frac{1}{n}}$.

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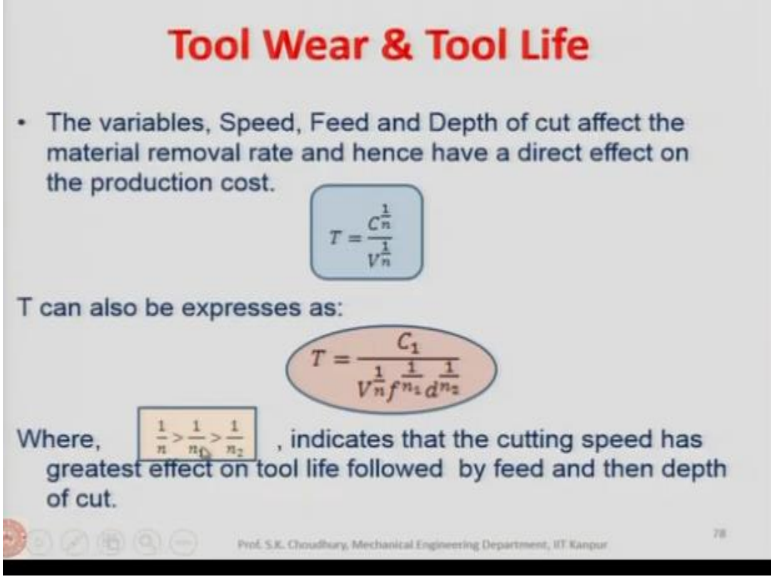

However, the variables, like speed, feed and depth of cut these are the cutting parameters which also affect the material removable rate and hence, they have a direct effect on the production cost. You understand that if the speed is more so the time taken is less and more parts will be produced; same in case of feed and the depth of cut. So, the tool life has to consider these factors because, as you are increasing the speed that tool life also decreases because the tool wears out faster as you increase the speed.

Similarly, as you increase the feed for example, the load on the tools will be increased and so as you increase the depth of cut then the tool wear will also be more. Therefore, all these 3 factors, not only the speed, that has been shown in Taylor's tool life equation, but also the feed and the depth of cut will also affect the tool life. Considering this, the subsequent research after the Taylor's tool life equation has been conducted.

Further research also shows that the tool life equation can be expressed in the following way that $T = \frac{C_1}{V^{\frac{1}{n}} f^{\frac{1}{n_1}} d^{\frac{1}{n_2}}}$. So, these powers that is n, n_1 and n_2 have been found experimentally in the following way that $\frac{1}{n} > \frac{1}{n_1} > \frac{1}{n_2}$.

Now, this experimental finding indicates that the cutting speed has greatest effect because this power of the cutting speed is more than the power of the feed, than the power of the depth of cut. So, cutting speed has the greatest effect on tool life followed by the feed and then the depth of cut. So, once again I would like to emphasize that $\frac{1}{n} > \frac{1}{n_1} > \frac{1}{n_2}$.

These are the powers of V, f and d respectively V is the cutting speed, f is the cutting feed and the d is the depth of cut. These constants are found out experimentally and the conclusion that the V has the more effect on the tool life than the feed followed by the depth of cut.

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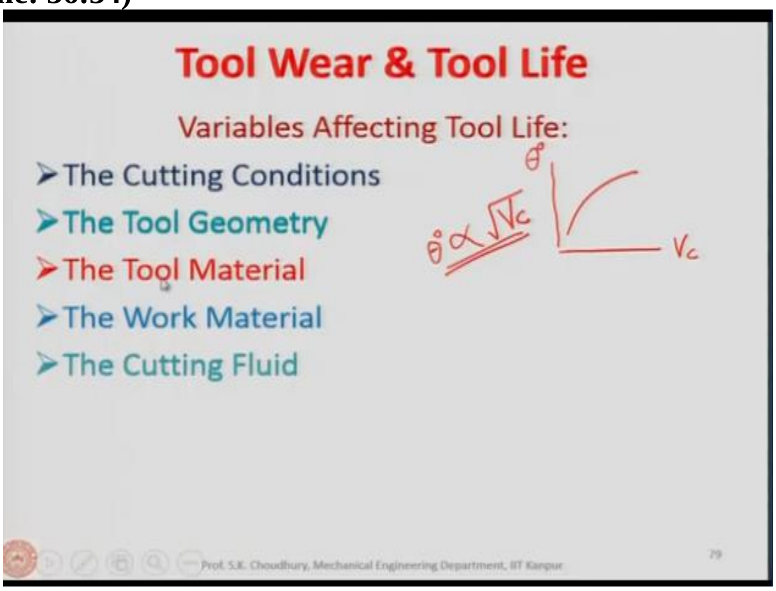

