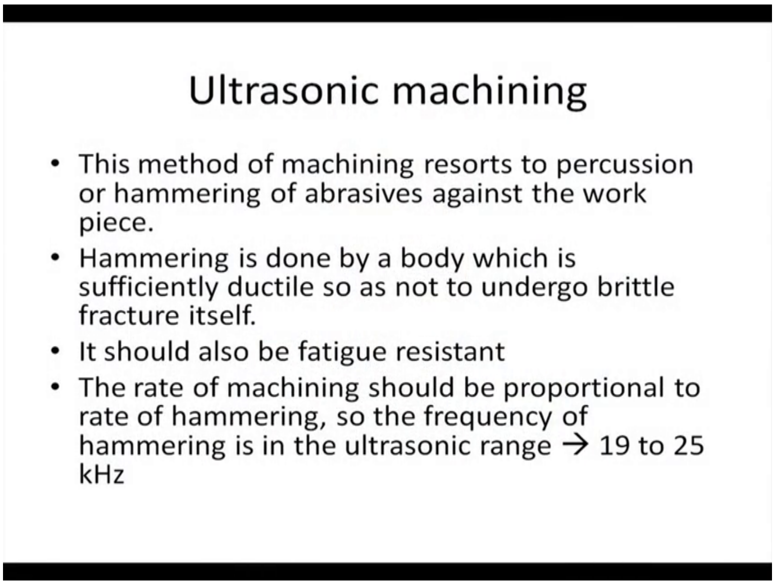
Non-traditional abrasive machining process: Ultrasonic, Abrasive jet and abrasive water jet machining

Prof. Asimava Roy Choudhury
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 02
Ultrasonic Machining

Welcome to the second lecture of the lecture series on the Non-traditional Abrasive Machining Methods. And after the introductory lecture, we will start today on discussion on ultrasonic machining.

(Refer Slide Time: 00:39)

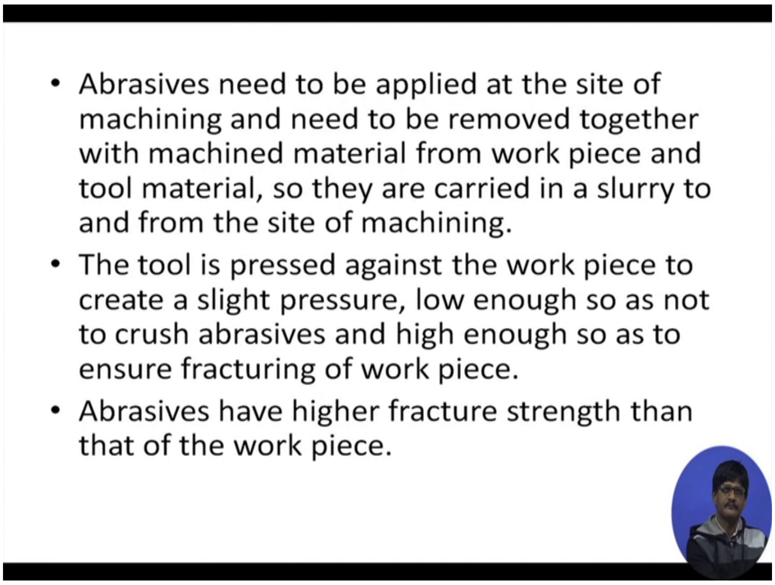


So, what is ultrasonic machining? In this method, the method of measuring resorts to percussion or hammering of abrasives against the work piece with the tool. So, we have tool, it is not directly impacting the work piece, but there are some abrasive particles put in between the work piece and the tool. These abrasive particles are hard and they are you know they can retain their shape that means they are rigid and therefore, they can cause impact erosion the work piece material when working in this particular mode of percussion.

So, hammering is done by a body which is you know known as the tool and the tool material has been sufficiently ductile, so that it itself does not undergo brittle facture. However, we cannot avoid the removal of material from the tool or parallely with the work piece, so tool wear is of sufficient degree and it should also be fatigue resistant because in order to increase the material removal rate we are increasing the hammering rate to ultrasonic frequencies. So, if that be so, there will be you know dynamic loading on the tool material. So, it should be fatigue resistant. And the rate of machining is proportional to this hammering and therefore, the frequency is typically say 19 to 25 kilo hertz.

So, if you are in front of an ultrasonic machine and its operating at certain frequency, if you are very sensitive then you might be hearing a very you know very high frequency sound, but most people do not hear, because it is beyond the audible range.

