Production Technology: Theory and Practice
Prof. Sounak Kumar Choudhury
Department of Mechanical Engineering
Indian Institute of Technology Kanpur

Lecture – 17
Economics on Machining

Hello and welcome to the discussion sessions of production technology: theory and practice. Let me remind you that in our last session, we started discussing the economics of machining because we said that our aim or the aim of the production is to make a part of particular shape, size, finish and accuracy with minimum cost. To have the minimum cost, we have to look into the different aspects particularly the cutting parameters for us it is more important and convenient to see how the cutting parameters will have the effect on the cost.

Then it has been found out also from the Taylor's Tool Life equation that since the tool life is affected by all three parameters, namely cutting speed, feed and the depth of cut and there is an optimum value of the cost and this is a compromise between the cutting speed and tool life because as you are increasing the cutting speed although the machining time decreases, and the production rate is increasing, cost is decreasing but the tool life is becoming less.

So, tool cost will be more. Therefore, there is a relationship or compromise between the cutting speed and the tool life so that the cost could be minimum. Therefore, we can conclude that on the minimum cost there will be effect of cutting speed, feed and the depth of cut.

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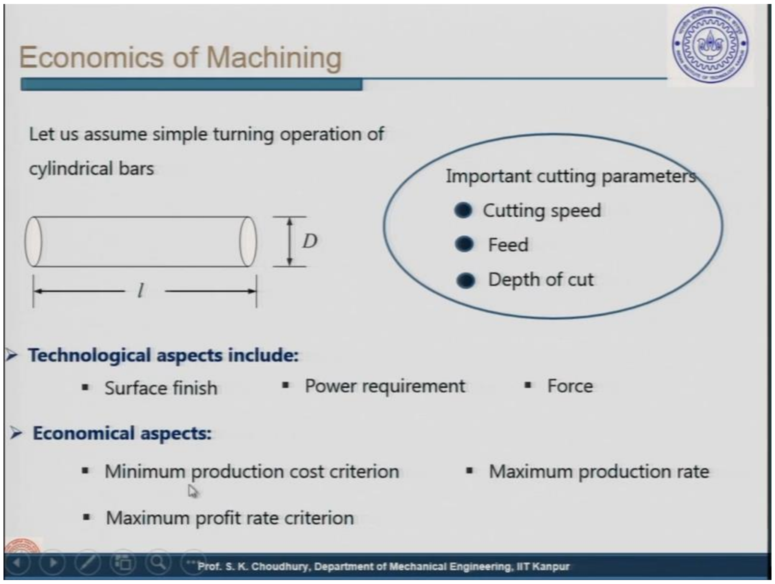

What we said here is that we are assuming that we are turning cylindrical bar here it is L because after that we have used the L for the length, this is the diameter of the cylinder and we are turning this. We have the important cutting parameters as cutting speed, feed and the depth of cut technological aspects we said that these are the surface finish, power, force and the economical aspects are minimum production cost criteria maximum production rate criteria and the maximum profit rate criteria.

What I said and what I discussed with you is that the each of these criteria that is either it is a minimum cost criteria or it is a maximum production rate criteria or is the maximum profit criteria you will have a certain optimum parameter on cutting speed, optimum cutting feed and the optimum depth of cut. But these optimum parameters may not satisfy the maximum production rate or maximum profit rate. And vice versa that is the optimum value of the cutting speed; feed and depth of cut for the maximum production rate may not satisfy the criteria for the minimum cost or maximum profit rate and so on.

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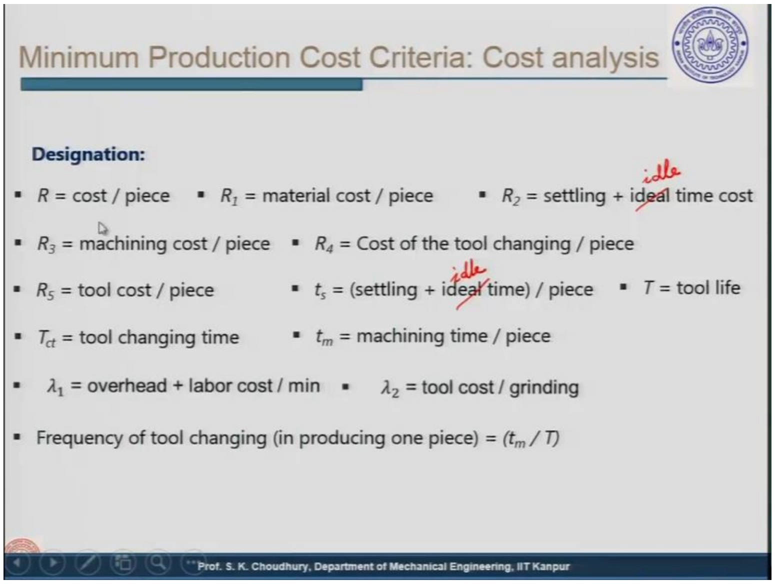

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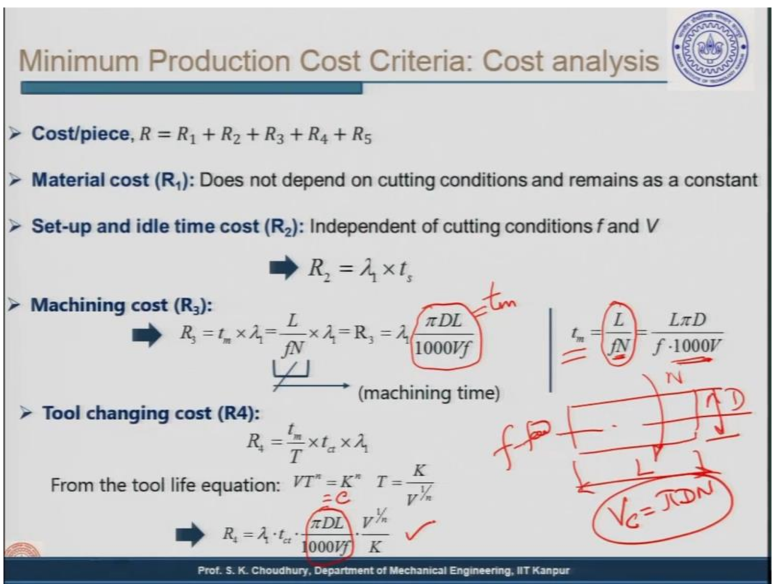

Then we said that the overall cost per piece consists of the raw material cost plus settling an ideal time cost plus the machining time cost per piece then the tool changing time cost per piece and that tool cost per piece. These are the five basic costs which are involved in the overall cost per piece that is a final product. In here the material costs R_1 and the idle time setup and idle time cost per piece cost they are not actually dependent on the cutting parameters like speed, feed or depth of cut.

So, they remain independent of the cutting parameters. Now the settling and idle time cost R_2 is equal to the time taken for this setup. And we said that this is the settling and idle time cost per piece is t_s that is multiplied by the in a payment that you are making for this time. That we said as the λ_1 which is overhead plus the labour cost per minute. overhead, I explained that overhead is everything else rather than labour cost.