Now, let us discuss next, what are the variables that affect the tool life. Basically there are 5 factors which will affect the tool life, that is cutting conditions which we have already discussed; that is the cutting speed, feed and the depth of cut. Next variable is the tool geometry, in the tool geometry we know that these are the tool angles, that is the 3 sets of angles, namely one set of rake angles, one set of flank angles and one set of cutting edge angles along with the tool nose radius. These all are included in the tool geometry.

So, each one of them, that is, the rake angle, flank angle and the cutting edge angle along with the nose radius, affects the tool life that we will discuss. Tool material: depending on the tool material that is being used, the tool life will depend or tool life will be affected by the choice of the tool material, this is very obvious. Going ahead I should tell you that if the tool material is soft, the tool wear will be more or if the workpiece is hard, for example.

So, the tool material has to be properly selected in case the work material is hard or work material is brittle. Next is the work material. This is related to the tool material. I just told you that if the work material is hard, then the tool material cannot be soft . By the way the hardness of the tool material has to be always more than the hardness of the workpiece material.

During the machining process, the plastic deformation is created only in the workpiece material and the chip that is the excess material from the workpiece surface is segregated. So, when we say that tool material has to be soft, then we mean that this is relatively soft, but its hardness has to be always more than the workpiece material hardness. Finally, the cutting fluid: we all know that cutting fluid is necessary because a lot of heat is produced during the machining.

And I have already shown it to you, I will remind you once again that the temperature which is occurring during the machining, depends on the V_c in this way and the temperature versus the V_c curve goes in like this. So, this is the relationship that the temperature varies with the cutting velocity as $\theta \infty \sqrt{V_c}$ and this says that at higher cutting speed the temperature will rise.

Most of the heat is taken out by the chip. However, the remaining heat is conducted to the tool because tool is in constant touch with the chip, chip is flowing along the rake face of the tool provided it is the ductile material. In case of brittle material, the chip breaks and in that case the conduction of the heat to the tool will be relatively less and a part of the heat will be flown to the workpiece.

Those things we will discuss little later when we will discuss the thermal aspects of machining. So, overall if you see the cutting conditions, tool geometry, tool material, workpiece material and the cutting fluid, all these 5 factors affect the tool life, how they affect let us discuss now.

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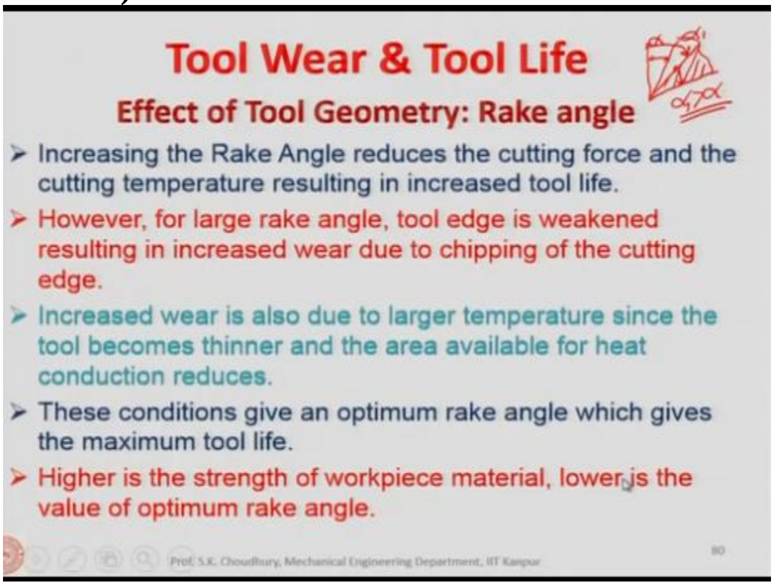

Now, effect of cutting conditions we are not discussing separately because here we have already shown that apart from the cutting velocity, the feed and the depth of cut also affect the tool life and this is in this way that the cutting speed has the greatest effect followed by the feed and then the depth of cut. How the tool geometry affects the tool life? Let us consider first the rake angle.