(Refer Slide Time: 02:52)



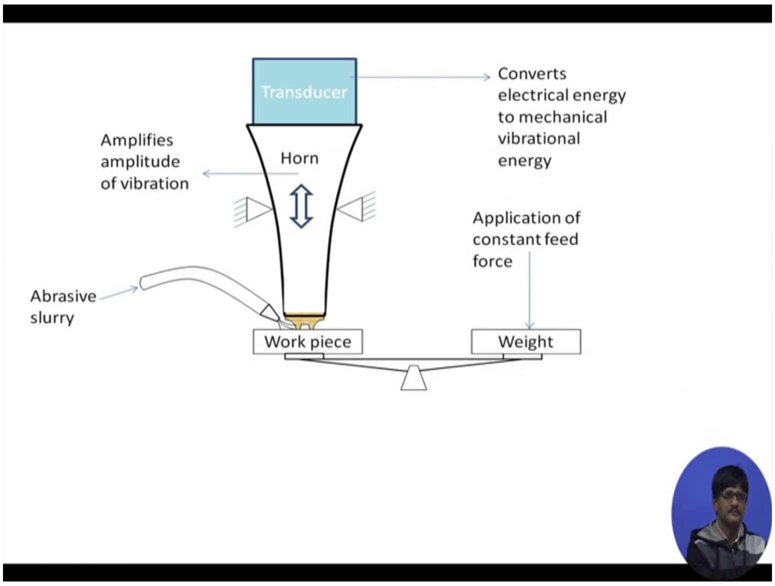
So, let us quickly see what are the support systems which will be allowing us to remove material by this means, first of all abrasives have to be supplied. So, they are applied at the machining side by being carried in you know in a water medium generally and it is called a slurry. Say you put volume per volume say 20 parts of abrasives in 100 parts of water and let it be applied by a nozzle that means, by a jet at the machining side, so that all the time the machine site is receiving fresh abrasives and the debris of machining; that means, remove material broken abrasives, all these things are removed by that jet of water only.

Once abrasives are used this should not be used again because first of all abrasives in that case will be contaminated with debri coming out of machining; and second due to such a high rate of hammering many abrasive particles will also be undergoing fracture themselves. So, fractured abrasive particles will not be that efficient as you know the fresh abrasives. So, abrasive slurry has to be provided to the machine site an generally there should not be insight.

The tools has to be pressed against the work piece with a slight pressure, because if there is no pressure there will be no machining, no matter how much frequency or wide machining you are providing because ultimately if the tool the work piece will recede away from the tool if they are not pressed together. However, if we apply a higher pressure thinking that higher will allow us to remove material faster maybe that is true for some area of work, but it will not ultimately help us because higher and higher loads pressing the work piece and the tool together will ultimately lead to crushing of abrasives. Once again if the abrasives are crushed to smaller sizes they would not be as efficient as before.

And of course, abrasives have to have a higher fracture strength and that of the work piece, the abrasive the tool has to have higher fracture strength; obviously, because you know lot of high frequency vibrations are coming in heating lot of stresses.

(Refer Slide Time: 05:51)

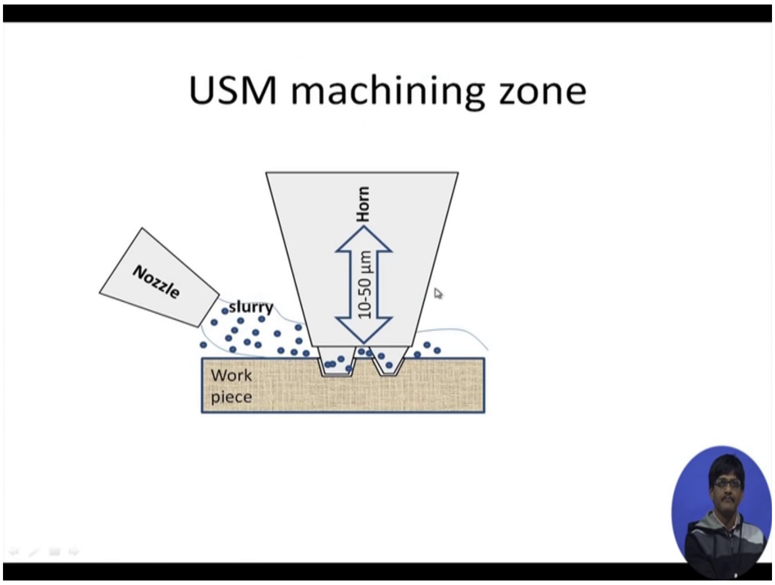


This is a pictorial view of the basic you know support systems, which are required in case of ultrasonic machining at the top we have a transducer. What does the transducer mean, transducer means that it converts electrical generally electrical energy to mechanical vibrational energy. What can be the way in which we it can be done with this we will discuss in more detail later on it has to have you know either some piezoelectric crystal to give rise to in you know piezoelectric effect I mean the reverse of it; that means, you are providing electrical energy you are getting mechanical vibration. And you can also be done by magnetostriction in which you are providing once again electrical energy and due to magnetostrictive substance changing its dimensions under that effect, it will provide vibration.