Which is the building, the facilities like the electricity, water hydraulics then the pneumatic then the chip removal caring out of the chip caring out of the cutting feed, wasted cutting feed and so on. Then we said the λ_2 is the tool cost per grinding this is used later. After the setup and idle time cost is determined we will find out the machining cost and this has already been discussed in our last session.

We said that this is equal to the machining time that is incurred and for that we are paying the overhead and the labor costs. Now t_m we earlier found out is $t_m = \frac{L}{fN}$ and we are assuming that this is for one pass because this was into multiplied by the number of passes. if the number of passes 1 the machining time can be expressed by $t_m = \frac{L}{fN}$.

N can be found out as $N = \frac{V_c}{\pi D}$ and that can be multiplied by 1000 because it is the RPM to second because these are the millimeter per minute so that we are using as the second. t_m m we found out in second is $t_m = \frac{\pi DL}{1000 fV}$. Now here of course as I said that this is the N which is the RPM, rotational frequency, D is the diameter and L is the length.

That is why πDL is the velocity, cutting velocity and therefore the machining cost will be this multiplied by λ_1. This is $R_3 = \lambda_1 \frac{\pi DL}{1000 fV}$. Next is the tool changing cost, tool changing cost is R_4 which will be determined by how many times we have changed that tool into that time taken for changing the tool, each time we are changing the tool. And that multiplied by the overhead and the labor costs.

So, $\left(\frac{t_m}{T}\right)$ is the frequency of tool changing into time that is taken for changing the tool, t_{ct},we said t_{ct} is the tool changing time. Now this multiplied by the frequency into the overhead and the labor will give you that tool changing cost. Now here this T is the tool life. From the Taylor's tool life equation we can say that $VT^n = C$.

Let us say this is equal to C constant and constant can be said as K^n, that is $VT^n = C = K^n$. C this constant can be expressed by this K^n where both this K and this n are the constants. Therefore, $T = \frac{K}{V^{\frac{1}{n}}}$ If we put this value of T, then the R_4 can be expressed as

$$R_4 = \lambda_1 t_{ct} \frac{\pi DL}{1000\,fV}\left(\frac{V^{\frac{1}{n}}}{K}\right).$$

And the t_m we know, we have already found outas machining time. And that machining time we are using here.

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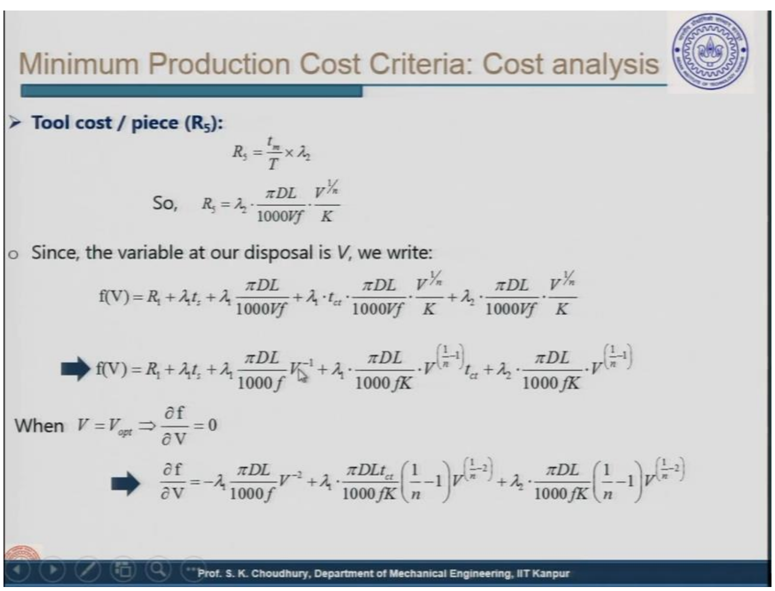

Next is the tool cost per piece that is the R_5 and for this again we have to find out how many times we have changed the tool or the frequency of the tool changing this is $\left(\frac{t_m}{T}\right)$ as we have said here is the frequency of tool changing, that we are multiplying by the λ_2 which is the tool cost per grinding. Now what we are saying is that the person who is doing that we are not paying the overhead and the labor cost in this case.

Because this is the part of that tool cost. Let us assume that another operator is giving the tool. The operator is changing these many times and for each time you are paying the $\lambda_2 \left(\frac{t_m}{T}\right)$ is the frequency of tool changing for that you are paying the tool cost and λ_2 is tool cost per grinding.

So, each time it is being ground, it is grounded by somebody, so the operator who is here he is passing on to another operator who will be grinding, for that he is I mean our operator is not being paid. Therefore, λ_1 is not considered here for this part, this piece. Now this R 5 therefore will be equal to $R_5 = \lambda_2 \frac{\pi DL}{1000\, fV}\left(\frac{V^{\frac{1}{n}}}{K}\right), \left(\frac{t_m}{T}\right)$ we can easily find out because this we have already done it here.

Now the variable at our disposal is *V* only that is the cutting velocity we are not considering the cutting feed and the depth of cut and as I said that those also can be considered, in that case with respect to f we had to take. Now here this equation or the cost per piece, R is only dependent on the cutting velocity.

We are considering that only because we are trying to find out the optimum cutting velocity for the minimum cost. So, here is the cost as shown in the slide and this equation is dependent on a function of the cutting velocity only. Total cost per piece, R can be estimated by summing up all the costs from R_1 to R_5 as shown in the slide.

Then what we are saying is that this cutting speed, V will be optimum cutting speed if we take the first derivative of this equation and make it equal to 0.

So, here we are saying that this is the optimum velocity, this is the maximum velocity that we can operate at so that the cost is minimum. Therefore, we are taking the first derivative, partial derivative and making that equal to 0. So, if you take the first derivative of this equation then it will be $-\lambda_1 + \lambda_1 \frac{t_{ct}}{K}\left(\frac{1}{n}-1\right)V_{opt}^{\frac{1}{n}} + \lambda_2 \frac{1}{K}\left(\frac{1}{n}-1\right)V_{opt}^{\frac{1}{n}} = 0$. Here, R_1 and R_2 are not considered because they are not dependent on the cutting velocity.

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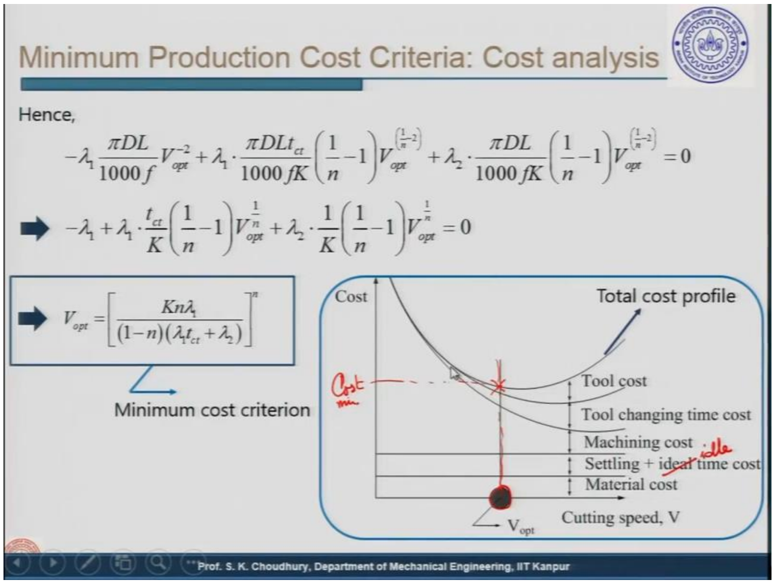

Then we are making that equal to 0. Now, as soon as we are making this first derivative equal to 0,this V will be V_{opt}, this cutting velocity will be optimum cutting velocity because we are taking the first derivative and making it equal to 0. Therefore, everywhere we are putting V_{opt} in place of V.