I have already made very clear that increasing the rake angle reduces the cutting force and the cutting temperature that will result in the increased tool life. So, we increase the rake angle as far as possible because increasing the rake angle ultimately increases the tool life by decreasing the cutting force and decreasing the temperature which is occurring during the machining process.

The reason I have already told you, we have already discussed the physics behind. What happens to the shear plane as the rake angle is changed? Shear plane is changing and because of that as the rake angle increases, since the shear plane is decreasing, length of the shear plane decreases. So, this results in less effort in the cutting and less forces applied. As I said already that the less force applied means the cutting tool life will be increased and also the surface finish will be better.

Now again, for large rake angle the tool edge is weakened resulting in the increased wear due to chipping of the cutting edge. So, what we mean to say is that this is the initial rake angle and if we are increasing the rake angle let say in this way this will be α_1 . So, α_1 is more than α . in that case the cutting angle is decreasing and the tool is becoming weaker. It means that the tool edge is weakened and this will result in the increased tool wear.

The cutting edge may break or it may chip-in because it is weak. It may even result in the mechanical breakage of the cutting edge. Therefore, we cannot really infinitely increase the α although the increase in the rake angle resulted overall in the increased tool life but to some extent because at larger rake angle again the tool life will be less.

So, there should be some kind of compromise between the tool life and the rake angle that how much rake angle we can afford to increase so that the tool life could be at a desired level. Now increased wear is also due to larger temperature since the tool becomes thinner as you can see the tool is becoming thinner and the material available for the heat conduction from here will be less since the material available is less.

That we have already discussed earlier also once, that since the material is available for the heat conduction is less, so, there will be more heat accumulation and due to that there will be more thermal deformation of the tool and the tool wear will be more because tool will be softened, thermally softened and the tool wear will be more. These are the two reasons, one is that the tool is getting weakened, and it can break and the tool wear can be more.

Second reason is that the tool wear will be more because of the thermal softening of the tool because it is getting thinner and less material is available for the heat conduction from this tool. Now, these conditions give an optimum rake angle which gives the maximum tool life.

This is the compromise between the rake angle and the tool life, that we will increase the tool life till the tool life is acceptable.

And we will not increase to that extent where the tool can actually break or the tool can be thermally deformed and softened. So, this is the conditions that give an optimum rake angle which gives the maximum tool life. Higher is the strength of workpiece material, lower is the value of optimum rake angle. So, we have reached to an optimum level of the rake angle by adjusting the rake angle so that tool life is maximum and the rake angle taken is lower when the strength of the workpiece material is high.

Because to cut the hard material you need the fatter tool, you need to have more material available for the heat conduction because for hard material, the level of the heat which is being produced, this will be more. Therefore, higher is the strength of workpiece material, harder is the workpiece material lower is the value of the optimum rake angle. So, optimum rake angle in that case has to be increased. Because then the tool has to be fatter, tool has to have the more material for the heat conduction.

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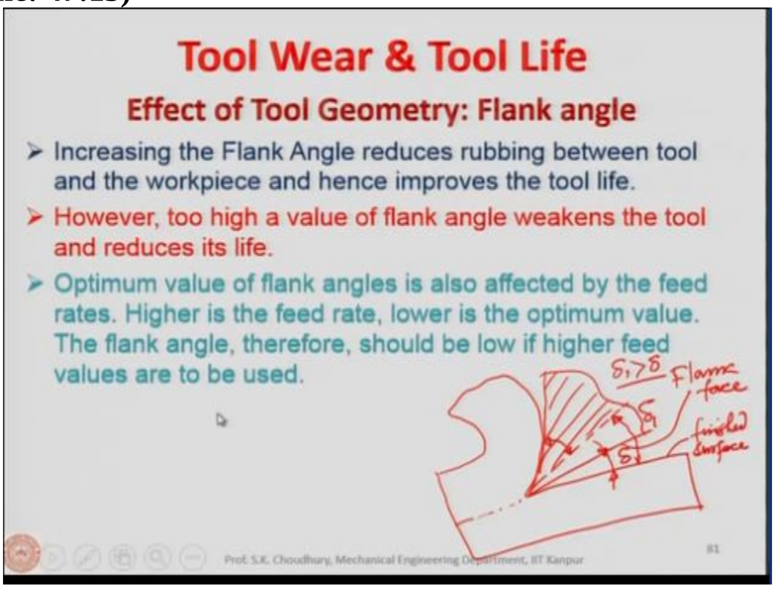

