# Production Technology: Theory and Practice
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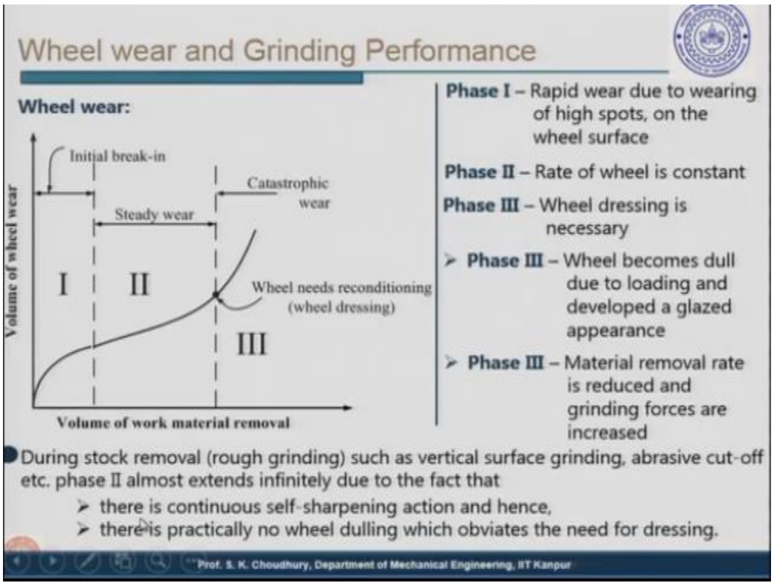
## Lecture - 16
## Wheel Wear and Grinding Performance

Hello and welcome to the discussion sessions of production technology theory and practice. Let me remind you that in our last session of discussion we started discussing the specific energy in grinding and we said that the specific energy in grinding is very high and I discussed it with you that there are basically 3 reasons. One is the size effect which means that when the $t_1$ is small, uncut thickness is small or thickness is small then the specific energy becomes very high.

I have shown it to you graphically how it can be presented. And the other points are that when the grinding process takes place or abrasive machining processes take place, then initially the grains do not remove the material, but they rub more. After that as the normal force increases, then there is a flowing action instead of metal removal action and with further increase in the normal load, the material removal takes place.

Since initially there are the rubbing and flowing, so that consumes a lot of power, a lot of specific energy. Along with the size effect that during the grinding process takes place at a very thin $t_1$ at a very thin depth of cut where the imperfections do not exist and the material behaves almost like an ideal material, the specific energy goes very high in comparison to any other normal processes like turning, milling, drilling etcetera.

Having said that, next we told about the wear of the grinding wheel and we said that in grinding will also initially when the grinding wheel comes in contact with the workpiece it happens like the single point cutting tool that since all the grains are sharp and the stress concentration is very high around the sharp edges, as soon as the grains come in contact with the workpiece, they get rapidly worn out. Wearing action of that those sharp grains becomes very rapid and that was the initial wearing action. **(Refer Slide Time: 03:07)**



## Wheel wear and Grinding Performance

**Wheel wear:**

**Phase I** – Rapid wear due to wearing of high spots, on the wheel surface

**Phase II** – Rate of wheel is constant

**Phase III** – Wheel dressing is necessary

- **Phase III** – Wheel becomes dull due to loading and developed a glazed appearance
- **Phase III** – Material removal rate is reduced and grinding forces are increased

- During stock removal (rough grinding) such as vertical surface grinding, abrasive cut-off etc. phase II almost extends infinitely due to the fact that
  - there is continuous self-sharpening action and hence,
  - there is practically no wheel dulling which obviates the need for dressing.

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We said that this was the initial break-in. After that, we said the that the steady wear takes place because there apparently a self-sharpening phenomenon happens that as the grains wear out they get dislodged easily from the surface of the grinding wheel. And therefore, this steady wear goes for a long time and this is specified as the self-sharpening of the grinding wheel.

After that, when the wear takes place quite a lot in the sense that the wear flats become more and more then there will be a catastrophic wear and wheels needs the reconditioning because after this point the wheel will not provide the specific machining quality that is desired because of the wheel wear, because it may be glazed surface, because the wearing action has taken place including the initial break in and the steady wear.

At that point, the wheel needs dressing and the dressing I have already explained to you that dressing is also required when the wheel is glazed or the wheel is loaded, to remove the worn out grains or the chips which are clogged in the voids of the grinding wheel surface. So, these are the phases that I have discussed with you that these three phases come within the grinding wheel during the material removal. these are explained that there is a self-sharpening what is the self-sharpening and there is practically no wheel wearing in this steady wear region.

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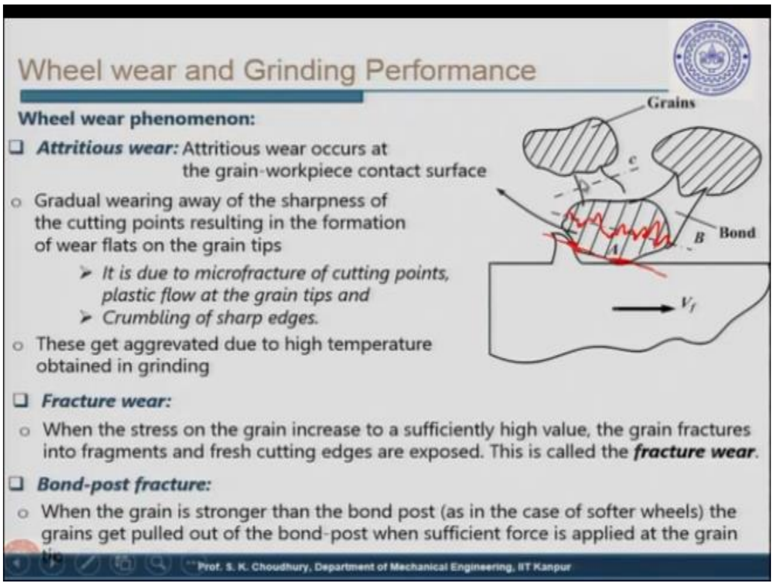

## Wheel wear and Grinding Performance

**Wheel wear phenomenon:**

- ❑ ***Attritious wear:*** Attritious wear occurs at the grain-workpiece contact surface
  - ○ Gradual wearing away of the sharpness of the cutting points resulting in the formation of wear flats on the grain tips
    - ➢ *It is due to microfracture of cutting points, plastic flow at the grain tips and*
    - ➢ *Crumbling of sharp edges.*
  - ○ These get aggrevated due to high temperature obtained in grinding
- ❑ ***Fracture wear:***
  - ○ When the stress on the grain increase to a sufficiently high value, the grain fractures into fragments and fresh cutting edges are exposed. This is called the ***fracture wear***.
- ❑ ***Bond-post fracture:***
  - ○ When the grain is stronger than the bond post (as in the case of softer wheels) the grains get pulled out of the bond-post when sufficient force is applied at the grain tip

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Then we started discussing in our last session that how the grinding wheel wears out so these are the grains which are bonded together and the entire thing is a grinding wheel which is in contact with the workpiece and it rotates along with the $V_f$ and then the material is removed from the workpiece surface. Like it is shown here that each grain will remove a small amount of the material in terms of small chips.

