Machining Science - Part I

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Lecture - 15

Hello and welcome to the 15th lecture of the Machining Science course. In the previous lecture we started discussing abrasive machining processes and we said that the basic abrasive machining process is the grinding. There are 5 factors on which the performance of the grinding will depend, which are the type of the abrasive material, the grain size, the grade, the structure and the bonding material.

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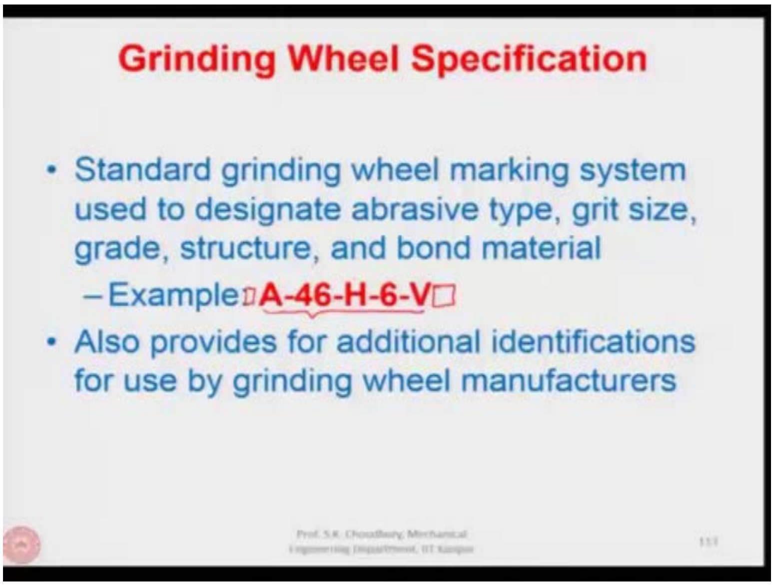

The grinding wheel is specified by 5 factors that is the type of abrasive, then the abrasive size then the grade, then the structure and then the bond.

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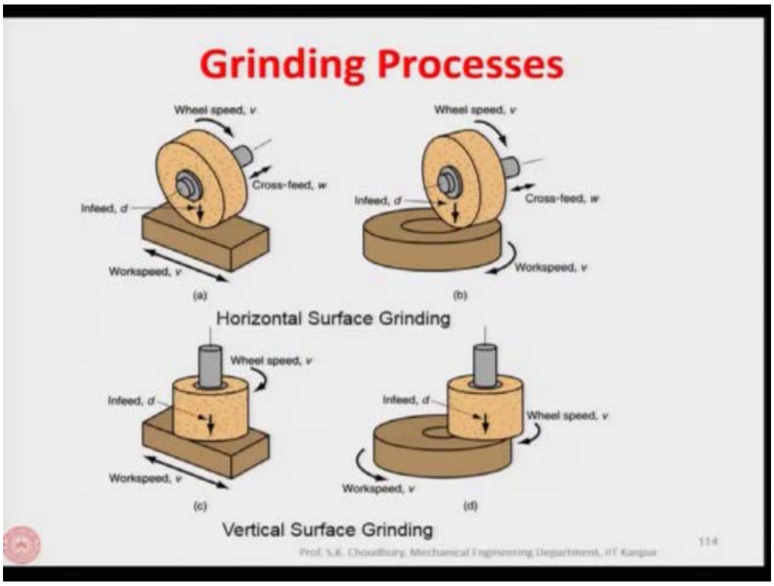

Now, let us see different kinds of grinding processes. Basically in the grinding we can generate the flat surfaces. If the axis of the grinding wheel is horizontal, it is called the horizontal surface grinding, and if the axis is vertical, it is called the vertical surface grinding.