The above equation can be solved to find out the V_{opt} which will be $V_{opt} = \left[\frac{Kn\lambda_1}{(1-n)(\lambda_1 t_{ct} + \lambda_2)}\right]^n$ this is the minimum cost criteria for which the V is optimum that is the cutting speed is optimum. Now if we draw the curve of the cutting speed here in the x axis and the cost along the y axis what you will find out is that that this cost total cost profile will consist of five costs.

One is the raw material cost, second is the idle time and the settling time cost, third is the machining cost per piece, fourth this the tool changing cost per piece and the tool cost per piece. All those we can plot together to find out the total cost profile so that is what it has been done here. Now this is the cutting speeds so with respect to cutting speed the material cost is constant it does not depend on the cutting speed.

Similarly settling an idle time cost will be also constant, this will also be constant this will not change with the change in the cutting speed as I said earlier. Now the machining costs R_3 we found out like that, so, it is a nonlinear curve. Because R 3 will be $R_3 = \lambda_1 \frac{\pi DL}{1000f} \left(\frac{t_m}{T}\right) V^{-1}$. this is therefore, will be a curve which is nonlinearly changing with the increase in the cutting speed and this is decreasing as the cutting speed is increasing the machining cost will actually decrease as you can see here.

Similarly, the tool changing time cost R_4 we found out as this, this is also a nonlinear equation and therefore this curve goes like this, this is the tool changing time cost, R_5 where we have the component $V^{(\frac{1}{n}-1)}$ and hence, the equation is non-linear.. This is the tool cost, so here in this total tool cost profile will be like this, as shown in the slide which is actually summing of the tool cost, tool changing cost, machining cost, settling and idle time cost and the material cost raw material cost.

Now if we look at this total cost profile, mind it that this is the total cost profile that sums up all the other curves. Here the scale is not maintained but only the profile is shown. Now in this profile you can see that there is a minimum, meaning that if we take this point at this point the cost will be the minimum, let us say here this is the cost which is minimum cost.

Therefore, this will be the optimum velocity and that optimum velocity for that optimum velocity the cost will be minimum. This is the idea of this analysis that we can find out the optimum cost. At this optimum cost, the tool will not be wearing out that much so that the cost will be accessing and the time taken will be optimum. So that the cost of the product remains minimum. Overall, if we operate at this cutting velocity the cost will always be minimum. And if we take the cutting velocity less than that or more than that in both cases the cost will be more.

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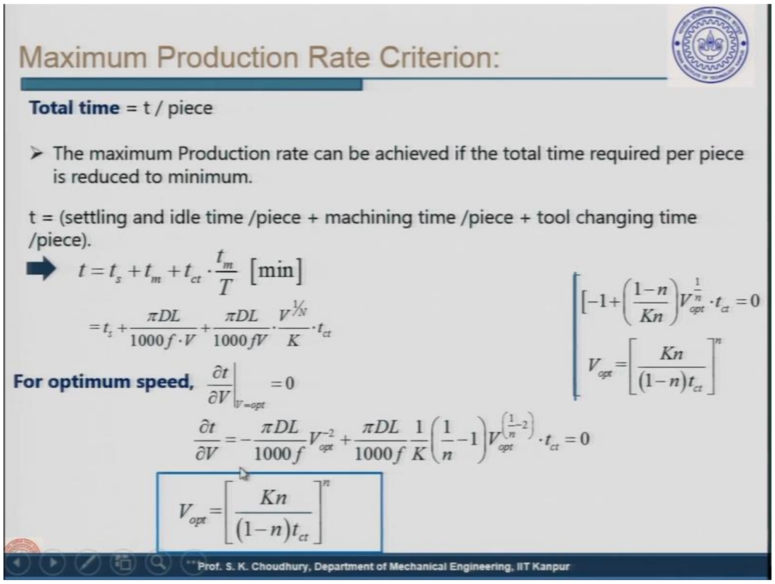

Next, let us say maximum production rate criteria what will be the optimum value of the cutting speed for which we will be getting the maximum production rate. Let us say the total time to make a piece make a product is *t* per piece. The maximum production rate can be achieved if the total time required per piece is reduced to minimum; this is understood that when the time is minimum the production rate is higher rate is 1 / time.

Production rate is 1 upon production time, *t* is the total time, it consists of the three different times that is settling and idle time per piece, machining time per piece and the tool changing time per piece meaning that while we are machining one part we spend time in these 3 activities, that is we are settling and some idle time for each piece for machining the part we need some time so that is the machining time per piece.

And the tool changing time per piece means how many times we are changing the tool and for each time how much you are paying as I have shown it. But overall, this is the tool changing time how much time we are spending. This we are expressing as t_s is the settling and idle time per piece, t_m is the machining time per piece and the tool changing time is the t_{ct} into the frequency of tool changing.

That is how many times we are changing the tool that I have shown it to you earlier this $\left(\frac{t_m}{T}\right)$ and that value becomes $\frac{\pi DL}{1000 fV}\left(\frac{V^{\frac{1}{n}}}{K}\right)$. this is t_m machining time divided by tool life that multiplied by the t_{ct} tool changing time is the tool changing time per piece, because mind it t_{ct} is the tool changing time we set and per piece will be multiplied by this frequency of tool changing.

t_m we have already calculated. So, this t_m value we can put here divided by T, so this is the equation for the total time per piece equal to as shown in the slide. Now for optimum speed, like in case of a minimum cost this first derivative is equal to 0 with respect to V_{opt}.

If we take the first derivative of this equation with respect to V, we are segregating the V as the V optimum because as soon as it is made equal to 0 the V will be V optimum and like we have done in the earlier case we find out the V optimum value segregating this V optimum and you can see that if we simplify this the whole thing will be common it is getting into this is 0 then the V optimum will be equal to $V_{opt} = \left[\frac{Kn}{(1-n)t_{ct}}\right]^n$.

These constants are the tool life equation constants, Taylor's tool life equation constants. Once again, I will come back these n and the C which are the material dependent n and the K in this case because K^n is the C now n and C or n and K in this case these are the material dependent meaning that they depend on the combination of the tool and the work piece material.

And depending on the tool and the work piece material these values will be given in the handbook. So, you can find out these values and depending on the t_{ct} you can say that this will be the value of your optimum velocity.