When these grains rub along the workpiece and remove material from the workpiece there are 3 types of wear that I have mentioned to you in our last session. Let us see that in more details. First is the attritious wear, attritious wear occurs at the grain workpiece contact surface. This I have shown to you earlier that these contact areas, these contact points where the grain is in contact with the workpiece while removing the material gradually wears out.

This wearing action is the gradual wearing away of the sharpness of the cutting points resulting in the formation of wear flats on the grain tips as I have shown it here that there will be kind of a flat formed, these are the wear flats because of the wearing action gradually on the on the grain tip. This kind of wear which happens at the contact point between the grain and the workpiece is called an attritious wear; this is one type of wear.

it is due to the microfracture of the cutting points because points are still sharp, plastic flow at the grain tips and maybe because of the crumbling of the sharp edges. Overall the result is that this is a gradual wearing action of the cutting tips which are still sharp and they just started removing the material. These are the 3 phenomena that happen, that is microfracture, plastic flow and the crumbling of the sharp edges.

Because of these 3 factors, the grains wear out and this is called the attritious wear. These gets aggravated due to high temperature obtained in grinding and the flat becomes more. Once the flat is made, then it creates more temperature and along with the temperature which is anyway created because of the grinding process this flat becomes more and the attritious wear increases.

Next type of wear is called the fracture wear. This happens along the plane B within the grains, when the stress on the grain increases to a sufficiently high value the grain fractures into fragments and fresh cutting edges are exposed, this is called a fracture wear. when this flat is increasing in attritious wear, the forces on the grain also will be increase because the flat is more.

Finally, what happens is that the stress applied or the force applied on a particular grain will be so much that the strength of the grain will not be able to withstand that kind of magnitude of force and simply breaks. When it breaks, the new grains are exposed, because it will still stay within this bond. When it is broken, just imagine, it will not be broken in along one line, it will be broken in an irregular way.

And you can see that these are the sharp edges which are exposed and these sharp edges, I am exaggerating, will serve as the new sharp grains, which will have less rubbing, less power consumption, less force requirement and it will be not providing and not creating high temperature because it is a new sharp grain. This is called the fracture wear it is fracturing along the line inside the grain.

Next type of fracture is the bond post fracture; it happens either within the bond here or within the bond here. When the grain is stronger, the force is increasing in this fracture wear, but if the grain is stronger than the bond post then the strength here with the bond and the grain, in that case the grains get pulled out of the bond post when sufficient force is applied at the grain tip. When it happens? It happens normally in the soft grains, for soft wheels.

In soft wheels, the bond is soft, means, it will allow the dislodging of the grains easily; in that case, instead of grain breaking within the grain surface like this, like the fracture where it will be pulled out from the bond post. Normally it has been seen that this wear is connected to the grain bond and the grain interface, it is stronger than the post within the bond post. Therefore, fracture will normally happen within the bond post here.

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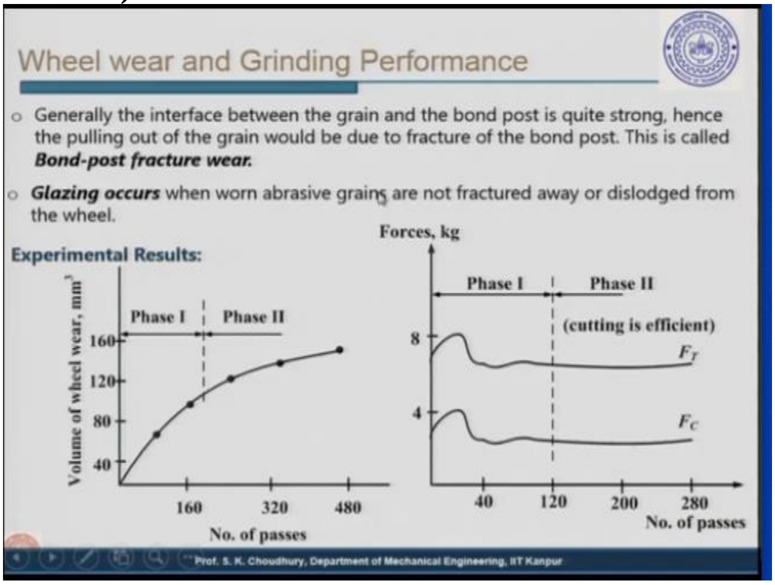

Wheel wear and Grinding Performance

- Generally the interface between the grain and the bond post is quite strong, hence the pulling out of the grain would be due to fracture of the bond post. This is called ***Bond-post fracture wear.***
- ***Glazing occurs*** when worn abrasive grains are not fractured away or dislodged from the wheel.

**Experimental Results:**

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Generally, the interface that isthe interfaces between the grain and the bond post is quite strong. Hence, the pulling out of the grain would be due to fracture of the bond post, it will not be along this line or along this line, it will be along the line somewhere inside the bond, because these interfaces between the bond and the grain normally are very strong, this is called the bond post fracture. When it is fracturing within the bond post, it is called a bond post fracture.

glazing occurs when worn abrasive grains are not fractured away or dislodged from the wheel. As I said that, if it is not getting dislodged when it is worn out, then the glazing occurs. These are some experimental results I am not going into details here.