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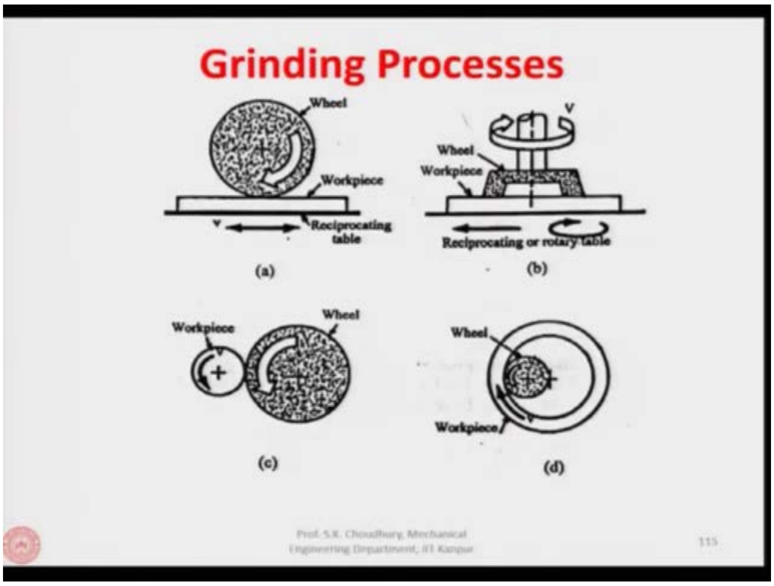

The vertical surface grinding can also have a cup type of grinding wheel which along with the workpiece rotates. Other examples of grinding includes the cylindrical grinding, which may be either external cylindrical grinding, in which the external surface of the workpiece is ground or it can be an internal cylindrical grinding in which the internal surface of the work piece is ground.

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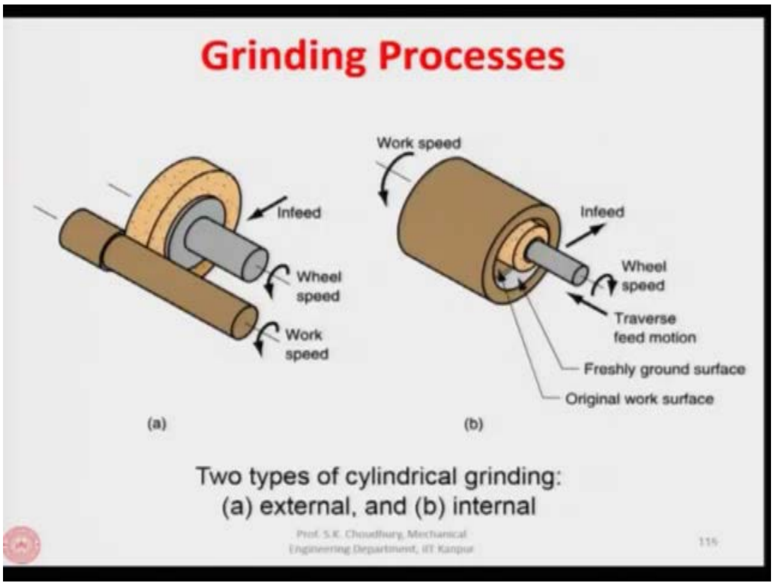

External cylindrical grinding and internal cylindrical grinding can be best represented as shown in the above slide. In internal cylindrical grinding, the grinding wheel rotates with respect to the work piece and the work piece also rotates in opposite direction and the grinding wheel reciprocates along the axis of the work piece.