Now, let us discuss the flank angle. Increasing the flank angle reduces the rubbing between the tool and the workpiece and hence it improves the tool life. Once again, I will remind that this is the tool and here is the workpiece, this is the workpiece, this is the tool. So, this is the flank face or the flank surface or as I said that it is also known as the clearance face and this is the flank angle, flank angle we designated by δ.

Now, if we increase the flank angle the rubbing will be less because this flank face will be cleared and it will be safe it will not any more rub with the finished surface. This is the finished surface, finished work surface. So, suppose we are increasing this flank angle like this and here the flank angle has been increased from δ to δ_1 where the δ_1 is more than δ.

In that case the same phenomenon happens as in case of the rake angle that we have discussed just now, that the cutting angle which is this is less and the tool is becoming thinner, tool is becoming weaker and the material available for the heat conduction will be less. So, the tool will be thermally deformed. Therefore, there has to be a compromise and there has to be an optimum flank angle.

This is so that the tool life could be maximum with increase in the flank angle. After that if you increase the flank angle further, tool life will be decreased. So, there is an optimum level of the flank angle as well, like in case of the rake angle. However too high a value of flank angle weakens the tool and reduces its life that is what I discussed.

Optimum value of flank angles is also affected by the feed rate, higher is the feed rate lower is the optimum value because as the feed rate increases, we need to have more strength of the tool, because for higher feed rate, the tool has to be stronger, because the more force will be exerted on that because feed rate is more. The flank angle therefore, should be low if the higher feed values are used. So, this is an important suggestion that the flank angle which we have determined as the optimum flank angle for the maximum tool life that has to be lowered in case the higher feed rate values are used.

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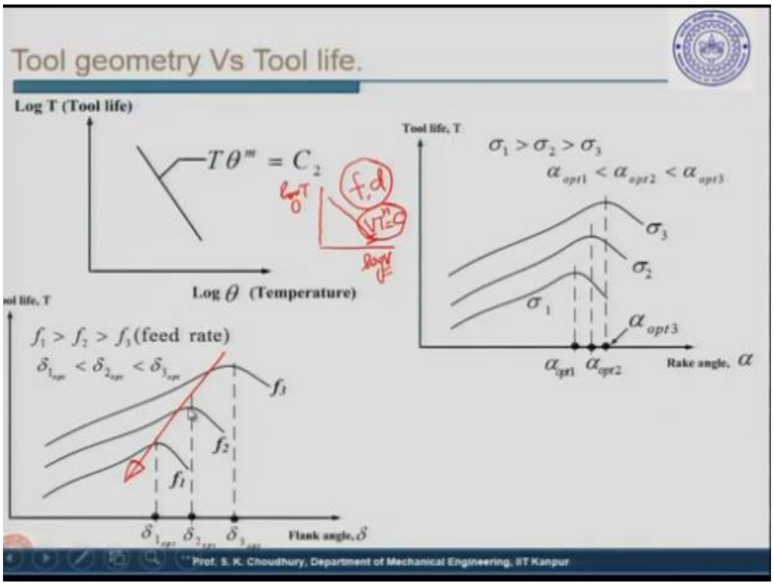

These are shown in the curves. First of all, once again I will come back to this and this is the reference point that tool life and the temperature in the log scale. This is in the T theta m to the power C 2. So, this is something that we have not discussed so far this says that this is the curve between the tool life and the temperature in the log scale. So, earlier in the tool life equation we have seen that the tool life equation in the *log T* and vs. *log V* curve and this was given as a straight line.

