Manufacturing Processes-II
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Lecture No. 36
Ultrasonic Machining

Good morning! Welcome to the class on NPTEL sponsored Manufacturing Processes II. Today we are going to discuss Ultrasonic Machining which belongs to the module number 9 on non-traditional manufacturing. We have started module number 9 with abrasive jet machining. So today is our second class. So lecture number today is 9.2. I am Soumitra Paul of Department of Mechanical Engineering, IIT Kharagpur. Before starting with the lecture, let us go to the instructional objectives.

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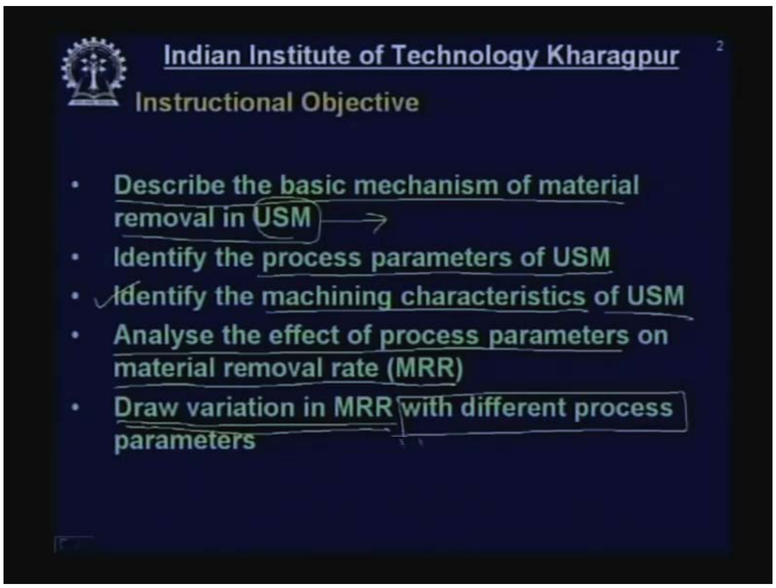

Once you go through this particular lecture, you would be able to describe the basic mechanism of material removal in USM. What is USM? USM is ultrasonic machining. You would be able to identify process parameters of ultrasonic machining. In any machining process, machining characteristics is very very important. So once you go through this lecture you would be able to identify the machining characteristics of ultrasonic machining. Describing something or identifying something is good, but you would also be able to analyze the effect of different process parameter on one of the most important machining characteristics which is material removal rate or MRR.

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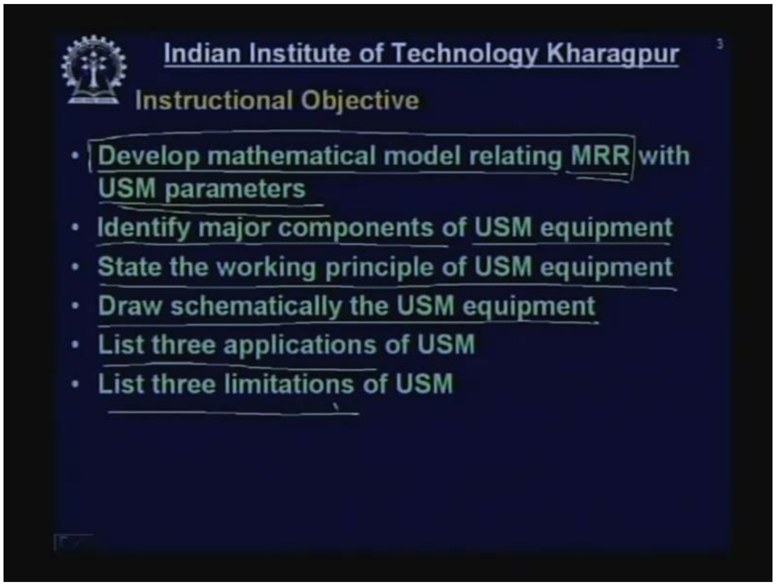

Once you have done that, you would be able to draw variation in MRR that is whatever is the variation in material removal rate, when someone is changing different process parameters. Other than that you would be able to develop mathematical model relating material removal rate with different USM process parameters. Understanding the basic effect of process parameter from experimental data is one thing and developing full mathematical model gives you much more better inside into the process. Any non-traditional machining process or for that matter conventional machining process requires equipments.