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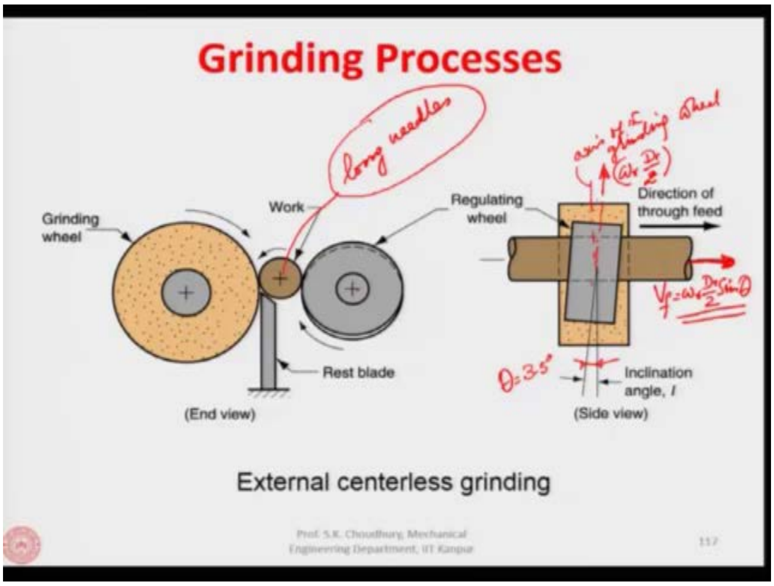

A very typical grinding process is the centerless grinding process which is schematically shown in the above slide. It includes a grinding wheel, a workpiece and a supporting wheel which supports the work piece, in the sense that it actually controls the outer speed of the work piece. The peripheral speed of the work piece is controlled by the supporting wheel. The supporting wheel is located at an angle with respect to the work piece and the grinding wheel. From the side view, it is clear that the axis of the supporting wheel is tilted with respect to the axis of the grinding wheel, with an angle of around 3 to 5 degree which is a very small angle.

So, the axis of the grinding wheel and the axis of the regulating wheel are making an angle of 3 to 5 degree. This is particularly given so that the work piece which is not held by anything, but just supported by a knife which is called the rest blade. It is neither supported by a 3 jaw chuck nor by centers like in the case of the other grinding processes or a magnetic table but is only held by the rest blade, sometimes it is called the knife. The outer peripheral velocity of the work piece is regulated by the supporting or regulating wheel. As well as, it gives a feed in the direction along the axis of the grinding wheel, because the regulating wheel is inclined with respect to the grinding wheel.

Suppose, if during the process if $\frac{\omega_r D_r}{2}$ is the force along a line perpendicular to the axis of the regulating wheel; so the feed velocity will be $\frac{\omega_r D_r}{2}\sin\theta$, where θ is the inclination angle. This is the speed at which the work piece will be fed because work piece has to be fed in this case. The work piece is very thin, like long needles, and they are very fragile, they cannot be ground by a simple external cylindrical grinding process. Therefore, this process is used.

Long needles are used for example, as bearing element or needle bearing which are used as thrust bearings. Needles are those bearing elements which are ground using the centerless grinding process. It is a very effective and very quick process and gives a good surface of the needle without bending or buckling of the needle. Needles cannot be ground otherwise using any other process .

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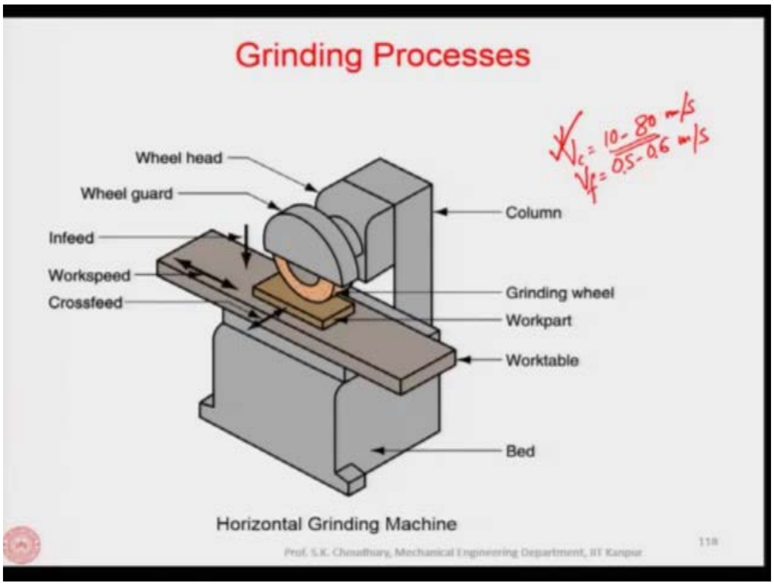

Pictorial view of overall grinding machine and the grinding process is shown.