So, once this vibration is set up this vibration is conveyed by that you know geometrically you can see we can define it as a tapered or an exponential decaying diameter, this body is called a horn. It transmits this particular vibrational energy from the transducer right up to the tool that slightly colored portion very small you know item sticking at the end of the horn is called the tool, it has a shape whose conjugate shape is going be produced on the work piece surface. So, the purpose of this horn which has the definite shape is to amplify amplitude of vibration. The amplitude increases from the transducer end to the tool end of the horn. Why do we do that because high level of amplitude is generally not produced by the transducer, so that its workload is low, but it is amplified by the horn is concentrated by the horn. The horn is held at a particular position shown by those two triangular supports at a position where you know the vibrational movement is zero, so that it is not damped out.

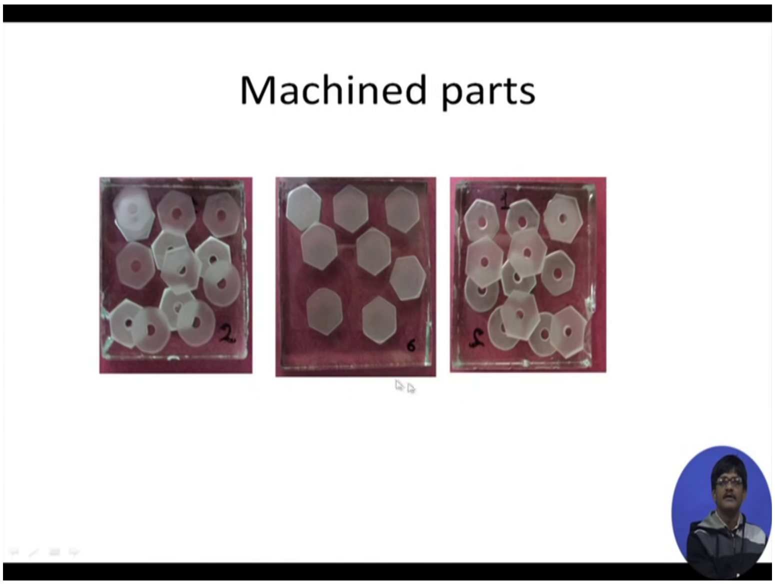
In this case, we have shown a small amount of weight put on a common balance by the help of which we are able to press the work piece and the horn together. Say if I put say on 1 kg weight how much is how much is the load that I am applying on the between the work piece in the horn and if the work is on the tool 10 Newton that is all so that way with these support systems and of course, the abrasive slurry is provided as shown. So, that abrasive fresh abrasive are always supplied at the machining site; so this way we can easily make use of the abrasives to get removal of material in case of ultrasonic machining. This is a very simple set up and we will discuss each aspect of the machine, for example, the horn, the system of applying loads between the work piece and the tool etcetera, all these things will be treated in good detail.

(Refer Slide Time: 09:37)



So, let us have a look at the ultrasonic machining zone or this actual site of machining. We have demarcated the tool by a trapezium by two trapeziums basically that means, the opposite of this shape is going to be produced on the work piece. Here we have shown that the amplitude of vibration and this end is 10 to 50 microns; that means, it may be 10, it maybe 20, it maybe 50 like that. So, this is the end of the horn the tool end of the horn from the nozzle slurry is coming out which means that in a water medium you are carrying abrasive particles. So, these abrasive particles are everywhere and after use they are getting deposit somewhere and the correct or recommended practice will be not to recycle them.

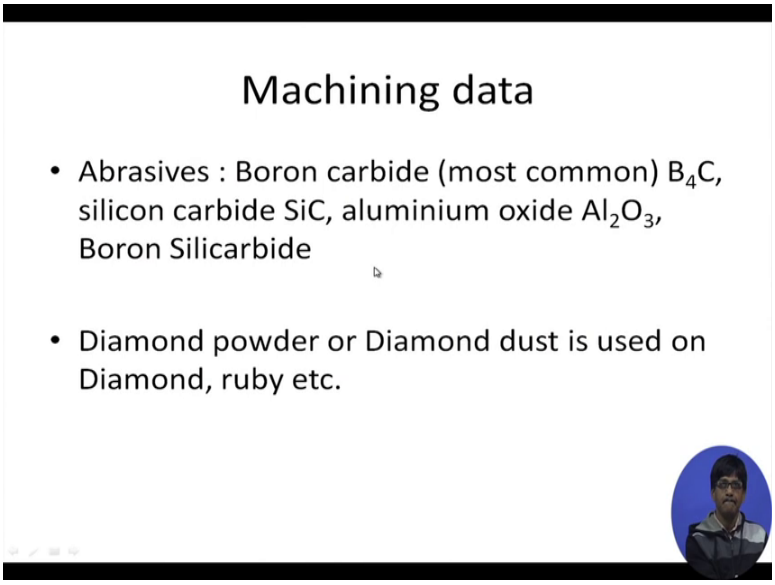
(Refer Slide Time: 10:35)