So for ultrasonic machining, there is ultrasonic equipment. So once you go through this lecture you would be able to identify the major components of ultrasonic machining equipment and state working principle of those modules or sub modules, you would be able schematically draw the ultrasonic equipment and like any other nontraditional process that we are covering in this module. You would be able to list at least three applications and at least three limitations of USM. Now, let us go into the classification of non-traditional manufacturing process. Earlier in my first lecture on introduction on abrasive jet machining, we have already gone through the classification. So once again we will briefly touch upon the classification of non-traditional machining processes.

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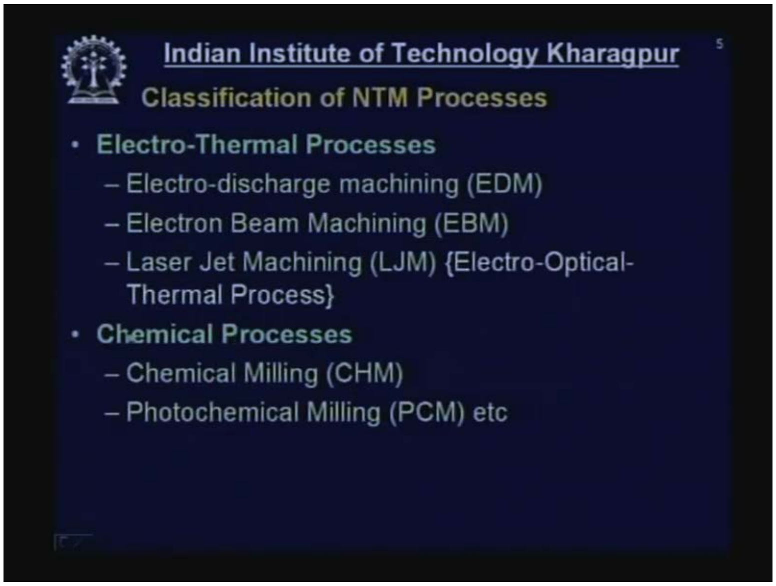

You have mechanical processes, you have electrochemical processes, you have electro-thermal processes and chemical processes. So these are the broad areas.

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Within mechanical processes, we have already discussed about abrasive jet processes. Today we are going to discuss about ultrasonic machining processes. Later on we will be discussing about water jet and abrasive water jet machining processes. In electrochemical machining, we will be discussing about ECM. In electro thermal processes, we will be discussing about electro discharge machining EBM as well as laser machine, but today we would be concentrating only on ultrasonic machining processes. So let us come to the process description of Ultrasonic Machining.

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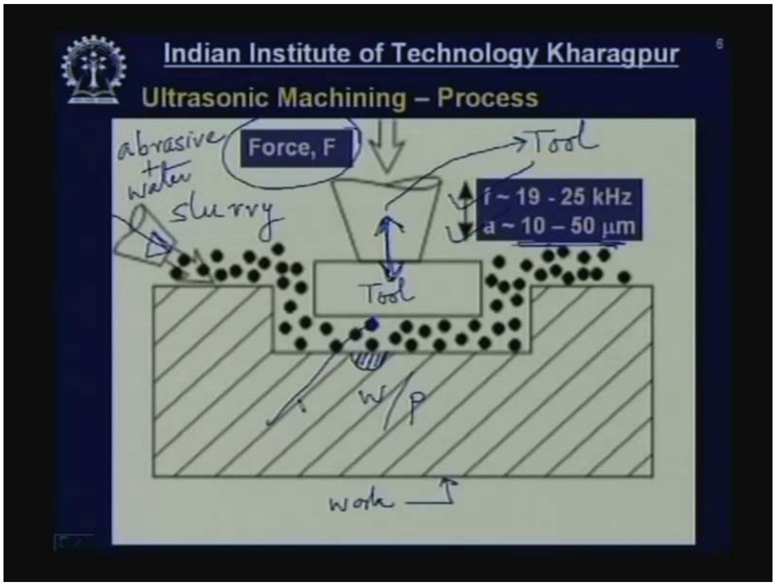

Like any other machining process, any other nontraditional machining process you are interested in machining a work piece. So, this one is my machining. This is my workpiece and there has to be a tool with which I am going to machine it. This is my tool this tool vibrates over the workpiece with what kind of vibration that vibration is around 19 to 25 kilo hertz. So this vibrates rather at a high frequency. What would be the amplitude of vibration? Amplitude of vibration is not much. It is around 10 to 50 micron. Other than that there is a force on the tool do you get material removal because of this vibration of the tool not exactly. This is my tool as we said earlier this is my work piece. So working between the tool and the work piece, this is the machining zone.