Before the grinding process starts, the grinding wheel has to be covered, because the speed of the grinding wheel is about 10 to 80 meter per second and the feed velocity V_f is about 0.5, 0.6 meter per second. As the cutting velocity is very high and at this velocity if any part of the grinding wheel breaks, it will be like a bullet. So, it should always be covered by a wheel guard and the wheel has to be properly balanced, particularly for the bigger wheels before it actually starts grinding, because of the same reason that it rotates at a very high speed. Without balancing, the grinding wheel can break.

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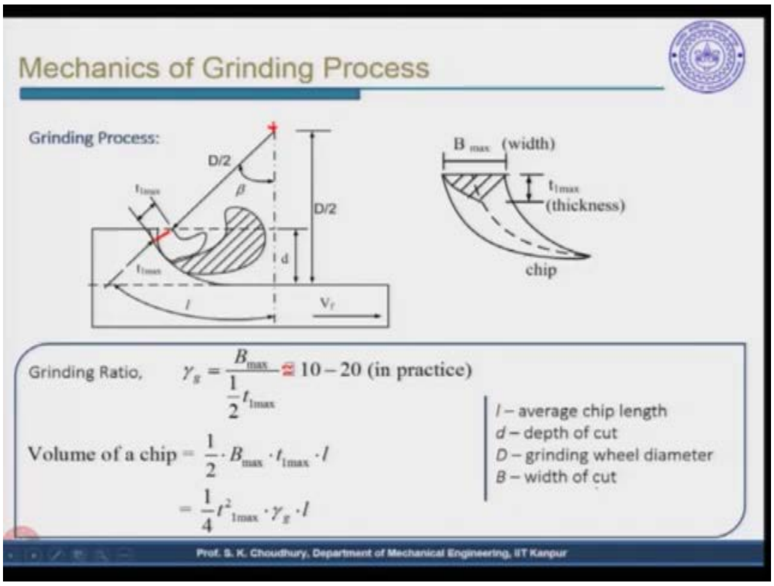

Now, let us see the mechanics of grinding process and why we should learn the mechanics. Like in the case of the turning that we have seen in the mechanics of machining, the mechanics of grinding process gives us the knowledge of how to control the grinding process and how to improve the grinding process overall.

Let us consider one grain that is shown in the above slide. The grinding wheel is consisting of many such grains, one grain is taken as an example. The grain is removing the material form the workpiece. Let D be the diameter of the grinding wheel, the radius will be D/2. Distance from the axis of the wheel to the work surface is also D/2.

Considering only one grain, like in case of milling, here also t_1 varies from 0 to maximum. Let t_{1max} be the maximum chip thickness, d be the depth of cut, l be the length of the grinding chip and B_{max} be the maximum width of the chip.

There is a concept of grinding ratio that grinding ratio is given by the ratio of B_{max} divided by half of t_{1max} . In practice normally it is between 10 and 20 roughly. The volume of a chip will be $\frac{1}{2}.B_{max}.t_{1max}.l$. Half of the B_{max} is taken since it is assumed to be a triangular.

Now, if you put the value of the B_{max} in terms of γ_g which is grinding ratio, volume of chip will be, $\frac{1}{4}.t^2{}_{1\max}.\gamma_g.l$.