These are some of the shapes that we have machined on glass ordinary boro silicate glass with the help of our ultrasonic machining. What does it show, it shows that glass is having a very polished surface, but the flat ends of these you know these machine zones are showing that the roughness is not that good I mean roughness is not that low as ordinary glass surface. But still just imagine if I give you a glass piece, and if I ask you to develop such resources such portions I mean such machine features geometrical features on this glass that we be able to do it by any means.

But here it is shown it is done very easily and each of these cavities where about 1 millimeter to 2 millimeters deep and they were done in about 1 minute of machining. Just 1 minute of machining so that means, you can do it very efficiently because you can reduce any type of shape that is that you have in mind and you can do it quiet fast also and you can do it on a material it is very difficult to machine by other means.

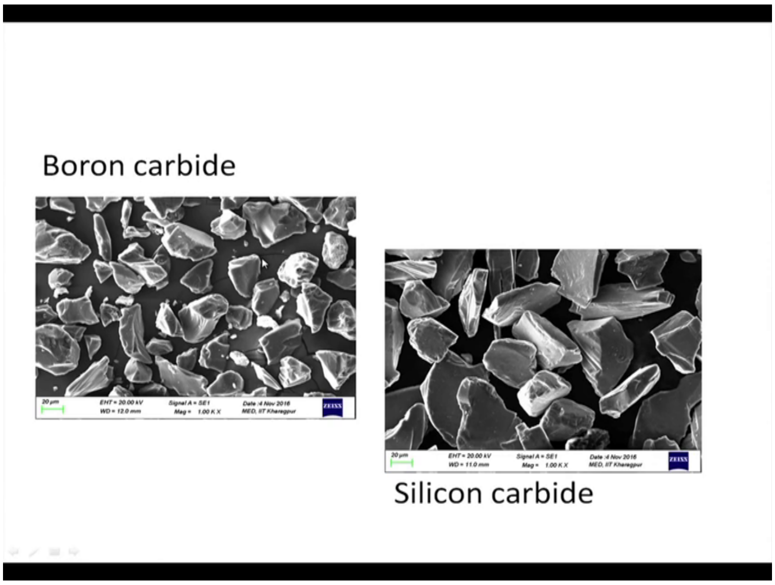
(Refer Slide Time: 12:07)



So, now a look at you know details of the machining process, what sort of a abrasives are we talking about. Abrasives can be boron carbide why boron carbide this is because boron carbide is the third hardest material at this moment in the list topped by diamond then comes cubic boron nitride. You might say then why do not I have diamond, well diamond powder can be costly, you know if it is not synthetic diamond, but natural diamond powder dust, it can be costly. So, what about cubic boron nitride that is also very costly, boron carbide is also costly, but not as costly as the first two.

So, it is sort of best option which is used very frequently in machining applications. You can also have silicon carbide, silicon carbide is not that costly, but its machining rate also will be less than say boron carbide. Aluminium oxide it is not as good as the previous ones, but it is not that costly boron silicarbide is known to be one of the promising candidates in this regard. Diamond powder or a diamond dust is used on diamond ruby etcetera.

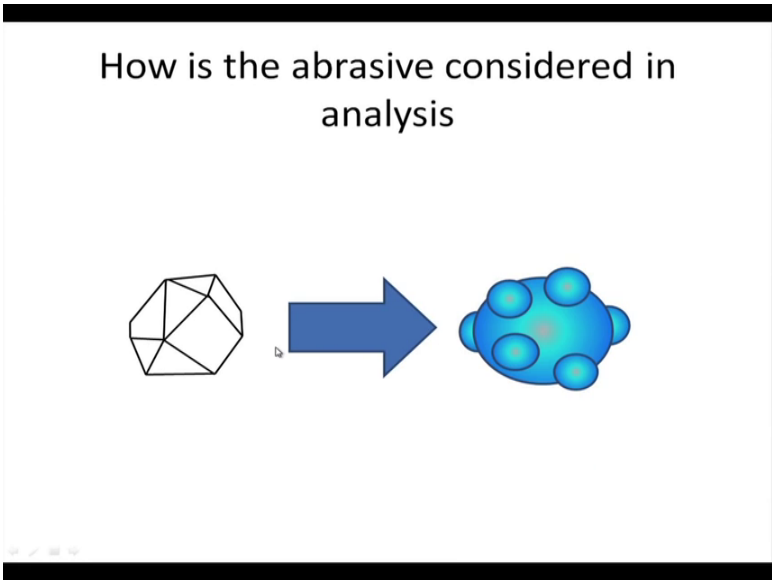
(Refer Slide Time: 13:35)