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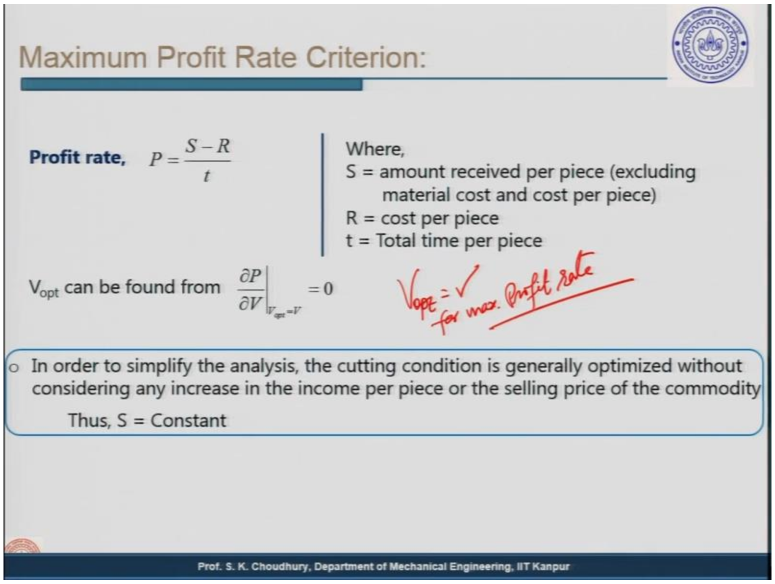

Next we can similarly find out that what is the maximum profit rate criteria; profit rate P is given by $P = \frac{(S-R)}{t}$, t is the total time per piece, S is the amount received per piece excluding the material cost and the cost per piece meaning that after selling how much you are actually getting, how much you are selling it for,in one word it is selling cost, it is the cost per piece, cost per piece we have already found out.

Then if we take the first derivative of this S is constant and find out the value of the R which is equal to $(R\ 1 + R\ 2 + R\ 3 + R\ 4 + R\ 5)$ divided by t, t value is this. So, you take the ratio of the $(R\ /\ T)$, S being constant then P you take as the function of the velocity and take the first derivative of this equation with respect to the V optimum and make it equal to 0, you will find out the value of the V optimum.

Here the V optimum value can be found out for maximum profit rate. Now here one thing I will again repeat that in here we are saying that in order to simplify the analysis the cutting condition is generally optimized without considering any increase in the income per piece. So, this selling price we are seeing as a constant as I said.

And once again I will repeat that this V optimum value will not give you the maximum production rate or minimum production cost or this value of the optimum velocity for which you are getting the minimum production cost will not give you the maximum production rate or maximum profit rate meaning that each one is unique for that particular criterion depending on which criterion you have selected.

You have to decide what do you want to go for? You want to go for the minimum cost or maximum production rate or maximum profit. Depending on that you have to use that particular value of the optimum cutting speed in this particular case. And once again I am telling you that here for the simplification of the analysis we have taken only the cutting speed.

For example, in this case let us say for minimum production cost criteria, we could have kept this V constant. So, instead of V optimum in that case it would have been *f* optimum and find out what is the value of the *f optimum*. Similarly, we bring into this process, into this equation the depth of cut and then we can similarly make that equation and find out finally what is the *d* optimum value.

And you will see that all these values can be found out but for the time constraint we are not discussing all these because that will take a lot of time but you can find out, this is a very similar operation that you can do as I said bringing the value of the f here but you can also bring in the value of the depth of cut and with respect to depth of cut then you take the first derivative equal to 0.

And then it will be the V optimum or f optimum if it is with respect to feed and so on. I hope this is clear now although we got these optimum values that is the feed, speed and depth of cut, we have some restrictions and we cannot always use these values exactly. Let us see these restrictions.

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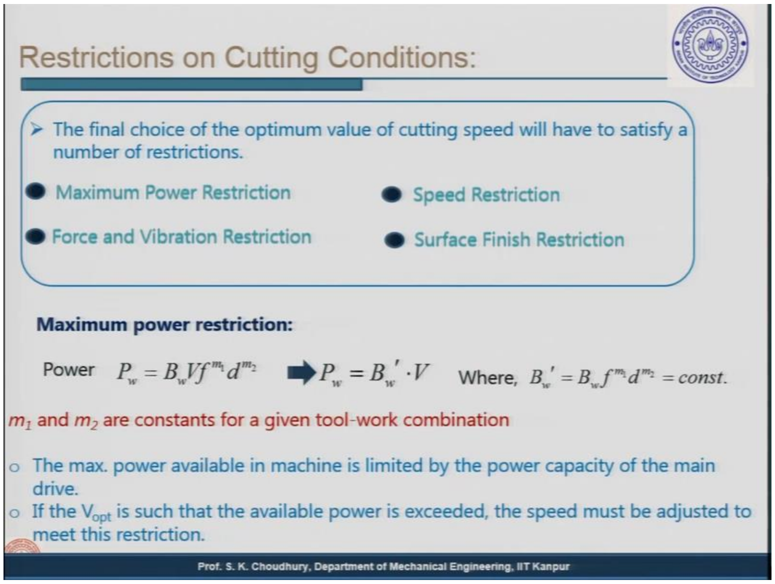

The final choice of the optimum value of cutting speed that we have determined we will have to satisfy a number of restrictions these are the maximum power restriction or force and vibration restriction, speed restriction or surface finish restriction I will quickly go through, that is a common sense for example if it is the maximum power restriction the maximum power can be found out by this equation.

This is the empirical relationship of the power that is given by the constant B_w, cutting speed then the feed to the power m_1 which is constant and depth of cut to the power m_2 which is constant. So, experimentally you can find out the values of the m_1 and m_2 and B_w. Suppose, you can find out the variation of the P_w with the velocity .

Overall, we can say that P_w that is the power this is constant let us say if we take this as constant that f is not changing, d is not changing, we will take only the cutting speed then it will be constant B_w' where B_w' is $B_w' = B_w f^{m_1} d^{m_2}$ which is constant, because only V is variable then in this equation m_1 and m_2 are constants for given tool-work combination.

The maximum power available in the machine is limited by the power capacity of the main drive, when you are selecting the main drive that is the motor that has a particular power and the power required for the cutting process cannot be more than the power available from that machine otherwise it will stop it will not work. So, this velocity that you have got as an optimum velocity for the minimum cost or maximum production rate or maximum profit rate that cannot exceed the power which we have for the main drive.

If the V optimum is such that the available power is exceeded the speed must be adjusted to meet this restriction. Now speed has to be lowered so that we can match it to the main driver prime mover which you have selected that is the point.