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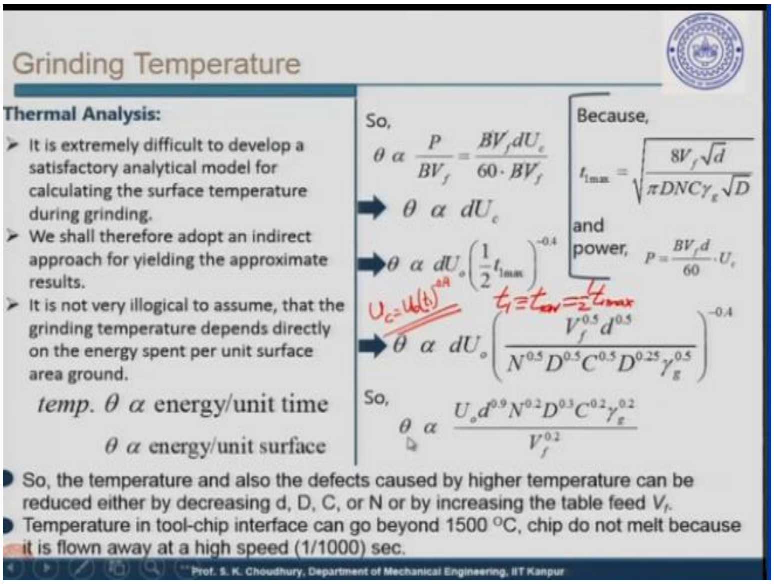

## Grinding Temperature

**Thermal Analysis:**

- It is extremely difficult to develop a satisfactory analytical model for calculating the surface temperature during grinding.
- We shall therefore adopt an indirect approach for yielding the approximate results.
- It is not very illogical to assume, that the grinding temperature depends directly on the energy spent per unit surface area ground.

$$temp.\ \theta\ \alpha\ \text{energy/unit time}$$

$$\theta\ \alpha\ \text{energy/unit surface}$$

So,

$$\theta\ \alpha\ \frac{P}{BV_f} = \frac{BV_f dU_c}{60 \cdot BV_f}$$

$$\Rightarrow \theta\ \alpha\ dU_c$$

$$\Rightarrow \theta\ \alpha\ dU_o \left(\frac{1}{2} t_{1max}\right)^{-0.4}$$

$U_c = U_0 (t)^{-0.4}$ $t_1 = t_{av} = \frac{1}{2} t_{max}$

$$\Rightarrow \theta\ \alpha\ dU_o \left(\frac{V_f^{0.5} d^{0.5}}{N^{0.5} D^{0.5} C^{0.5} D^{0.25} \gamma_g^{0.5}}\right)^{-0.4}$$

So,

$$\theta\ \alpha\ \frac{U_o d^{0.9} N^{0.2} D^{0.3} C^{0.2} \gamma_g^{0.2}}{V_f^{0.2}}$$

Because,

$$t_{1max} = \sqrt{\frac{8V_f\sqrt{d}}{\pi DNC\gamma_g\sqrt{D}}}$$

and power, $P = \frac{BV_f d}{60} \cdot U_c$

- So, the temperature and also the defects caused by higher temperature can be reduced either by decreasing d, D, C, or N or by increasing the table feed $V_f$.
- Temperature in tool-chip interface can go beyond 1500 °C, chip do not melt because it is flown away at a high speed (1/1000) sec.

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let us see, in grinding what happens as the temperature rises. So, this is the thermal analysis and this is very important because the grinding temperature has to be assessed, I am giving you a preamble that why this temperature model is important in case of grinding. Thing is that in case of grinding the measuring the temperature by any device is difficult because this process is very fast, there is chip flowing and then there will be sparks because of the small chips burning.

Therefore, there is a model that is some sort of analytical model by which we can assess the temperature which is occurring during the grinding process. Why it is important? If we can assess analytically the equation of the grinding temperature meaning what are the parameters on which the grinding temperature will depend, in that case we will have the full control on the grinding temperature.

We can control those output parameters or variables and by controlling that we can decrease the output temperature of the grinding process that is why it is very important to assess the parameters which depend and affect the grinding temperature. Let us see how it can be done. It is extremely difficult, as I said, to develop a satisfactory analytical model for calculating the surface temperature during the grinding.

Apart from the difficulty that we have in measuring the grinding temperature it is also difficult to directly make a model. We shall therefore adopt an indirect approach for yielding the approximate results. This indirect approach is that it is not very illogical to assume that the grinding temperature depends directly on the energy spent per unit surface area ground meaning that depending on the unit surface area that is being ground, the energy will depend, more surface area ground is more energy, in one word.

So, the temperature is proportional to the energy per unit time or energy per unit surface. So, we can write this in terms of an equation that this $\theta$ which is grinding temperature is $\theta \propto \frac{P}{BV_f}$. P is the power which can be expressed as $U_c$ multiplied by MRR. This is MRR because this is the feed velocity $V_f$ multiplied by the width $B$.

So, $B$ multiplied by $d$ is the area. Power divided by $BV_f$ will give you this proportionality because this is the per unit surface. So, if we do that, then we will find out that this is proportional to $dU_c$ that is the depth of cut and $U_c$, $U_c$ is the specific energy.

specific energy will write as $U_c = U_0 \left( \frac{1}{2} t_{\max} \right)^{-0.4}$ because you remember that we said that that $U_c = U_0 \left( t_1 \right)^{-0.4}$ in general. In case of milling or in case of grinding, as I said that $t_1$ is the $t_1$ average and $t_{1av}$ is $t_{1av} = \frac{1}{2} t_{\max}$. here the $t_1$ is equivalent to $t_{1av}$ which is equal to $t_{1av} = \frac{1}{2} t_{\max}$. This equation is applicable to the grinding process in the following way.

the $t_{\max}$ we have derived as $t_{\max} = \sqrt{\frac{8V_f \sqrt{d}}{\pi DNC\gamma_g \sqrt{D}}}$, D is the diameter of the grinding wheel, $\gamma_g$ is the grinding ratio and the power is given by $P = U_c \times MRR$. in that case the $t_{\max}$ value if we put in here, we will get the following after simplifying.

It will be that the temperature during the grinding process that is proportional to $\theta \propto \left[ \frac{U_0 d^{0.9} N^{0.2} D^{0.3} C^{0.2} \gamma_g{}^{0.2}}{V_f{}^{0.2}} \right]$.

let us see what this equation signifies. we kthat as per this assumption the temperature is proportional to the energy per unit surface area and that is not a very illogical as I said and this will be a valid assumption. Therefore, the temperature and also the thermal defects caused by higher temperature can be reduced.

It can be reduced either by decreasing depth of cut *d*, diameter of the grinding wheel, grain concentration, in case we can because we said earlier that grain concentration we are not touching since there is a particular grinding wheel, but if you can change the grinding wheel with different grain concentration if there is an option, then the temperature in the grinding process could be less or N, N is the rotational frequency of the grinding wheel.