Here we are seeing two pictures which we have taken for boron carbide particles roughly say 44 microns and silicon carbide particles roughly of the same size slightly larger. So, what do they show, they show us they looked just like you know randomly Sheppard's tone ships that we used very frequently in the making of concrete. They are not exactly spherical in shape that is what I wanted to convey to you, but they are having a flaky structure, but you will be surprised to know that in the mathematical models and in the analytical models that are you are applied in case of ultrasonic machining.

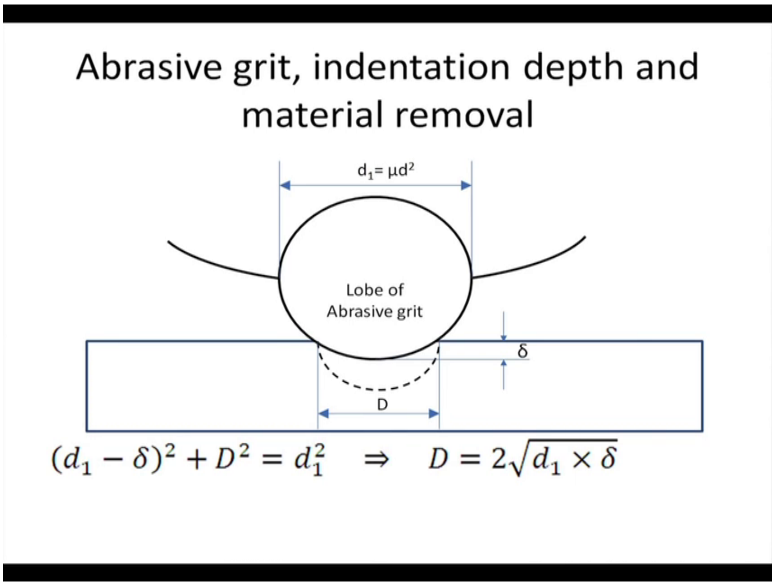
In most of the cases, you will find that they assumed abrasive particles to be spherical. Now obviously, that is wrong. So, in that case what we what is generally done is that it is assumed that they have a lobed structure and these lobes are you know mounted on top of a sphere, so that makes it a good not good, but a workable assumption or acceptable assumption of the shape of the abrasive particles. So, let see this is 20 microns can you see this is 20 microns which will which will give you a good idea of the size average size of these particles.

(Refer Slide Time: 15:21)



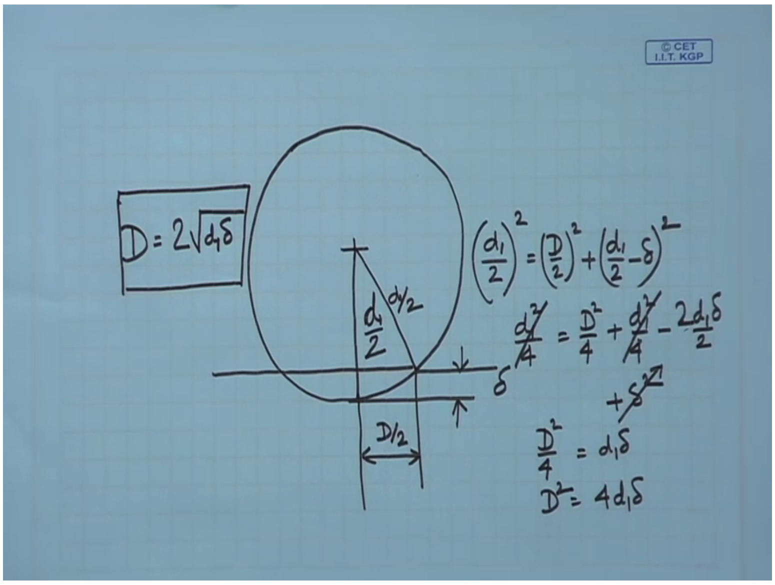
So, this is the assumption. If the abrasive particle looks to be you know bounded by straight sides and it has a flaky or it has a structure, which is of this type, it is assumed to be of this nature. Why so because this allows us to assume the shape, assume the shape to a degree of reality that means, it is not fully spherical to a degree of reality for analysis. If you take the shape to spend most of your efforts in you know representing this shape instead of that just assume this shape that means, there are some spherical lobes of smaller diameter on a largest sphere this is what we will assume.