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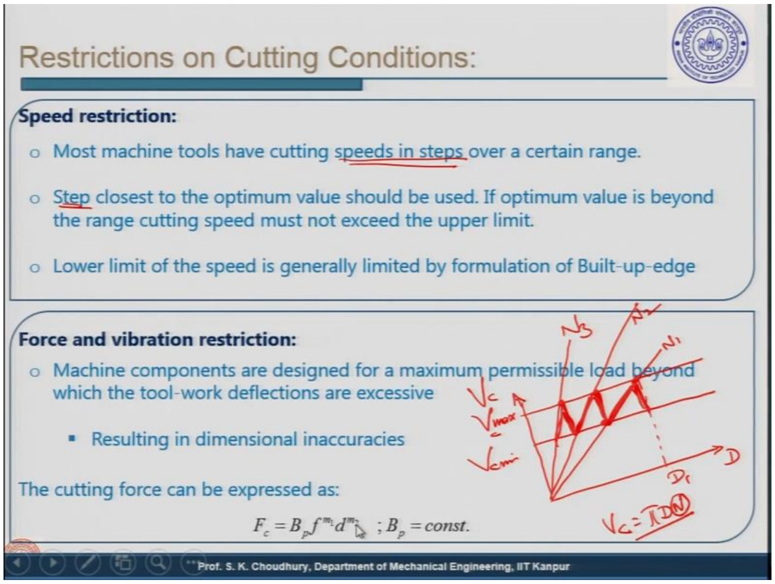

Next is the speed restriction now most machine tools have the cutting speed in steps over a range like for example if we have the diameter here, diameter and this is the speed V_c we said so this is the maximum and this is the minimum we have restriction this V_c minimum and this is V maximum cutting speed V_c. Now the N that is the RPM of the spindle cannot be more than the V maximum.

Since V_c is the πDN so you will give the value of the N and change the value of the N in such a way, given the diameter, that it is not crossing V_c maximum and it does not go below V_c minimum. Because you understand that if it goes beyond this or power will be exceeding and if it crosses less than V c minimum then it will be a restriction from the built-up edge formation.

Suppose you have the N 1 working here with the N 1 some RPM and that that RPM you have that D 1. So, you are going along this and you cannot cross beyond that because it will be crossing then with this D 1 then it will be crossing the power, velocity. Now you have to come back along this line and from here you just take the perpendicular to this line and you join this line.

Then this will be N 2, again you are going along this line up to this point you cannot cross this then you come back here and from here you take the perpendicular and then you join this line. So, this will be N 3, these are the steps that we are talking about that this is the step in the cutting feeds in steps that means N 1, N 2, N 3 and this curve is called the saw diagram.

Because this looks like a saw, the way the steps are changing. These steps, as you know that they can be in geometric progression so that the headstock could be compact, that is a gearbox can be compact. Now step closest to the optimum value should be used whatever optimum value that you have found out that should match the step available. If not then you come back to the next step.

With the closest V and then V has to be adjusted the V optimum that you have calculated from the minimum cost or maximum production rate in that case that has to be adjusted accordingly that is the point we are saying that lower limit of the speed is generally limited by the formation of the built-up edge that is what I said already. Now the force and vibration restriction the machine components are designed for a maximum permissible load.

Beyond which of course the tool work deflection will be excessive and that will result the dimensional inaccuracy meaning the diameter will be defective or the length will be defective I mean the deflection and so on. Therefore, the cutting force can be expressed in this way, it depends on the feed and the depth of cut, velocity does not have much effect on that. Therefore, if we say that B_p is constant then it will be depending on the feed, *f* and the depth of cut, *d*.

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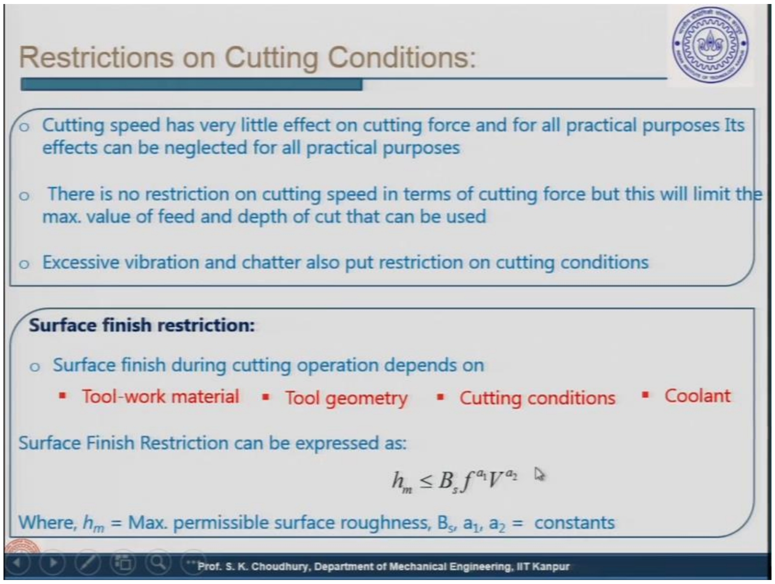

So, cutting speed has a very little effect on the cutting force as I said there is no restriction on the cutting speed in terms of cutting force but this will limit the maximum value of feed and depth of cut that can be used here, feed and the depth of cut they will affect the cutting force. Excessive vibration and chatter also put restriction on the cutting conditions. Meaning that whatever V_m you have selected or the optimum value you have selected.

Now the surface finish restriction. Surface finish during the cutting operation depends on the tool work material, tool geometry, cutting condition and the coolant; these are the 4 factors basically which will affect the surface finish. Now the surface finish restriction can be expressed as this that it has more effect from the feed and the velocity.

And therefore, whatever V optimum that you have selected it has to satisfy this equation if not then the V optimum that you have already calculated for the optimum for the maximum profit rate or maximum production rate or minimum cost that has to be adjusted this is what it has been said. This is what I wanted to discuss in the economics.

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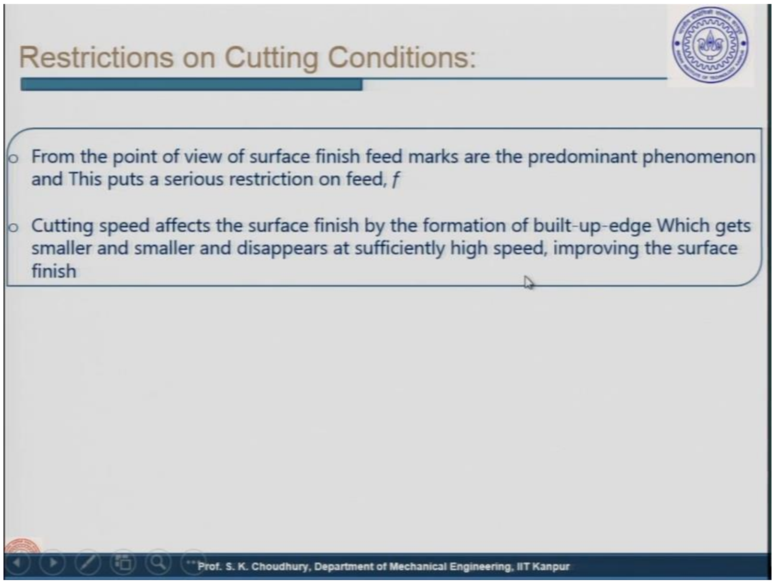

Now from the point of view of surface finish, feed marks are the predominant phenomenon and this puts a serious restriction on the feed because feed has to be regulated so that feed marks are do not remain on the machine surface cutting speed affects the surface finish by the formation of the built up edge which gets smaller and smaller and disappears at sufficiently high speed when the temperature goes beyond the temperature of the crystallization. And then the surface finishing proofs. So, these are the 2 points which are important here.