If we can decrease these 4 factors or if we increase the table feed $V_f$ then we can reduce the temperature. Temperature in the tool chip interface can go beyond $1500^0$C which is very high temperature and when we will go to the lab he will see, I will show you the grinding process; you will see the tool grinding. We will show you how the rake face of a grinding tool is reground when the rake face is spoiled or worn out.

We will see that always whenever the grinding wheel is in contact and removing material from the workpiece surface, there will be spark and that spark is burning of the very small chips and the spark because it is this high temperature of $1500^0$C. Chip sometimes do not melt because it is flown away at a high speed so it flows away at *(1/1000)* per second so it is a very high speed and sometimes it is not melted it burns up at that high temperature.

This is I hope is understood that these are the parameters on which the temperature of the grinding depends and therefore we have a possibility of regulating the grinding process so that the temperature is within the range or within our desired level so that there is no thermal deformation of the material that is being ground; this is important because normally the grinding process is done after the heat treatment.

And after the heat treatment normally we find that some of the surfaces are distorted because of the high temperature that is involved in the heat treatment process. So, to smoothen the surfaces and to get the accurate surface that is desired, we normally perform the grinding process. Therefore, we cannot afford to have the further surface deformation because of the grinding process. And further deformation can come either because of the very high force involved in the grinding or very high temperature which is occurring during the grinding.

In this case what we have discussed is that there are still provision that grinding temperature can be reduced by manipulating those 5 parameters.

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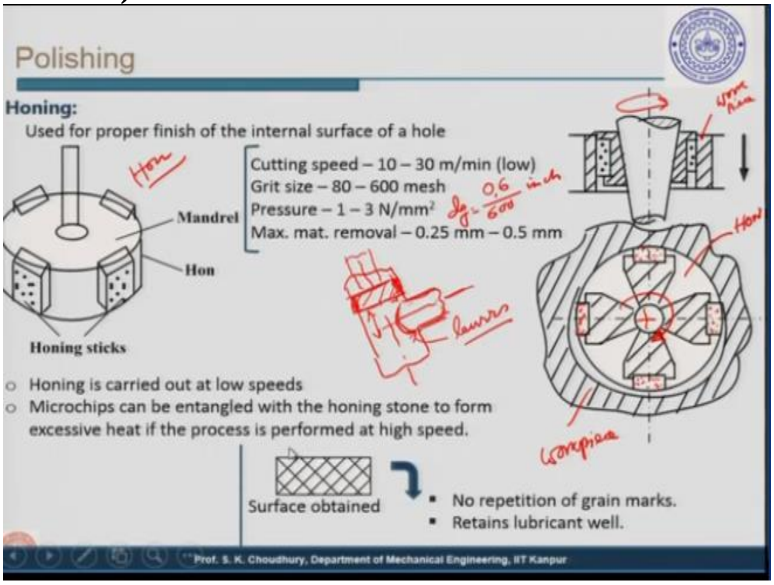

Polishing

**Honing:**

Used for proper finish of the internal surface of a hole

Cutting speed – 10 – 30 m/min (low)
Grit size – 80 – 600 mesh
Pressure – 1 – 3 N/mm²
Max. mat. removal – 0.25 mm – 0.5 mm

- Honing is carried out at low speeds
- Microchips can be entangled with the honing stone to form excessive heat if the process is performed at high speed.

Surface obtained

- No repetition of grain marks.
- Retains lubricant well.

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apart from the grinding process, there are processes like honing. Honing process is used for proper finish. It is not for as much to remove the excess material, but it is basically for removing the undulations after the grinding, if any. Undulations means those are the surface roughness or asperities. It is very important to remove them because if we have a part like this which is a cylindrical part and here there is another part.

This kind of a part normally exists in the cylinder of the automobile in the internal combustion engine. That means a piston will go up and down, this is a piston this will go up and down and this is for the automobile to run. where it is going up and down these are the two surfaces, these two cylinders are made first you make a cylinder and then you make a hole from here and then you make a hole along this axis.

These two axes then will be perpendicular to each other, but then while you are drilling this hole, there may be some burrs that mean the unfinished material, these chips are not able to be taken out and they stick to the surface, they are called the burrs. Removing of those burrs is extremely important and very often these kinds of burrs you can see inside the cylinder.

That may be very difficult to remove. It can be removed either by honing or by any chemical technique or by unconventional machining like electro discharge machining, electro chemical machining, which we will be discussing after this. in case of honing normally the cutting speed is low it is about 10 to 30 meter per minute and this is the honing.

The instrument or device or tool that is used is called the hon and that is why the process is called the honing. hon itself is a metallic arbor like that. And around this on the periphery of this outer cylindrical part of the madrel, as it is called, there are honing sticks which are made of abrasive materials. These abrasive grains are very fine. It can be up to 600 mesh which means 0.6 / 600 inch is the diameter of the grain.

Therefore, up to 600 mesh are very fine grains and it will be very fine honing sticks with a very fine abrasive grains that will remove very small amount of material from the inside diameter of the hole, but it will mostly smoothen in the surface, it will smoothen the asperities if it is inside. This is the view of the hon, in other view it is like this.

The honing sticks are mounted on this mandrel which is shown here. This mandrel sits on this axis or on this spindle that spindle is little tapered, here it is exaggerated, this is because when the mandrel rotates or when the hon rotates, it will also go up and down along the length of the hole along this. While doing so, the honing sticks have to have some kind of depth which it will be removing like the depth of cut.

That depth is given like in feed in case of the grinding that I said this depth of in feed is given by expanding that and pressing the honing sticks towards the internal walls and that is done by tapering the mandrel or tapering the spindle. So, when it goes up and down, it gets pressed depending on the amount of the tapering that has been made here. Here is another view you can see that this is the workpiece and here this is the workpiece.

This is the hon and these are the honing sticks, this is one this is another, this is the third and this is the fourth one these are the honing sticks. here this rotates and then it goes up and down so this also rotates. This goes up and down and rotates so that the entire length of the internal hole can be covered. the grit size as I said is up to 600 mesh.