(Refer Slide Time: 16:18)



So, now the scene will change a bit that means on the basic spherical abrasive particle, we are having the lobe and that is what we have represented and its diameter is represented by a constant multiplied by the square of the abrasive diameter, abrasive grit diameter.

(Refer Slide Time: 17:40)

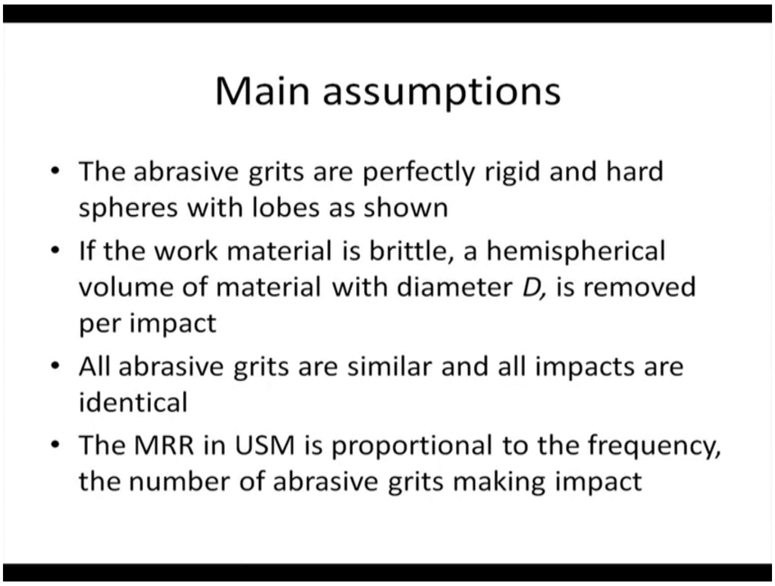


So, the basics sphere that we have it still has a diameter of d and the lobes that we have they are proportional to the square of the diameter and this constant of proportionality is mu. So, this way we can relate the lobe diameter to the actual abrasive grit timing. And in this case we can establish a relation between d 1 delta indentation and large D, which is the diameter of the indented circle. What is this particular relation, we can have a quick look if you have a look at this piece of paper. Suppose, this is the sphere I mean this is a lobe; therefore, we can say this must be d by 2; and this must be delta, and therefore, this is also d by 2, and this must be large D by 2. So, in this case, we can frame the equation to be sorry this is d 1, d 1 by 2 whole square is equal to D by 2 whole square plus d 1 minus D by 2 minus delta whole square Pythagoras theorem.

Now, if this be so let us quickly see what it gives us, d 1 square by 4 equal to D square by 4 plus d 1 square by 4 minus twice d 1 delta by 2 plus delta square. Now, since delta is very small delta square can be neglected; and this goes out, this goes out with this. And therefore, we have D square by 4 equal to d 1 delta which means D is equal to 4 d 1 delta or to write it clearly here D is equal to twice sorry D square D is equal to twice root over d 1 delta, this is the relation that we get. This is the relation that we get in this case simple geometrical theorem from Pythagoras theorem.

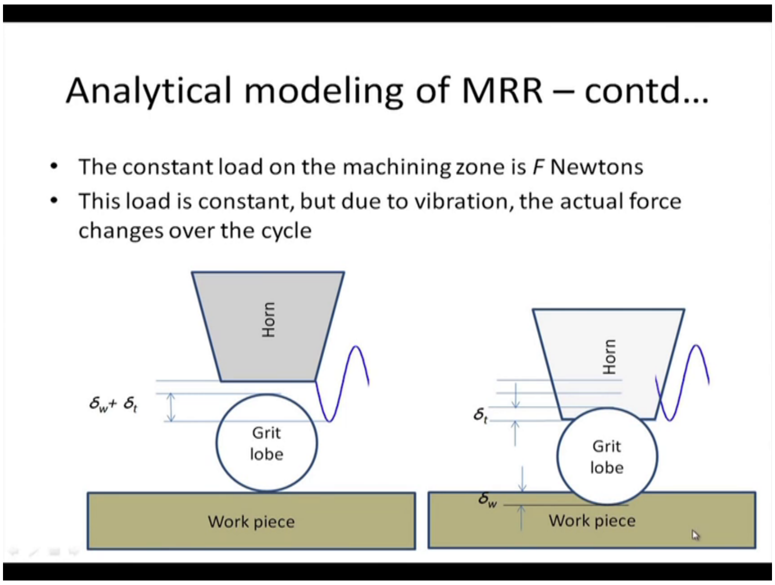
Here if we go back to the expression here D is equal to twice d 1 into delta. Please note that here there is a slight mistake the two I mean the four underneath D square and the four underneath I mean the two underneath d 1 etcetera and the four underneath this d 1 they have been missed or none of denominators have been provided. But you already know this calculation that from the calculations by and that we have performed and therefore, this is acceptable because we have already proved it. So, kindly note the corrections to be made here when I provide you with the power point files, I will make the correction in this one in that. So, please note this needs some correction, but this one is correct.