Then I mentioned that it is not only the cutting velocity, but the feed and the depth of cut also affect the tool life. So, here it was $VT^n = C$ .This is the Taylor's tool life equation where only the velocity has been considered as the parameter affecting the tool life. Now, here this curve says that the effect of the *f* and the *d* or the feed depth of cut and the velocity on the tool life can be combined in terms of the temperature.

What is meant here is that as the speed is increased or you are increasing the depth of cut for all this combined effect is that the temperature increases. So, if we monitored the rise in the temperature, overall we can say that this is how the tool life is affected because of the increase in all these three parameters, i.e. cutting velocity, feed and the depth of cut. .

Therefore, this curve, that is the *log T* vs. log θ which is the temperature, says that there is a combined effect of the velocity, feed and the depth of cut in terms of temperature and this is the line or this is the curve in the log scale. This can be described by an equation $T\theta^m = C_2$, this C_2 is different than the constant that we have taken in the Taylor's tool life equation *C* and this m is different from the constant n which you have taken in the Taylor's tool life equation. T is the tool life.

Now, as we said the in case of rake angle, higher is the strength of workpiece material, lower is the value of optimum rake angle. We said that there is an optimum rake angle at which the tool life is maximum. Suppose you take any curve any one of them let say this curve. So, this is the curve describing how the rake angle varies with the tool life. So, initially as we are increasing the rake angle that tool life increases.

Tool life increases, because the cutting force decreases, surface finish becomes better and the temperature reduces and that means the tool life is increasing. However, at this point when we achieve the maximum tool life, look at that point this gives the maximum tool life. After this point, if we further increase the rake angle, the phenomenon, that I have already explained, happens, that is, the tool becomes weaker, less material is available for the heat conduction and the tool life decreases.

So, here if you see the right portion of this curve that the tool life decreases so, here is the optimum tool rake angle. Now, suppose if we increase, suppose this is the curve that has been taken for a particular strength of a material, so, if the material is stronger, that is, let say this is the material with strength σ_1. Another material which is of σ_2 strength and let say $\sigma_2 < \sigma_1$ and σ_3 even less than that. This curve is made for the machining with the same tool.

But with different workpiece materials, this workpiece material is stronger, this is less strong and this material is even less strong than this and this. Therefore, we said that $\sigma_1 > \sigma_2 > \sigma_3$, this is the strength of material, so, it is stronger material. In that case, you can see this optimum value of the rake angle is lower in case of the hardest tool material, more strength of the tool.

If the strength of the workpiece material is less than this in that case the optimum rake angle can be taken as little more. In all these 3 cases we have a maximum tool life. Keeping in mind that maximum tool life, we are determining what is that optimum rake angle. So, you can see that higher is the strength of workpiece material, lower is the value of optimum rake angle.

Exactly that is what it is demonstrated here, that this is the optimum rake angle for the hard material, here it is said that high strength for this material. So, the strength of workpiece material is hard, is more and the optimum rake angle is lower. Now, for the flank angle we said that if the feed is more in that case flank angle which is optimum has to be lower. I would like to show it here that the optimum value of flank angles is also affected by the feed rates, higher is the feed rate lower is the optimum value.

So, higher is the feed rate, in case of this curve which is made with a feed rate of f_1 which is more than the feed rate used here for this operation and this is more than the feed rate operation feed rate that is used in this case. So, f_1 is the maximum feed in comparison to f_2 and the f_3, $f_2$is more than f_3 in that case as the feed rate is increasing in this way that $f1 > f2 > f_3$.

So, when the feed rate is maximum, comparing these three cases, then the optimum value of the flank angle will be minimum out of these three. Now, here if you take any one of these curves what you can see here is that as the flank angle is increasing, the tool life increases like in case of the rake angle. And the reason we already mentioned that as the flank angle is increasing, then the rubbing between the flank face and flank face of the tool and the already machined workpiece is less.

So, the rubbing is less means that the temperature occurring is less and the tool life increases. After this point when we have achieved the maximum tool life, after that if you further increase the flank angle exactly the same thing happens as in case of the rake angle that the tool life falls because with further increase in the flank angle, as I have shown it to you, the tool cutting angle is decreasing and the tool is becoming weaker and the less material is available for the heat conduction.

Therefore, afterwards it falls, after this point if we further increase the flank angle tool life falls. The rest of the material I will discuss in my next session of discussion. Thank you for your attention.