So, the grains are very fine and the pressure which is given on the internal surface of the hole, is about 1 to 3 $N/mm^2$, this is a very low pressure. So, you can understand that this tapering has to be very gentle and the maximum material removal is 0.25 to 0.5 *mm* which is very less amount. Maximum is 0.5 *mm*, but it can also go starting from 0.25 *mm*.

the honing is carried out at lower speed because otherwise the small chips because it is 0.25 millimetre in size, those very small chips can get entangled between the honing sticks and the internal surface and since the honing process is to increase the surface finish,this cannot be allowed.

If on those surfaces there will be a scratch made by the entangled very small thin chips then the surface will be spoiled. Therefore, is rotated at a lower speed, so that by vacuum we can take out the chips and the small chips are lightweight, but if it is at a higher speed, this can scratch before we are able to take them out. Microchips can be entangled or with the honing stone to form excessive heat if the process is performed at high speed.

Another reason is that apart from the scratching it will create heat and then it can create the thermal workpiece. in case of honing the surface roughness also is obtained like that, that means no repetition of the grain marks. And this is done for the obtaining the mat surface for retaining the lubricant oil particularly when we are using the solid lubricant, like molybdenum sulphide. In case of bearing, you kthat bearings you do not oil.

The solid lubricant is placed and sealed, and that lubricant is sufficient for the entire life of the bearing. In that case, if we have kind of a surface where the grain marks are not repeated in that very fine undulations, the solid lubricant can stay. For some other parts also apart from the bearing, particularly that is very important because the lubricant will be retained otherwise when the two parts are rotating with respect to each other, excessive heat will be produced.

Then there will be temperature and at that temperature the fluid viscosity will decrease and in that case it will be fluidic. Suppose the solid lubricant has been applied. Under the high temperature it becomes fluid and it will flow away, it will not be retained there. But in case we have the kind of surface that I am saying here in that case the lubricant can be retained to a large extent.

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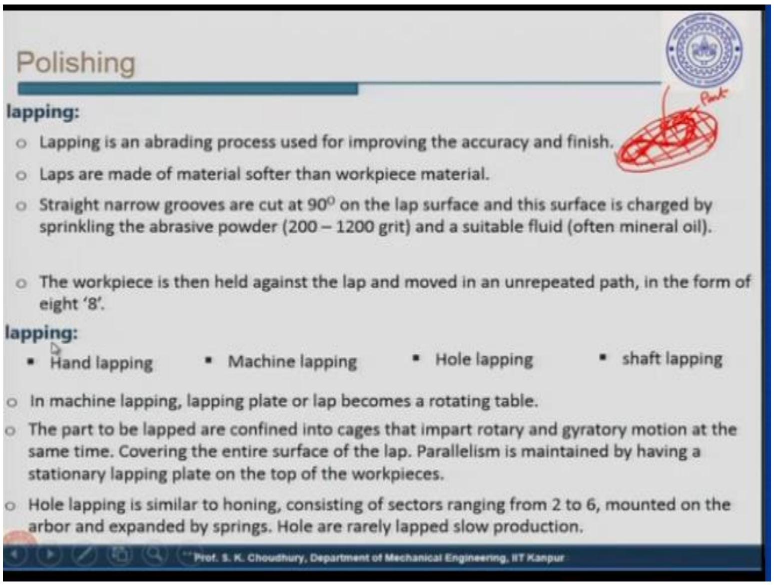

## Polishing

**lapping:**

- Lapping is an abrading process used for improving the accuracy and finish.
- Laps are made of material softer than workpiece material.
- Straight narrow grooves are cut at $90^0$ on the lap surface and this surface is charged by sprinkling the abrasive powder (200 – 1200 grit) and a suitable fluid (often mineral oil).
- The workpiece is then held against the lap and moved in an unrepeated path, in the form of eight '8'.

**lapping:**

- Hand lapping
- Machine lapping
- Hole lapping
- shaft lapping

- In machine lapping, lapping plate or lap becomes a rotating table.
- The part to be lapped are confined into cages that impart rotary and gyratory motion at the same time. Covering the entire surface of the lap. Parallelism is maintained by having a stationary lapping plate on the top of the workpieces.
- Hole lapping is similar to honing, consisting of sectors ranging from 2 to 6, mounted on the arbor and expanded by springs. Hole are rarely lapped slow production.

Part

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next process is the lapping which is an abrading process or abrasive process used for improving the accuracy and finish. Laps are used is the instrument, like drill in case of drilling, hon in case of honing, lap in case of lapping are made of material softer than the workpiece material. It is a kind of a plate like this and there are grooves. These are straight grooves , perpendicular to each other at $90^0$ to each other.

This material is softer than the workpiece material, straight narrow grooves are cut at $90^0$ angle on the top left surface and this surface is charged by sprinkling the abrasive powder which is very fine powder. This powder may have up to 1200 grit. This, as you can see, is even finer than the abrasive grains used in honing, and a suitable fluid. What is done is here you sprinkle some very fineabrasive powder plus the fluid so that such a fine powder does not flow away.

There is a paste formed with the abrasive powder and mineral oil and applied on this surface so the surface will be covered by that paste. And then the workpiece is held against the lap and moved in an unrepeated path in the form of 8. Suppose there is a path here, this is the small path, this will be repeated like this it will be moved in this path. So to get a surface with the unrepeated grain mark.

So, this is the part and here this will be rotated like that and it will go like this, in the form of 8. in case of lapping we have the hand lapping as we said that here you put the part on the plate and the plate is of a soft material, at least softer than the part then you hold the part by your fingers; this is the hand lapping and move it at the path of 8 on this with a bit of pressure.

it can be also machine lapping, in case of machine lapping normally the lapping is made for small parts. It can be of course the part which is stationary which is relatively bigger like I said in case of automobile cylinders, it can be hole lapping or it can be shaft lapping. For shaft lapping and the hole lapping you hold it with the paste and then you can go forward and backward and you can rotate the shaft. It will be kind of a polishing.

Similarly, for the hole lapping also you can have the lap inside and then rotate the cylindrical part so that the internal hole of this can be polished. in machine lapping the small parts could be taken in a bag holding the parts with the top surface exposed. That bag with the parts will be kept in between the 2 lapping plates and then the lapping can be done by moving the plates.

The parts will be lapped, parts will be having the smooth polished surface; that is the machine lapping. In machine lapping, lapping plate or lap becomes a rotating table. The parts to be lapped are confined into cages that impart rotary and gyrator motion at the same time.