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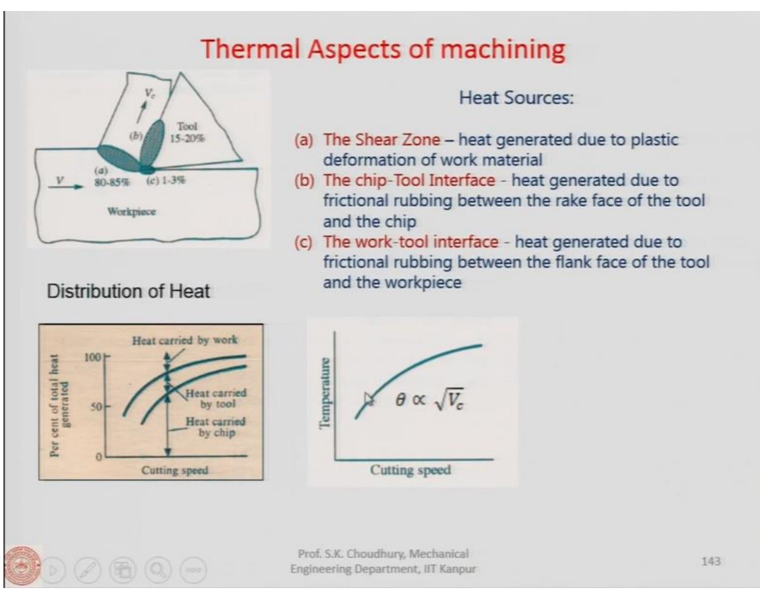

In our next topic quickly I will go through the thermal aspects of machining where I would like to show you particularly how the temperature occurs, where the temperature occurs and how this temperature is disbursed, rather distributed. When the cutting process happens there is the plastic deformation occurs and the chip is formed from the shear zone.

Here the material is completely plastic and then it will actually the plastic deformation takes place here in the shear zone and the chip moves over the rake face of the tool. Because of the plastic deformation a lot of heat is produced and in this shear zone almost 80 to 85% heat is produced because of the deformation plastic deformation. you should understand that plastic deformation is the basic factor why the temperature occurs.

Next this heated chip will flow over the surface of the rake face. So, during the flow of the chip over the rake face there is a friction between the chip and rake face of the tool due to which 15 to 20% of the heat is produced actually and about 1 to 3% heat is produced because of the rubbing between the flank face of the tool and the already machined surface this is what it is said here. Now the distribution occurs almost in the similar way as they have produced that the heat is carried away by the chips.

This is majority of the heat carried away by the chips then the heat carried by the tool this is about 15% and less than about 5% or carried away by the work. So, majority of the heat is carried away by the chip followed by heat conduction in the tool and the work piece. And remind you that the temperature changes with the cutting velocity in this way.

As the cutting velocity increases, temperatures will change in this way and this is the distribution or the disbursement of the heat to the chip to the tool and to the work piece.

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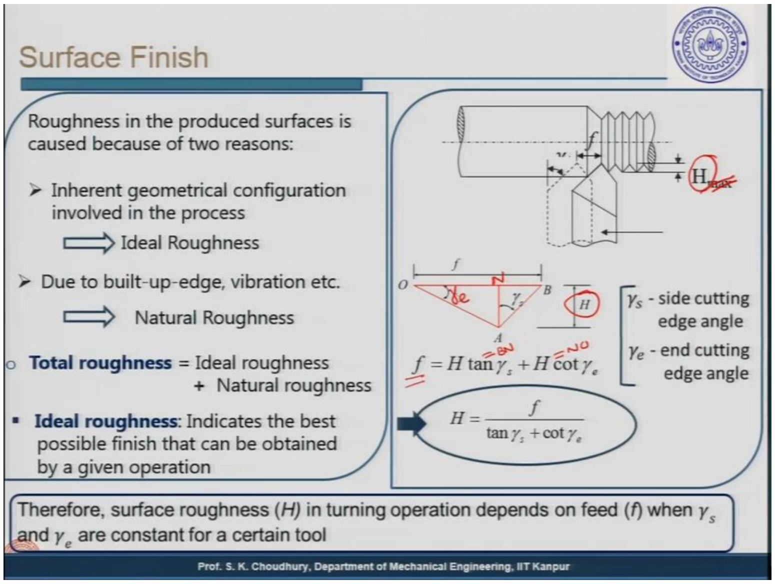

Now let us talk about the surface finish, what is surface finish? There are undulations on the surfaces that this is the surface roughness. And if you look at any surface which is machined under the microscope, we will see that there are surface undulations, it cannot be absolutely smooth. The surface finish is defined by the height of those spikes, how big those spikes are, how big is the surface roughness?

Roughness in the produced surface is caused because of 2 reasons, 1 reason is the inherent geometrical configuration involved in the process that is the ideal roughness, inherent geometrical configuration means that we already have, the tool with a certain angle we will have, we have certain machining conditions, parameters, we have a certain machine on which we are working that will have certain accuracy.

So, these are the inherent properties they cannot be changed. Now second is due to the built-up edge, vibration etcetera. The first cause which you cannot change is the ideal roughness and the second cause, that is, because of the built-up edge vibration etcetera they constitute the natural roughness. Total roughness is the ideal roughness plus natural roughness. Now on the ideal roughness we do not have much control.

Because they are inherent, they will happen, so ideal roughness indicates the best possible finish that can be obtained by a given operation, we cannot have any control on them. Therefore, surface roughness in turning operation when we are determining, this is the exaggerated form, this is the depth of cut from here to here. And this is the undulation this is the surface roughness so surface roughness will be determined from peak to valley distance between this point and this point.

This will be given by H max. This is the movement of the tool in one revolution of the work piece from this point to this point. Now if we see this triangle, let us say this is A this is B and this is C this is O.

This is the triangle A, O, B. O, B is the feed. From this point, A if we put a normal, let us say this is AN. In that case the feed,f is equal to (BN + NO). This distance, AN is equal maximum roughness, H_{max}. This is from peak to valley of the surface undulation or roughness. Now, $BN = AN \tan\gamma_s$ and $NO = AN \cot\gamma_e$. Therefore, $f = AN \tan\gamma_s + AN \cot\gamma_e = H \tan\gamma_s + H \cot\gamma_e$ from where we find out the value of the roughness as $H = \dfrac{f}{\tan\gamma_s + \cot\gamma_e}$.

This will be the formula that will tell us on which factors the surface roughness or surface finish will depend and in this case that is the turning with the sharp tool. We can see that it depends on the feed mostly because for a certain tool our side cutting and the end cutting edge angle will be constant and the *H* is directly proportional to the *f*.

So, when we are changing the feed, surface finish changes, as we are increasing the feed, the surface roughness, H increases and hence surface finish deteriorates.