This machining zone is flooded with the slurry. What kind of slurry? This is a slurry of abrasive particles plus water. So, this slurry is continuously supplied between the tool and the workpiece at the machining zone. As the tool vibrates over the workpiece say for example, you have say for example you have this particular abrasive particle. This is one abrasive particle as the tool comes down this abrasive particle indents. As it comes down it gets accelerated and indents the work surface. As it indents, there may be a brittle fracture of the work material if it is brittle in nature and there would be a hemispherical crater formation.

So this is the basic mechanism of material removal in ultrasonic machine. So, there is a tool and there is a workpiece and the tool vibrates at ultrasonic frequency. The amplitude of vibration is around 10 to 50 micron and the machining zone between the tool and the workpiece is continuously supplied with the slurry. This slurry is a slurry of abrasive particles and water. As the tool vibrates, these abrasive particles are forcibly sent towards the workpiece and in the process they would be indenting the workpiece and leading to a hemispherical crater formation and this is the basic mechanism of material removal.

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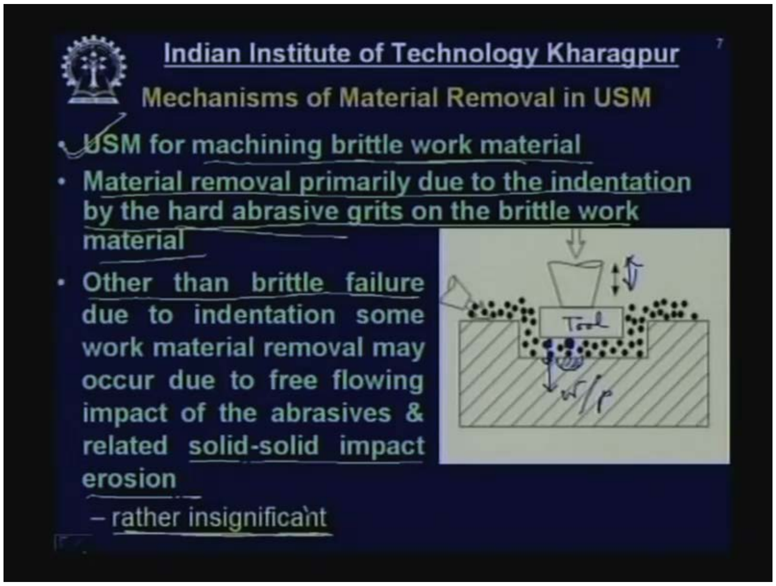

So once again summarize, what we have told thus for USM as because we are relying on brittle fracture of the material is typically done for machining of brittle work material. As we said already, material removal primarily due to indentation by the hard abrasive grits on the brittle work material. This is my tool. So we have the tool. This is my tool, this is my work piece. Once again this was vibrating and in the process it was making these abrasive particles indent the workpiece leading to brittle fracture. Thus, we require a brittle work material and we require hard abrasive particles. But, there is another concept. The concept is other than brittle failure some due to indentation there will be brittle failure. Some work material may also get removed because of pre-flowing abrasives interacting with the work piece. However, due to solid-solid impact that means what we have said something like this.

You have an abrasive particle here. It is flowing freely here and because of the solid. Solid impact also there would be some material removal, but for all practical purposes such material removal is not at all significant. So it is rather insignificant. So when we go for developing the mathematical model, then we would only consider material removal because of indentation by hard abrasive particles which lead to brittle fracture. We will not consider pre-flowing abrasive interacting with the workpiece leading to some material removal due to solid-solid impact because that is very insignificant from practical view point. Now, we are continuing with that tools vibration that leads to

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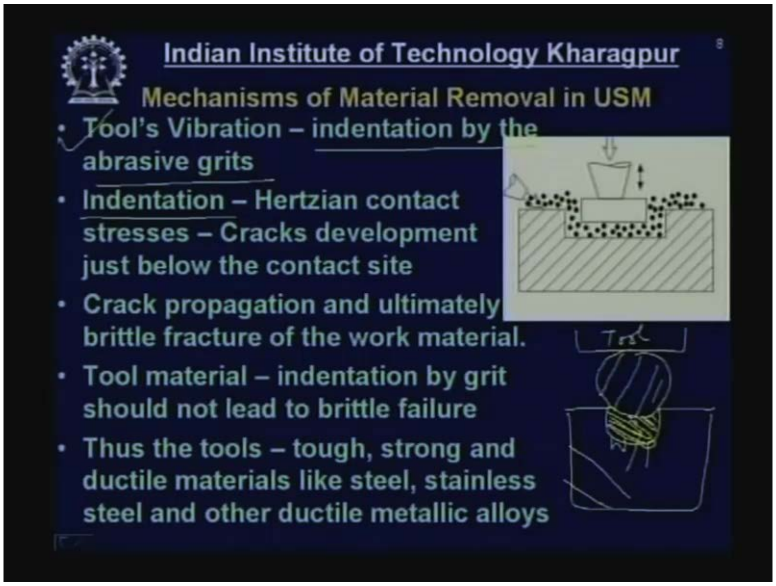