This is done so that all the surfaces of the part can be polished equally well. Covering the entire surface of the lap parallelism is maintained by having a stationary lapping plate on the top of the workpieces So, there will be a plate and on the top of that the lap rotates and given the gyratory movement. To keep the parts in contact with the lap on the top of the parts, at the top of the cage there will be another plate which will be guiding or supporting the parts to keep them in contact with the lap.

Hole lapping is similar to honing consisting of sectors ranging from 2 to 6 mounted on the arbor and expanded by springs. Holes are rarely lapped because it is a slow production. in the hole lapping as I said that this will be something like hon but of course those sticks will be much finer, it is up to 1200 and grit size, the $S_n$ number, then it will be mounted on the arbor and it will be expanded by spring.

So that there could be a small pressure on the on the lapping stick and the internal hole can be lapped although the internal holes are rarely lapped because of very slow process. These are the processes belonging to the abrasive processes. Here we will stop our discussing on the abrasive machining processes.

Next we will be discussing the economics of machining because if you remember initially what we said is that the idea of producing a part is to make the part with the right accuracy, right shape, size, finish and it has to be of low cost.

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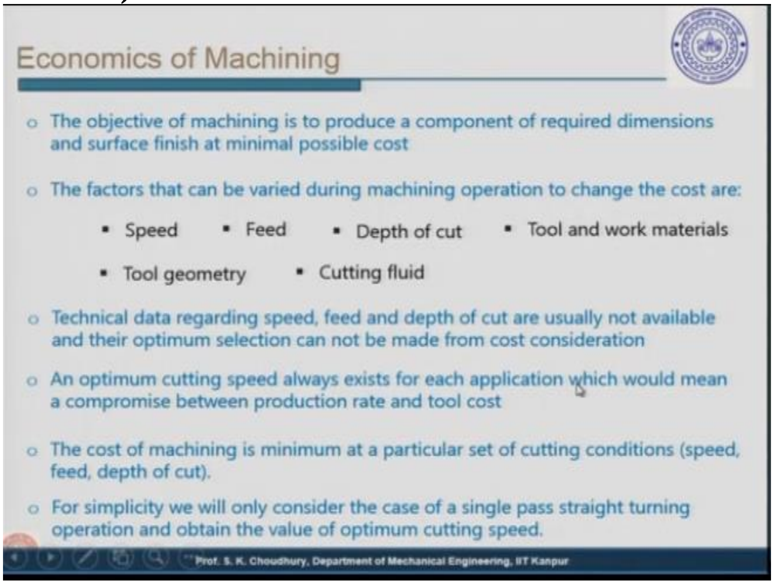

## Economics of Machining

- The objective of machining is to produce a component of required dimensions and surface finish at minimal possible cost
- The factors that can be varied during machining operation to change the cost are:
  - Speed
  - Feed
  - Depth of cut
  - Tool and work materials
  - Tool geometry
  - Cutting fluid
- Technical data regarding speed, feed and depth of cut are usually not available and their optimum selection can not be made from cost consideration
- An optimum cutting speed always exists for each application which would mean a compromise between production rate and tool cost
- The cost of machining is minimum at a particular set of cutting conditions (speed, feed, depth of cut).
- For simplicity we will only consider the case of a single pass straight turning operation and obtain the value of optimum cutting speed.

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So, the objective of machining is to produce a component of required dimensions and surface finish at minimal possible cost. the factors that can vary during the machining operation to change the cost are speed, feed, depth of cut, tool and work materials, tool geometry, cutting fluid and so on. Our idea will be to have a minimum cost of the product so that we can compete in the market.

The components that can vary that we have found out are the cutting speed, feed, depth of cut, other cutting parameters, overall tool and the workpiece material, tool geometry, cutting fluid and so on. If we have the cutting speed more, in that case the time taken is less and more products will be made within the given time and the product costs will be decreased as a result.

Similarly, the feed, similarly the depth of cut, similarly the tool and the workpiece material, because if the tool material is very costly in that case the final product will be costly. Similarly, if the workpiece material will be costly that being the basic material, then you cannot afford to produce a component at a lower cost and so on. Overall, what we are saying is that we can identify the parameters which can be regulated.

So that the cost could be minimum, and cost minimum means that you can compete in the market with other manufacturers of the same kind of parts. the technical data regarding speed, feed and the depth of cut are usually not available and their optimum selection cannot be made from the cost consideration alone. An optimum cutting speed always exists, as I said that speed increases your time for the production is less, you are making the part faster. So, within the stipulated time, more products are made.

But what happens to the tool is that at a higher cutting speed the tool wear also will be fast, but tool is expensive. So, that means for the same part you are incurring more cost in the tool as you are increasing the speed. Therefore, you cannot infinitely increase the speed because in that case you have to pay more for the tool. So, you have to have a compromise. That compromise we are saying as the optimum cutting speed. Always there will be an optimum cutting speed for the minimum cost.

Where you will not have as much tool wear so that the cost becomes very high or it will not be as slow so that the time taken is very high; it will be an optimum value of the cutting speed and at that cutting speed the cost could be minimum. For each application there is an optimum cutting speed, which would mean a compromise between the production rate and the tool cost.

The cost of machining is minimum at a particular set of cutting conditions. What we said about the speed, the same thing we can say about the feed, about the depth of cut, because we have shown in the tool life through the Taylor's tool life equation or rather through the modified version of the Taylor's tool life equation that on the tool life you will have the effect of cutting speed, feed and the depth of cut.

Therefore, all these 3 parameters, namely cutting speed, feed and the depth of cut will regulate and they can be regulated to obtain the minimum cost. For simplicity, we will only consider the case of a single pass straight turning operation and obtain the value of optimum cutting speed. Although we said that on the cost there will be effect of cutting speed, feed and depth of cut - all 3 parameters, but it will be very difficult or it will be very complicated to analyse all these 3 and take care of all these 3 parameters.

I will show you the analysis to get the minimum cost for only one parameter, that is the cutting speed and similarly, you can get the optimum parameter for the feed and the optimum value for the depth of cut.