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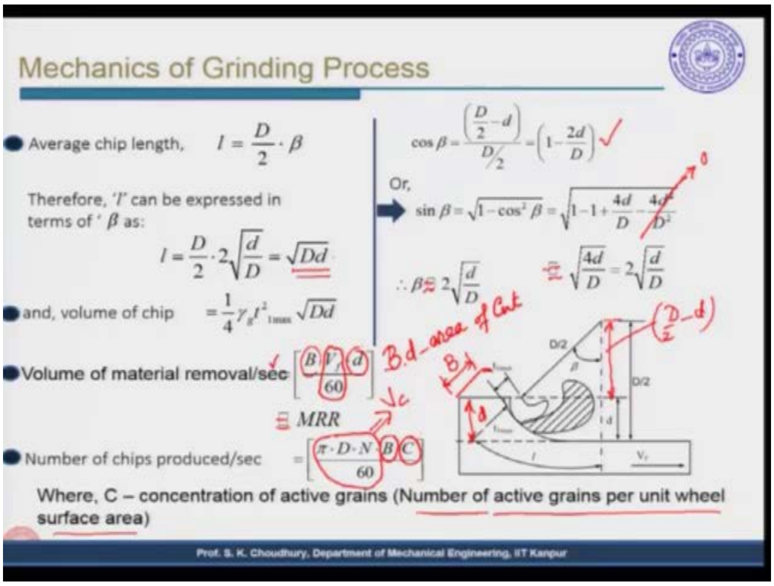

Now, the average length of a chip is given by $\frac{D}{2}.\beta$, which can be assumed as $\frac{D}{2}.\beta = l$.

Therefore, l can be expressed in terms of β as $l = \frac{D}{2}.2\sqrt{\frac{d}{D}} = \sqrt{Dd}$. Let us see how β can be obtained.

From the triangle, $\cos\beta = \frac{\left(\frac{D}{2}-d\right)}{\frac{D}{2}} = \left(1-\frac{2d}{D}\right)$.

As $\sin\beta = \sqrt{1-\cos^2\beta} = \sqrt{1-1+\frac{4d}{D}-\frac{4d^2}{D^2}}$. Ignoring $\frac{4d^2}{D^2}$, we have $\beta = 2\sqrt{\frac{d}{D}}$. As β is very small, $\sin\beta \approx \beta$ and hence, $\beta = 2\sqrt{\frac{d}{D}}$. This we have seen earlier also when we derived the equation for the milling. Therefore, we are getting $l = \sqrt{Dd}$.

The volume of chip is $\frac{1}{4}.t^2{}_{1\max}.\gamma_g.l$. Now, the volume of material removal per second which we call as the material removal rate will be given by speed into area. You remember earlier we said that the material removal rate is speed into area. Area is the width into the depth of cut and the speed is the $\frac{V_f}{60}$ just to make it mm^3/s. So, area will be B into d and the speed is $\frac{V_f}{60}$. $\frac{BV_f d}{60}$ will be the volume of material removal per second or which we call normally as the material removal rate.

Now, let us see the number of chips produced per second. How many chips will be produced per second will depend on, first of all, the cutting speed, which is given by $\frac{\pi DN}{60}$. Then it will depend on how much is the width of cut, if more width of cut it will be more number of chips. Therefore, $\frac{\pi DN}{60}$ will be multiplied by B.

Another factor on which the number of chips will depend is the number of active grains per unit area, this is called the grain concentration C; that means, how many grains are there per unit wheel surface area. More number of grains will give you more number of chips, because each grain is producing a chip. You saw earlier that one grain is producing one chip, so next grain will produce another chip and so on.

The number of active grains participating in the unit area of the wheel will be the grain concentration and the number of chips produced per second will depend on that. Therefore, overall the number of chips produced per second will be given by velocity into B, that is a width and the grain concentration, C. Now, let us see why we have derived all these equations.