Indentation by the abrasive grits that means, if the abrasive grits are larger than the amplitude of vibration, then only there would be indentation. Once there is indentation by the tool, this is my abrasive particle, this is my tool, this is my work piece, which has been already indented. Because of that there would be a hemispherical crack hemispherical brittle failure. So due to this indentation there would be Hertzian contact stress at this particular level I can possibly draw that once again. So this is your abrasive particle.

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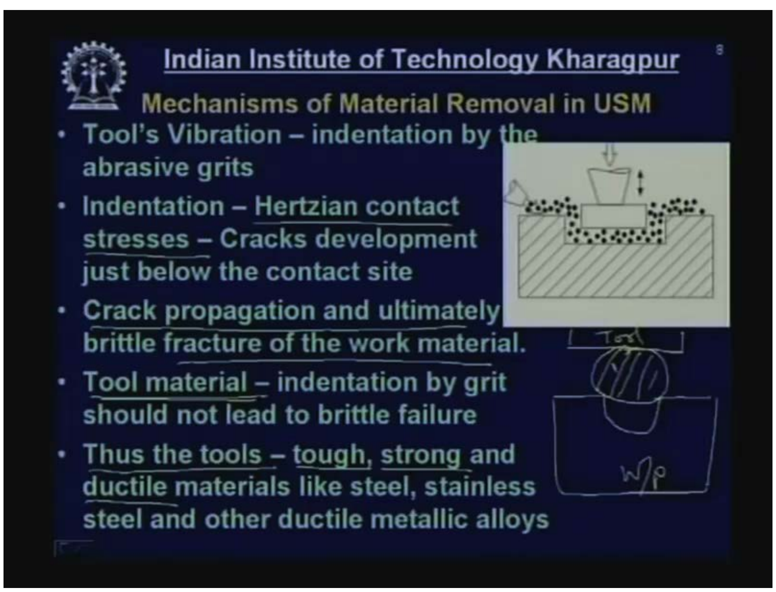

This is your workpiece and this is your tool because of the abrasive indent, indentation there would be failure brittle fracture. This occurs because of Hertizian contact stresses. Once the Hertizian contact stresses goes beyond the flow strength of the material, there would be crack development and brittle fracture. So crack propagation and brittle fracture would ultimately occur. Now tool material should be such that again such indentation tool would also be indented. It would be react or interacting with the workpiece via this abrasive particle but that should not lead to brittle fracture. Thus the tool material should be tough strong and ductile, then it not be brittle if they are brittle when the abrasive particle is indenting the workpiece they will also create brittle fracture on the tool. So I should choose my tool material in such a manner that it is rather ductile, it is tough and strong and it is not brittle. So typically steel, stainless steel and other ductile material metallic alloys are used as tool material. Now, let us try to identify the process variable.

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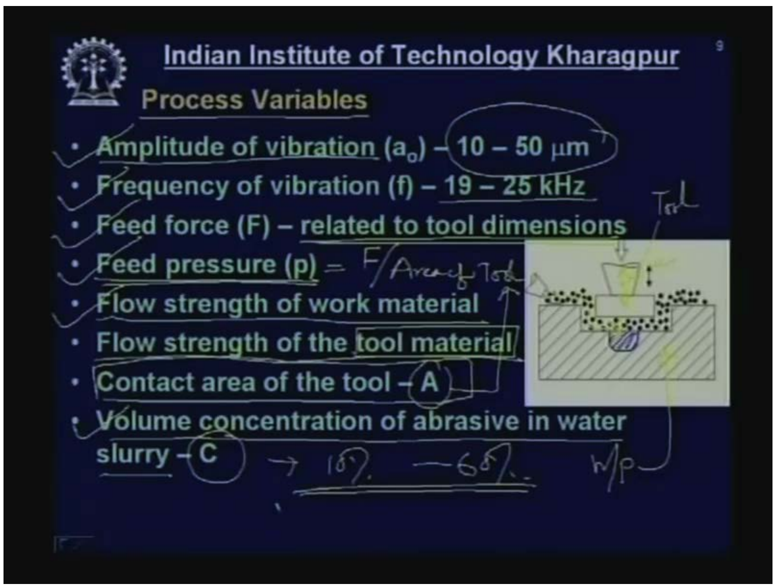