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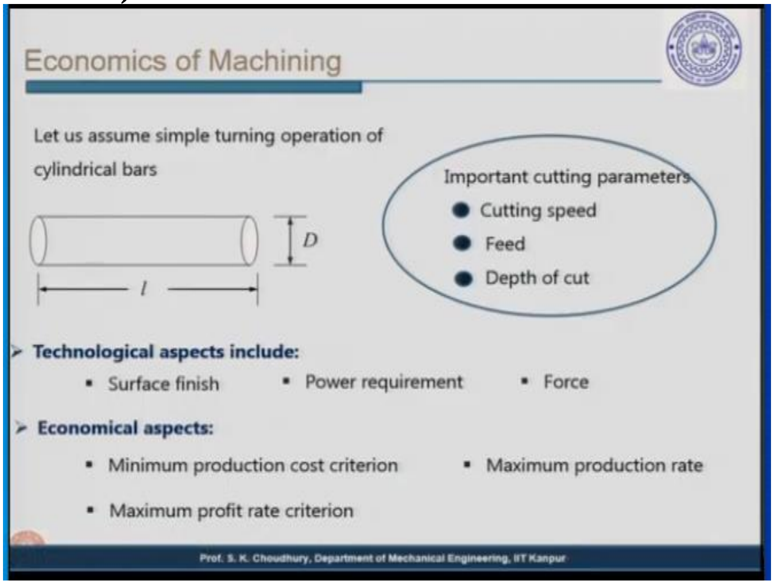

Economics of Machining

Let us assume simple turning operation of cylindrical bars

Important cutting parameters
- Cutting speed
- Feed
- Depth of cut

- **Technological aspects include:**
  - Surface finish
  - Power requirement
  - Force
- **Economical aspects:**
  - Minimum production cost criterion
  - Maximum production rate
  - Maximum profit rate criterion

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Let us assume the simple turning operation of a cylindrical bar, the cylindrical bar is of this type where the diameter is $D$ and the length is $l$. We are turning that. To do that the important cutting parameters are the cutting speed, feed and the depth of cut. The technological aspects include what will be the surface finish, what is the power requirement, what are the forces acting and so on. So, these are the technological aspects.

Economical aspects so far we have not discussed because we have discussed the important cutting parameters like cutting speed we have discussed, feed we have discussed, depth of cut we have discussed in the tool life and in the tool wear section we will be discussing surface finish, power requirement we have discussed, force we have discussed these are the technological aspects.

In the economic aspects we have the minimum production cost criteria, maximum production rate criteria and the maximum profit rate criteria. What is said here is that we will have a particular optimum value of the cutting speed or feed or depth of cut. With optimum cutting speed we can have the minimum cost. Similarly, if we want to have the maximum production rate, there also you can get an optimum value.

But as you understand that these 2 optimum values will be different, for one value of the optimum speed we can have the minimum cost, but we may not get the maximum production rate using the same optimum value of the cutting velocity. same thing happens with the feed and the depth of cut and also with the same values of for which we are getting the minimum cost and the maximum production rate we may not get the maximum profit rate. For maximum profit rate we may have a value which is different from the other 2 values.

Going ahead I should tell you that we can have the optimum parameter for the cutting speed, feed and the depth of cut for which the cost will be minimum or production rate will be maximum or profit rate will be maximum. Let us see how we can get it.

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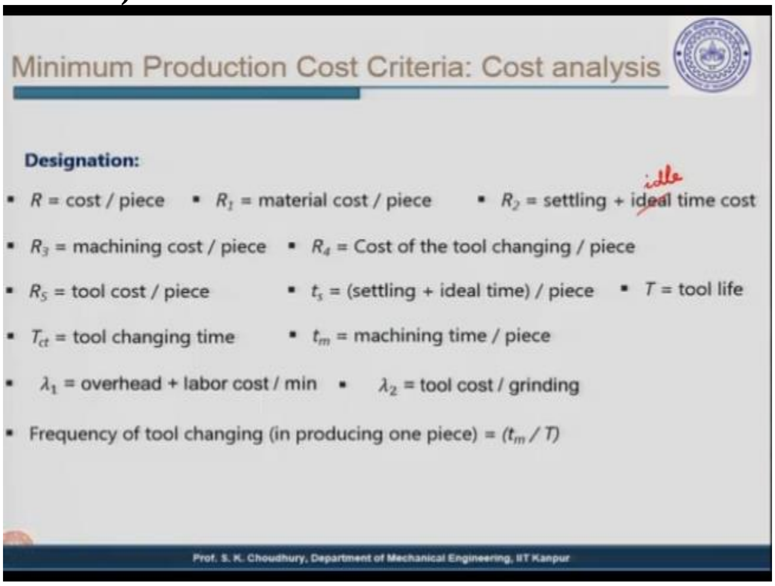

## Minimum Production Cost Criteria: Cost analysis

**Designation:**

- $R$ = cost / piece
- $R_1$ = material cost / piece
- $R_2$ = settling + ~~ideal~~ idle time cost
- $R_3$ = machining cost / piece
- $R_4$ = Cost of the tool changing / piece
- $R_5$ = tool cost / piece
- $t_s$ = (settling + ideal time) / piece
- $T$ = tool life
- $T_{ct}$ = tool changing time
- $t_m$ = machining time / piece
- $\lambda_1$ = overhead + labor cost / min
- $\lambda_2$ = tool cost / grinding
- Frequency of tool changing (in producing one piece) = $(t_m / T)$

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Let us have the designation that R is the cost per piece, cost per piece of the finally produced part. Here the $R_1$ is the material cost per piece, $R_2$ is the settling plus idle time cost, material cost per piece is the basic raw material cost, raw material which is required for making the final part that is to add value to the raw material so that the final part can be obtained.

$R_2$ is the settling plus idle time cost, when the machine does not work. So, settling plus idle time cost is the one where the operator needs to clamp the part, change the tool to put that in at a certain angle, make the adjustment in the tailstock if it is required, because the part can be also mounted on the centres and so on. For all these adjustments, this is the settling and that time the machine does not work.

But for that time, which is spent on that activity you are paying to the operator. Therefore, that time has to be included, $R_3$ is the machining cost per piece. Machining cost per piece; you understand that for the entire machining process, certain time elapses and what is the cost of that time? By cost of that time, I mean that you are incurring some overall expenditure for the entire process entire production. Within that you can find out how many parts are being made in a month or in a day or on an average.

And on one part, how much is being paid can be calculated easily. There are economists, engineer-economists, they calculate all those things. $R_4$ is the cost of the tool changing per piece, during the machining of one piece, how many times the tool is being changed, maybe one tool is worn out this has to be changed, this has to be reground or after the turning you need to do the chamfering, for that you need another tool.

So, you are changing the tool, this is the cost of tool changing, how much it costs for tool changing per piece. And finally, the $R_5$ is a tool cost per piece. Suppose one tool is required to make a piece after that that tool cannot be used, or one tool can be used for 5 work pieces. The tool cost will be in that case one fifth for that particular part per piece.