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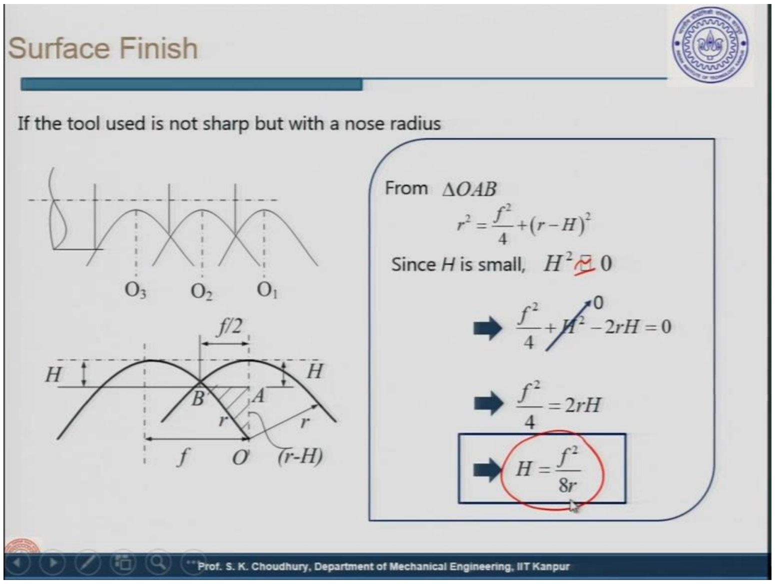

Now let us see what happens if we round off nose of the turning tool instead of having this sharp edge. If you are rounding off the tool nose in that case you can see in the slide in this way it is not sharp but with a nose radius. This is the center and this is the nose radius, let us say *r*. These are the 2 profiles means for each revolution of the work piece tool is moving from this point to this point by next revolution it is moving from this point to this point.

So, the distance between these 2 points will be equal to *f* this is the feed, this is what we are writing that from here to here valley it will be *f / 2* half of this distance. Now in these 2 profiles this is the r, this is *f / 2* because this distance is f and this distance is *(r – H)* this is the H which is the surface roughness. Therefore, from OAB triangle we can say that $r^2 = \left(\frac{f}{2}\right)^2 + (r-H)^2$.

From here H is very small. So, we can ignore H^2. So, we get $\frac{f^2}{4} = 2rH$. Therefore, $H = \frac{f^2}{8r}$. So, now if we compare this with the sharp tool we will find out that for a comparable value of the feed, the rounded off tool will give a better surface finish or less value of the surface roughness.

Therefore, we always say that tool should be rounded off up to 3 millimeters because beyond 3 millimeter I will remind you that those components of the normal force that is along the radial direction normal to the cutting tool edge will increase, that will detract the tool from the work piece and there will be self excited vibration. And if it is very small that is lower than let us say 0.5 mm or so then there will be high stress concentration because tool will be close to sharp.

Therefore, the tool has to be rounded off and how much it will be rounded off you can actually take the guidance from this theoretical judgment that this H, that is the surface roughness will depend on $\frac{f^2}{8r}$ and r is the nose radius, f is the feed.

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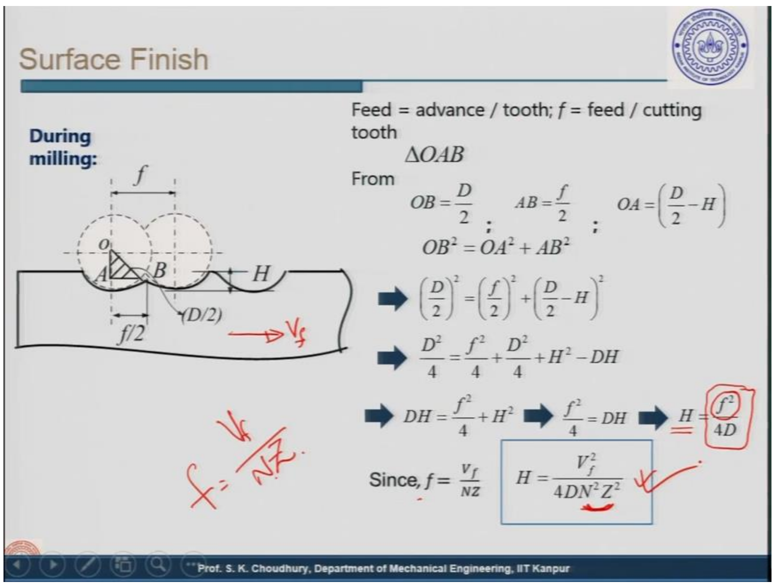

In case of milling, it is the feed which is advancement per tooth and f is the feed per cutting tooth. Let us take consider 2 subsequent positions of the milling cutter when the work piece is moving. Let us say work piece has the feed velocity which is V_f .

Here these are the two positions we are considering. This is the profile as the V_f is given to the work piece while the milling cutter is rotating. Here you can see that this is the radius of the milling cutter that is *D / 2* which is here. Now from O to B this is the feed and this is the feed per advancement of the tooth because this is for one tooth, this we have discussed for the milling.

From the OAB triangle, we can say that OB this is the *D / 2* this the radius and AB is the f / 2 since f is the complete distance between these 2 centers and this is the half of that. OA is equal to D / 2 and this distance is the H, this is from peak to Valley which is A to this point. Then from this triangle $OB^2 = OA^2 + AB^2$ from here we can put the values which you have seen here and we can say that H value we can find out as $H = \frac{f^2}{4D}$.

So, this is the value that is the surface roughness in case of the milling and this depends on the f square divided by 4 D, Dis the diameter of the milling cutter. Now *f* we said earlier is equal to $f = \frac{V_f}{NZ}$, these values we can put here. Finally we can get that $H = \frac{V_f^{\,2}}{4DN^2Z^2}$.

From this equation you can also see that for comparable feed in case of let us say turning and milling the surface finish in milling will be better. This is simply because the milling will be working with many teeth and the single point cutting tool particularly when the cutting tool is sharp the surface roughness will be more.

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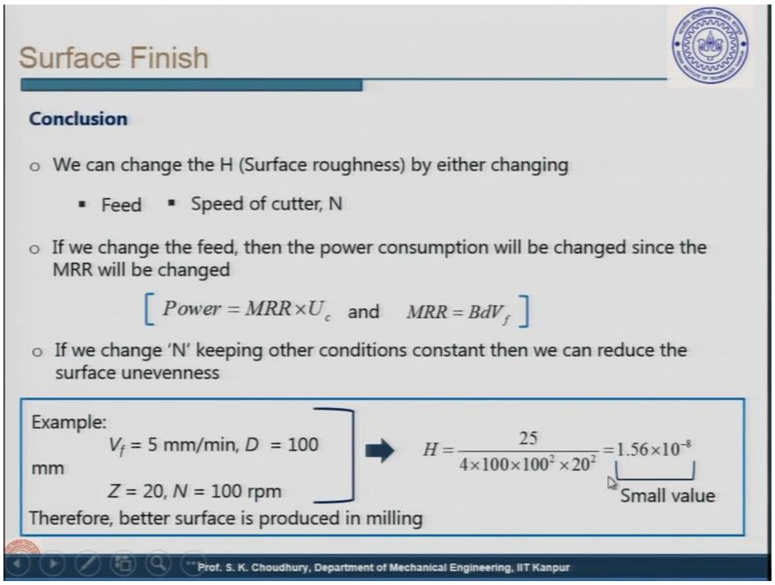

Now, if we see the grinding for example now here of course these are the changes that we have shown that power can be made as this and there is a small example given that if the V_f is given and the D is given, so how to find out the H. You can put in the formula all these values to find out what is the value of the H. And that is what I was telling you that you can see and compare that this is such a small value in comparison to what you can get in case of turning for example with a comparable feed value.