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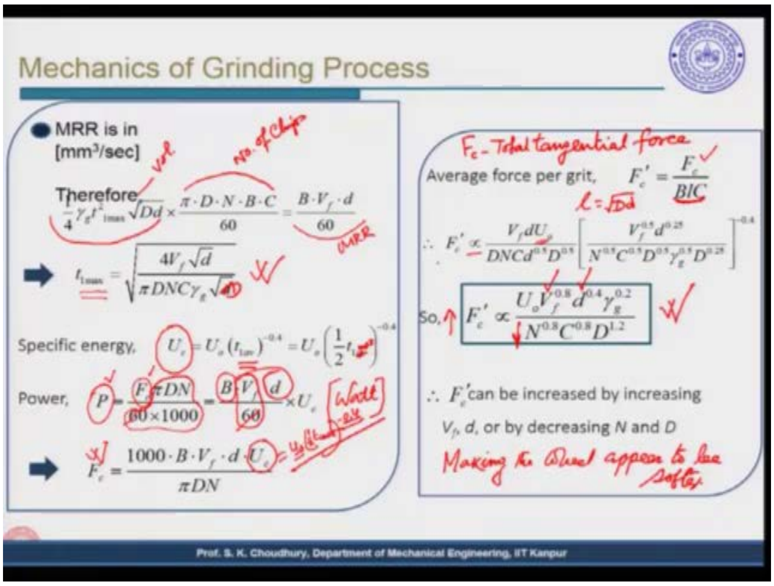

The number of chips produced per second into the volume of a chip will be equal to MRR, volume of material removal. $\frac{BV_f d}{60}$ is MRR, Material Removal Rate. $\frac{1}{4}.t^2{}_{1\max}.\gamma_g.l$ is the volume of chips produced and $\frac{\pi.D.N.B.C}{60}$ is the number of chips produced per second. Volume of a chip into number of chips produced per second is equal to material removal rate.

From the equation, $\frac{1}{4}.t^2{}_{1\max}.\gamma_g.\sqrt{Dd} \times \frac{\pi.D.N.B.C}{60} = \frac{BV_f d}{60}$ you can find out the value of the t_{1max}, maximum uncut thickness which will be $\sqrt{\frac{4V_f\sqrt{d}}{\pi DNC\gamma_g\sqrt{D}}}$. Capital D is the diameter of the grinding wheel. So, if you solve this then you will find the value of the t_{1max} .

Why we are determining that is because in the specific energy we have the t_{1max} . So, half of t_{1max} will be t_{1av} . We need to have the t_{1max} value which we found out by equalizing the product of volume and the number of chips with the material removal rate.

Now, if we write that $U_c = U_o(t_{1av})^{-0.4} = U_o(\frac{1}{2}t_{1\max})^{-0.4}$ which we have seen earlier. So, the power can be given as F_cV_c, where F_c is the cutting force and V_c is the cutting velocity and we are using that 60 into 1000, to match the unit. The power is normally given in Watt, therefore converting minute to second and meter to millimeter. Power can be given as U_c and MRR. MRR is again B into d, which is the area into the velocity.

So, power is equal to $F_c V_c$ or U_c.MRR. From here we can find out that $F_c = \frac{1000.B.V_f.d.U_c}{\pi DN}$, 60 is getting cancelled. F_c is the total tangential force on the wheel.

We are actually not very much interested in the total tangential force, but we are more interested on the force per grit; that means, how much force is acting on each of the grit on the grinding wheel. This is because during grinding, when the maximum force is acting on the grit then we can have some kind of a control on that, so that the grit can be dislodged, particularly the worn out grits.

If you remember we said about the wheel glazing or wheal loading. Particularly in case of wheel glazing what happens is that the worn out grains do not come out of the grinding surface, because the wheel is very hard. Now, if we know the cutting force or the average cutting force per grit then we can have some kind of a control on that force, so that, the force can be increased. Let us see what how we can do that.

So, average force per grit, $F_c^{'}$ will be the total tangential force F_c distributed by the number of grains which are actively participating during the cutting process.

So, how many grains are there during the contact with the work piece will define that what will be the average force per grit. That means, average force per grit will be the total tangential force distributed by the BlC which is the total number of grains actively participating in that cutting zone i.e. $F_c^{'} = \frac{F_c}{BlC}$.