The $t_5$ is the settling plus idle time per piece, T is the tool life. $T_{ct}$ is the tool changing time, $t_s$ is the settling and idle time per piece and cost is $R_2$ for that time. the T is the tool life, $T_{ct}$ is the tool changing time and $t_m$ is the machining time per piece indicating how much time it is required to machine that and here if you see $R_3$ is the machining cost per piece.

For machining the entire part how much cost you have incurred. $\lambda_1$ is the overhead plus labour cost per minute. Let me explain what is the overhead and the labour cost labour cost. You understand that the person who is working, operator who is working needs to be paid and other expenses. The overhead is everything else that is required to be paid for the production of those parts.

For example, it is the premise, it is the building, the maintenance of the building the capital cost of the building, there is the electricity then it is the hydraulics, then it is the water, then it is the pneumatic cost and all the costs which are incurred for making that particular part per piece in minute. $\lambda_2$ is the tool cost for grinding, one tool maybe ground 5 times let us say.

So, tool cost per grinding will be the cost of the tool divided by 5 per grinding because after 5 grinding, it has to be thrown out it cannot be used. For each grinding, the tool cost will be the cost of actual tool divided by the times that it can be grond. The frequency of tool changing in production of one piece, we have the $t_m$ which is the machining time that if we divide by the tool life then you can find out how many times we have to change the tool for making that part.

I gave you an example that one complete tool may be required for making a part. We are not changing any tool for that part. However, it may so happen that the tool is changed because it is worn out. That frequency can be found out from the machining time and the tool life and the ratio of the machining time per piece and the tool life, this ratio, is the frequency of the tool changing in producing 1 piece.

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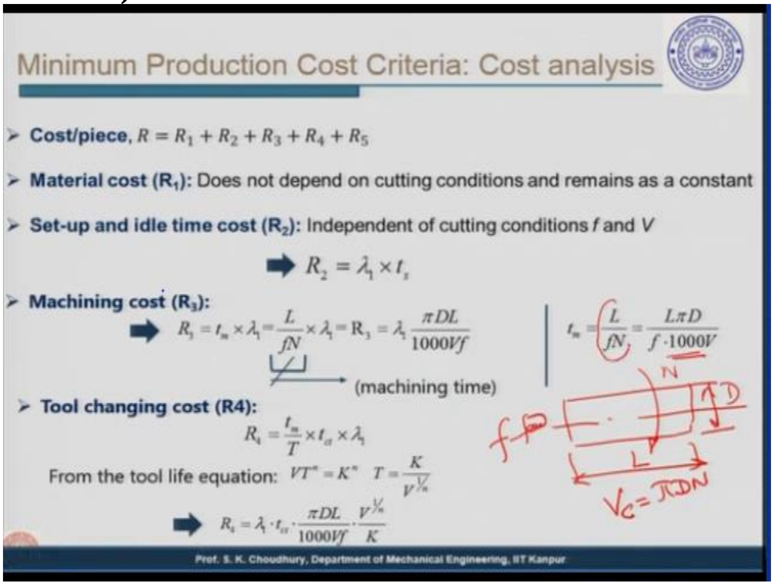

## Minimum Production Cost Criteria: Cost analysis

- **Cost/piece,** $R = R_1 + R_2 + R_3 + R_4 + R_5$
- **Material cost ($R_1$):** Does not depend on cutting conditions and remains as a constant
- **Set-up and idle time cost ($R_2$):** Independent of cutting conditions $f$ and $V$

$$\Rightarrow R_2 = \lambda_1 \times t_s$$

- **Machining cost ($R_3$):**

$$\Rightarrow R_3 = t_m \times \lambda_1 = \underbrace{\frac{L}{fN}}_{} \times \lambda_1 = R_3 = \lambda_1 \frac{\pi DL}{1000Vf}$$

(machining time)

$$t_m = \frac{L}{fN} = \frac{L\pi D}{f \cdot 1000V}$$

- **Tool changing cost (R4):**

$$R_4 = \frac{t_m}{T} \times t_{ct} \times \lambda_1$$

From the tool life equation: $VT^n = K^n$ $T = \frac{K}{V^{1/n}}$

$$\Rightarrow R_4 = \lambda_1 \cdot t_{ct} \cdot \frac{\pi DL}{1000Vf} \cdot \frac{V^{1/n}}{K}$$

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In this cost per piece R, we have therefore, all the 5 costs that is material cost per piece plus the settling and idle time cost per piece then we have the machining cost per piece followed by the tool changing per piece and the tool cost per piece. This is what has been shown that the tool cost consists of all these 5 costs. Let us see one by one. first one the $R_1$ you understand that this is the cost of the basic material, raw material.

So, material cost is $R_1$ that is not dependent on the cutting conditions or the cutting speed particularly because we will always keep in mind that what we said here is that we are trying to get the optimum value of the cutting speed, one of the parameters for getting the minimum cost. To get the minimum cost we are trying to find out what is the cost per piece, i.e. how much each piece will cost.

So, material cost does not depend on the cutting conditions and it remains as a constant with respect to if you take that as a function of the cutting speed only. The settling and idle time cost is also independent of the cutting condition, particularly the cutting speed that we are considering as well as the cutting feed and the depth of cut because whatever is your cutting speed this idle time or this tool changing time.

Therefore it is also constant, but the settling and idle time cost will be equal to the overall which you are paying that is the $\lambda_1$, $\lambda_1$ is the overhead plus labour cost per minute and how much time you are spending for setting up and the idle time. So, $\lambda_1$ if we multiply by this time, it will give you the settling and idle time cost.

Similarly, the machining cost; if you see the machining cost is $R_3$ here and that $R_3$ will be given similar to this; what will be the machining time this is $t_m$ machining time and for that machining time how much you are paying and this payment is the labour cost and the overhead cost as I explained to you both together. The $t_m$ is the machining time which we have already derived earlier that this is given by L which is the length of the part divided by $f$ and $N$.

This is a cylindrical part and this is the length which is $L$, this is the diameter, $D$ and this rotational frequency is $N$, $f$ is the feed. $V_c$ that is the velocity this is $\pi DN$ and here it is by 1000 because it is the minute to second. So, $\left(\frac{L}{fN}\right)$ is given as the machining time. In here the $N$ can be replaced by the cutting velocity with this formula and then how to proceed further that we will discuss in our next session of discussions. Thank you for your attention.