(Refer Slide Time: 21:46)



So, we will make some assumptions before trying to find out the rate of material removal that will be occurring in this case. What are these assumptions, they are actually very simple the abrasive grits are perfectly rigid and hard spheres with lobes as shown. If the work material is brittle a hemispherical volume of material with diameter D, is remove impact these thing actually we have discussed. All abrasive grits are similar and all impacts are identical. The MRR and USM is proportional to the frequency of the number of abrasive grits making impact. These will follow you know if you apply your common sense, I think you will definitely agree that yes, these are all accepted.

(Refer Slide Time: 22:29)

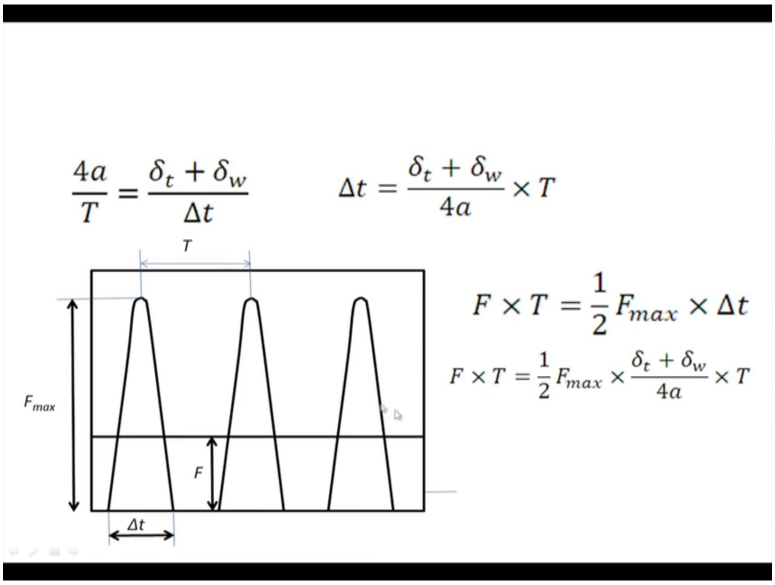


Now, let us see what is happening when the horn is vibrating. When the horn is vibrating, what happens is that I mean the horn at the end of the horn there is the tool which I have not drawn, I have just drawn one integral horn end of the horn is therefore, acting as the tool. So, first of all we are pressing the horn on top of the abrasives with a constant force F, on this is impressed that means, imposed on top of that we have the vibration which is going to cause a fluctuation in the lobe.

So, in that case, what do we have, first of all we have the horn executing simple harmonic motion due to the vibration. So, it goes down goes up goes down sinusoidally with time. Now, what is going to happen when it is you know first of all why have we drawn the horn and the grit lobe with the with the gap in between this means that abrasive particles actually are not of the same size. So, if you consider the average abrasive particle, it will definitely have a gap between the horn and itself because the those abrasive particles with maximum diameter with larger diameter and the average, they are going to hold up. The horn is going to rest on the larger diameter grits. So, the average grit is going to be slightly below that. So, there is a gap between the horn the horn end and the grit top most point.

So, when the horn is vibrating we find that the delta w plus delta t is the total amount of movement of the horn after it contacts the grit lobe I mean after it contacts the grit, I have shown only the grit lobe, but basically it is contacting the grit. So, when the horn has contacted the grit after that it is undergoing a downward movement of delta t plus delta w. Now, what is that, what is delta t and what is delta w. We are giving this way that since the abrasive grit is rigid, it does not change its shape; it does not go in undergo any deformation. But the horn undergoes I mean the tool undergoes deformation and the work piece undergoes deformation, so that ultimately this is delta t plus delta w movement is being you know sustained as damage or indentation on the tool surface around the work piece surface. So, total horn movement after contact is equal to delta w which is indentation of the workpiece and delta t which is indentation on the tool, so that is acceptable.

(Refer Slide Time: 25:46)



So, what we have written is we have made with that assumption that is the movement of the horn being equal to the movement of the I mean the indentation on the work piece and the indentation of the tool then we are drawing up or you know a similarity of the velocities of the vibrating element. What is that? We are arguing that just like 4 amplitudes are covered in a time period, so the distance is 4 amplitudes and the time is the time period.