Therefore, if we put the value of $F_c = \frac{1000.B.V_f.d.U_c}{\pi DN}$ and then divide by BlC; so, B will get cancelled, l is $\sqrt{Dd}$. So, you will get a formula like this that $F_c^{'} \propto \frac{V_f dU_o}{DNCd^{0.5}D^{0.5}}\left[\frac{V_f^{0.5}d^{0.25}}{N^{0.5}C^{0.5}D^{0.5}\gamma_g{}^{0.5}D^{0.25}}\right]^{-0.4}$.

U_o is coming because U_c is present in F_c and $U_c = U_o(\frac{1}{2}t_{1\max})^{-0.4}$. Since it is proportional, so we are not taking the constant values like $\frac{1}{2}$.

After simplification we get, $F_c^{'} \propto \frac{U_o V_f^{0.8} d^{0.4} \gamma_g^{\ 0.2}}{N^{0.8} C^{0.8} D^{1.2}}$

Above is the equation that we are having from the mechanics of grinding process, because then we can actually analyze the result to find out that if you are decreasing let us say N or if you are decreasing the grain concentration or if you are decreasing the value of the D that is the diameter of the wheel we can actually increase the $F_c^{'}$ or we can increase the $F_c^{'}$ by increasing the V_f the wheel feed velocity or increasing the d. d is the depth of cut. You cannot touch γ_g because it is a constant value and U_0 is also a constant value. Increasing the $F_c^{'}$ will actually facilitate the dislodging of the grains, particularly the worn out grains from the wheel surface.

Suppose you have a grinding wheel which is hard and you are grinding the hard work piece surface. So, as we said that because of the hard work piece surface the grains on the grinding wheel surface will be very quickly worn out. Now, we want the worn out grains to be dislodged because worn out grains will rub more, it will consume more power and it is not effectively making the grinding process. It will spoil the surface also.

To remove the worn out grains we need more force acting per grit which can be manipulated. Given a particular grinding wheel and a particular work piece, we can still make the wheel appear to be softer by increasing the feed velocity; let me write down that making the wheel appear to be softer. Why it is softer? Because in case of soft wheel the grains dislodge very quickly because the wheel is soft and the wheel is soft means the grade is soft. Grade means the strength of the binding material.

This is important while manipulating the grinding process and to improve the surface finish of the grinding process. Otherwise what will happen is that if you have a hard wheel and if you have a hard material in that case the grinding wheel surface will be spoiled. Because, the grains are not dislodged and worn out grains will be staying in the surface of the grinding wheel and will not be dislodged. So, this is the process by which we can still make the grinding wheel appear to be softer.

So, once again I will just repeat that. This is not a very complicated thing. What we have done is that, we found out that the volume of a chip. In finding out the volume of a chip we have the l which is the chip length equal to $\frac{D}{2}.\beta$; β being a small angle. We are putting the value of the small l which is $\sqrt{Dd}$ that we found out from the geometry. After that we find out the volume of material removal per second which is the MRR and is equal to the area and the velocity, area is the B into d, B is the width. The area into the velocity, $\frac{V_f}{60}$,we are making that for converting minute to second. This will give you the MRR. And then we are finding out the number of chips produced per second. Number of chips produced per second as I said will depend on the cutting velocity. On the width, more the width more will be the number of chips and the grain concentration which is defined as the number of active grains per unit surface area which is also called the concentration of active grains.

Therefore, more the concentration of the active grains more will be the number of chips. We did that to make an equation which says that the volume of a chip into the number of chips, will give you the material removal rate. t_{1max} is used while finding out the specific energy and the power. Because, specific energy $U_c = U_o(\frac{1}{2}t_{1\max})^{-0.4}$. t_{1av} is half of t_{1max}.

By doing that, we can find out the value of the power and the force finally. From the total tangential force we are finding out the force per grit. And then the parameters were found out which you can manipulate to increase the force per grit to dislodge the worn out grains from the wheel surface. That is the importance of the mechanics of grinding.

Rest of the things in grinding we will discuss in our next class.

Thank you for your attention.