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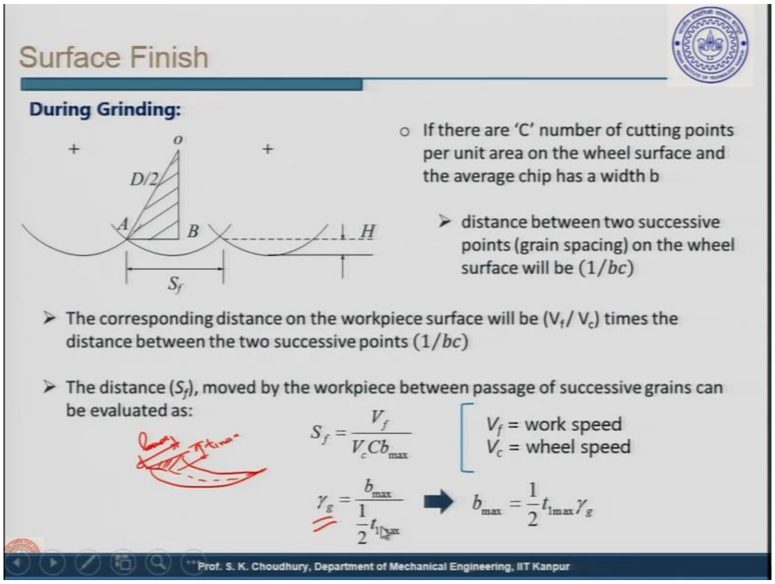

Now let us see what happens in the case of grinding. In case of grinding, these are the subsequent positions of the grinding wheel when the feed is given like in the case of the milling. Grinding wheel is rotating and the feed is given to the work piece. For each rotation of the grinding wheel the work piece is moving. Let us say that there are *C* number of cutting points.

Earlier we said that *C* is the grain concentration but unit area on the wheel. C is the number of cutting points per unit area on the wheel surface and the average chip has a width *b*. The distance between two successive points, is the grain spacing.

This will be (*1 / bc*) once again I will explain this to you that if we said that there are *C* number of grains per unit area, then from one grain to another grain that distance will depend on the *b* width, the width of the chip that a grain will be producing. Therefore, *(1 / b)* divided by the C will be the grain spacing, distance between the grains on the wheel. This distance on the work piece will be $\left(\frac{V_f}{V_c}\right)$ times the distance between the two successive points (*1 / bc)* on the grinding wheel.

$\left(\frac{V_f}{V_c}\right)$ is the ratio, why it is so because we have to multiply by the ratio of that feed velocity given to the table and the cutting velocity given to the grinding wheel. So, $\left(\frac{V_f}{V_c}\right)$ if we multiply by this *1 / bc* that will be the equivalent distance on the work piece with respect to the distance between two grains on the grinding wheel. this is the distance that is the S_f on the work piece.

on the work piece this distance is equal to $\left(\frac{V_f}{V_c}\right)\left(\frac{1}{bc}\right)$, *b* is the maximum width we are saying as a maximum width of the chip, because the two successive grains will produce the maximum chip width. $\gamma_g = \left(\frac{b_{\max}}{\frac{1}{2}t_{\max}}\right)$ we already found out this. Half of that $t_{\max}$ in the denominator because it is average chip thickness, *t*. So, the b_{max} therefore is equal to $b_{\max} = \frac{1}{2}t_{\max}\gamma_g$.

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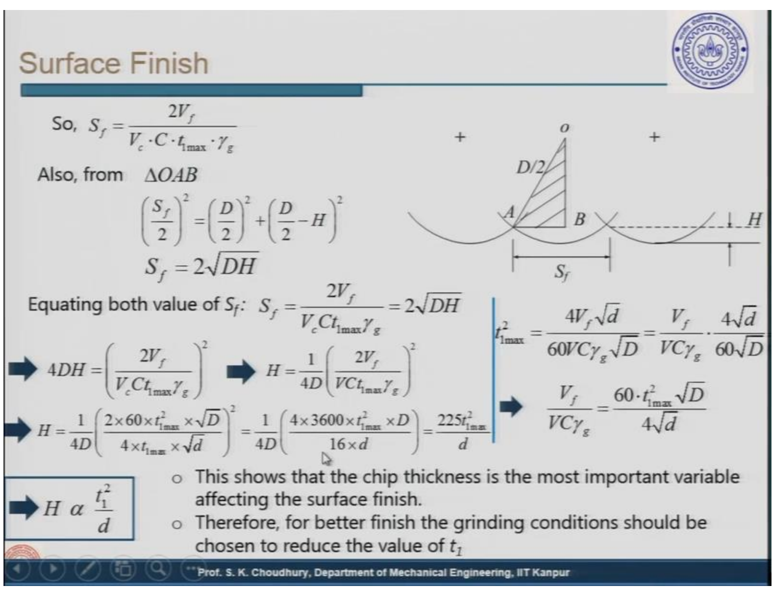

Now the S_f that we have written as this here we are putting the b_{max} value as this and we are getting the equation as shown in the slide. Now from this triangle like in case of milling $OA^2 = AB^2 + OB^2$. From here we can find out by ignoring this square which is small as the

$S_f = 2\sqrt{DH}$, D is the diameter of the grinding wheel. D / 2 is the radius like in case we have taken in milling.

Now equating both these S_f f, because S_f is this and here it is, we can find out if we equate that and then put the value of the t_{max} which we have earlier found out and from H we are replacing this value to get finally that $H = \frac{225 t_{max}{}^2}{d}$ d is the depth. So, the H is proportional to $t_{max}{}^2$.

Now this shows that the chip thickness is the most important variable affecting the surface finish. Therefore, for better finish the grinding condition should be such to choose the value of the *t* which will be reduced because if we can reduce the value of the t this is proportional to t^2 so H value will be reduced. And H is the surface roughness therefore the surface finish will be better.

Therefore, for better finish the grinding condition should be chosen to reduce the value of the *t*. So, here you can see that the surface finish of the grinding is better than in case of the milling which is better than in case of the turning particularly for the sharp tool and for the rounded off tool the surface finish is better than the sharp tool. This is what I wanted to tell you in the machining section. And I thank you for your attention. I will discuss the rest of the material in the course of the production technology in the next discussion session. Thank you once again for your attention.