So, the average speed is equal to total displacement divided by time 4 a if small a being the amplitude of vibration at the horn n have the at the tool end of the horn 4 a by T is the average velocity from that consideration. And the average velocity of the horn during the you know what you call it the impact the indenting period is total distance travelled during indenting period divided by the time taken for that and the time we are calling as delta t.

So, these two velocities we are equating saying they are occurring due to the displacement of the horn only both of them have the same source vibration of the horn. So, they must be equal. This is actually not very correct because whenever some body is vibrating it has the maximum velocity at the mean position with zero velocities at the you know extremities. So, it is not fully correct what is let us go ahead with this assumption and see what it yields ultimately.

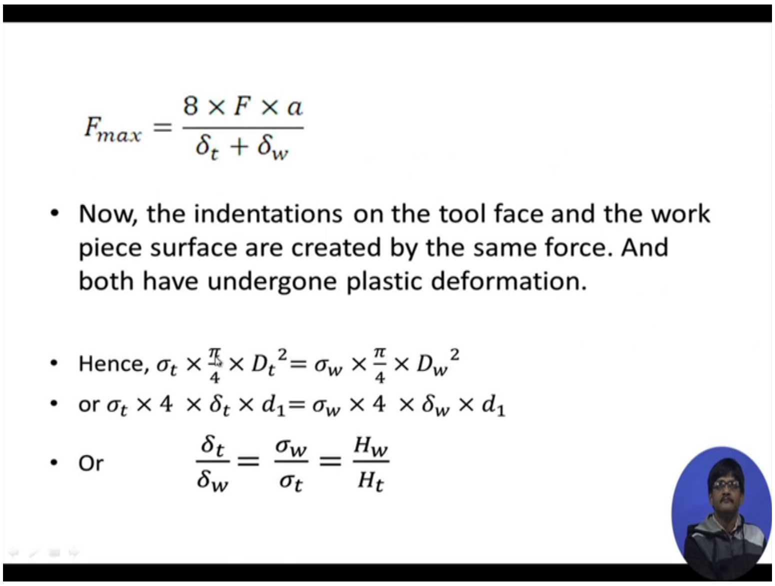
So, we have drawn up a relation between a relation for delta t delta t just by you know arranging these terms that is good. So, after that what we are saying is I am afraid some terms cannot be seen on the side I will definitely you know tell you what they actually mean because you cannot see it fully at least I cannot see full on the screen. So, F T the static force we are making an equality between you know impulses, what is impulse, impulse is force into time, force into time. So, we are saying that the steady static load which is you know remaining constant over cycles of vibration that that particular product force into time that will be equal to you know the same value for the instantaneous force, the instantaneous force multiplied by the time.

Let us see what we mean by that. So, instantaneous forces are changing, this is one instantaneous force, this is another instantaneous force. So, essentially it means if I try to multiplied in instantaneous force with the time, I will ultimately be getting the area under this particular curve. Now, what is this curve? This curve shows that as the abrasive is more and more indenting into the work piece and the tool material due to impact being driven by the horn by the hammering action of the horn as it is getting more and more impacted, it increases the force between the work piece and the horn goes on increasing. And when at end of vibration when the horn is receding its moving back then force comes down and ultimately it is reaches 0, this size actually much more steeper. So, the highest force which is experience that is called F max.

So, we can say how much is that F max if you ask me. So, I do not know, we have find out. So, we basically find out the area of this triangle as half the base into altitude half the base this is time axis, I am sorry I have not written it here, this is time and this is force. So, on the time axis, the interaction of the horn with the abrasive is only for delta t time when it is in contact the moment the horn reverses contact is lost after elastic deformation is released. So, we can say the area under this these curves is equal to delta t half the ways half into delta t into F max that is why we have written here half into delta t into F max. So that is be equated to force into the time period that is the steady force into the time period we are saying these two values will be equal.

If they be equal then delta t can be replaced from its original relation and it can be written out this way F into time period is equal to half into f max into delta t plus delta w divided by 4 a into what you call it into delta t sorry the that is not suppose to be delta t that is suppose to be time period t. So, time period t is on both sides and it will cancel out we still have little more time to see that.

(Refer Slide Time: 32:01)



Yes, F max ultimately comes out to be after cancellation of all the terms 8 into F into amplitude divided by delta t plus delta w. So, can you say whether can we have a relation I mean an expression for F max no, still not. While F is known, amplitude is known delta t and delta w have not been found out till now we do not know their values. So, let us proceed with the analysis to find out what can be delta t and delta w once it is found, we can know F max. Once F max is found, we can found out ultimately the material removal rate that is concurring.

So, I will stop here as the time is up for a second lecture. We will again continue with the third lecture in which we will ultimately find out the expression of material removal rate.

Thank you very much.