In any nontraditional machining process or for that matter conventional machining process, there are process parameters. Say for example, when you are turning in conventional machining you have cutting velocity, you have feed as well as depth of cut. For other non for nontraditional manufacturing process, for abrasive jet machining you has different process variables. Similarly in ultrasonic machining as well there are process variables which definitely affect your machining characteristics. So let us first try to identify those process variables. So what are our process variables in abrasive in ultrasonic machining? Amplitude of vibration: This was my tool as we have already discussed this is my tool my work piece is this one the tool is vibrating.

So as the tool vibrates I need to characterize that vibration. So I can characterize that vibration by amplitude of vibration typically that is around 10 to 50 micron, then there is frequency of vibration at what rate it is vibrating say it is around 19 to 25 kilohertz. We have also discussed that the tool is given a downward force. So that feed force is related to is related to tool dimension but feed force is also a parameter or we can say depending on the area of the tool, there is feed pressure which is nothing but force divided by area of the tool. So in this way these are the four process variable other than these process variable. There are other parameters as well, flow strength of the work material flow strength of the tool material contact area of the tool already this contact area of the tool has appeared here and volume concentration, flow strength of the work material what does it mean? When the work piece when the abrasive particle is indenting the workpiece there would be some stresses depending on how much area would be removed due to single indentation is definitely dependent on the flow stress. Do flow stress of the workpiece is very very important.

Similarly flow stress of the tool material is also important not only the tool material has to be ductile it should also be having high flow stress flow strength. So that there is less of tool wear contact area of the tool is an issue because it ultimately decides how much is the feed pressure, we are feeding abrasive slurries in the work piece. So volume concentration of the abrasive you know water slurry is important. Ten percent twenty percent to possibly sixty seventy percent; so this is the range in which the volume concentration varies. All these parameters are process parameters in USM and they definitely effect by machining characteristics. One of the main machining characteristics is material removal rate. What are the other process variables as I said?

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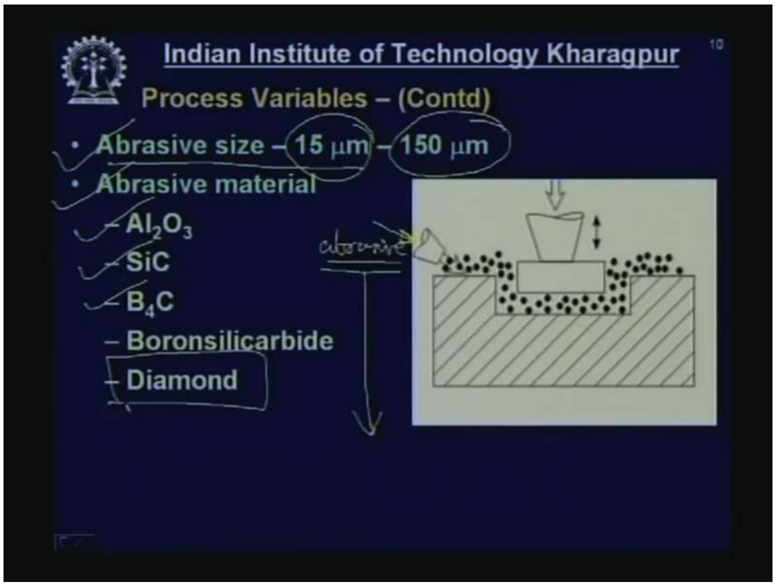

I am giving I am feeding abrasives. So these abrasive parameters are also going to be process parameters. So abrasives are characterized by there what is the material as well as what is the size? Typically 15 micron to 150 micron the mean grit size of the abrasive particles are used and typically the materials are aluminum oxide and silicon carbide. Other than that boron carbide is also used. Sometimes even diamond may be used but such USM would definitely be much costly because the cost of the abrasive particles. Now let us come to the ultrasonic machining equipment:

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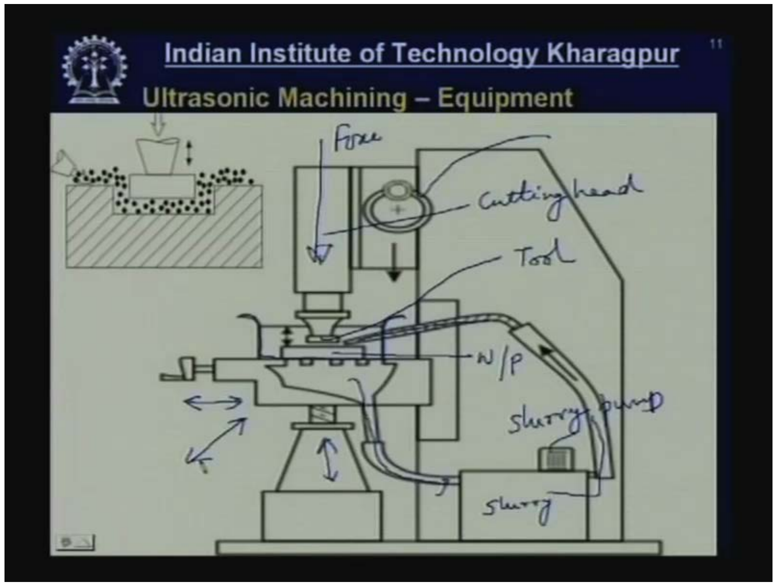

What we have to do? We have already understood what we have to do. There is a tool and there is a work piece. Somehow by some method I have to vibrate this tool at ultrasonic frequency which is 19 to 25 kilohertz. So there has to be a vibrator there has to be slurry to be supplied. So there has to be a method of supplying slurry. There has to be a downward force. So this is my requirement and this is the equipment where I implement this. So this is my tool the tool has been shown here. This is my tool the lower part of it. This is my tool, the tool is mounted on a cutting head. As machining goes on this cutting head can be lowered. Further move, a force can be a downward feed force can also be given on the cutting head.

This is handle or a wheel by which I can fix the position of the cutting head at any particular position. This is my work piece. So there is they are could be voice on which the work piece can be mounted. This is my working tank were the slurry is being feed this is my slurry tank. So this is my slurry pump. So from the slurry tank, slurry is being feed in the work piece zone. Once it has pass through the working zone or machining zone, it is once again feedback. Table can be moved up and down. It can be given a motion in this direction as well as, it can be given a motion in this direction. So, this is the basic description of ultrasonic machining equipment. Let us talk about ultrasonic machine equipment modules.

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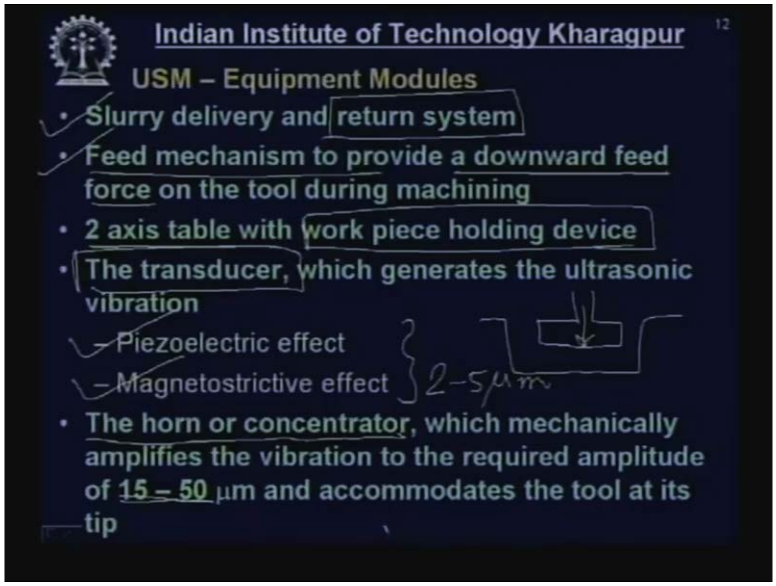

So we have already shown you the figure. We have slurry delivery system and after the slurry is used we need to return it to the slurry tanks. So they are a return system. Now as machining is going on gradually or tool, this is our tool this will come down. So I need to have a feed mechanism to provide a downward feed force on the tool during machining. Moreover, if you remember if I have to use this system for machining at different places I require at two axis table so that I can go to the site of machining along with work holding devices. Now let us come to the most important part of the machine that is the transducer. The transducer which provides vibration to the tool and that particular vibration of the tool enables machining using abrasives with ultrasonic vibration.

So there are two different types of transducer. One is called piezoelectric transducer. Another one is called magnetostrictive transducer, we will talk about transducers after sometime but this transducer they provide very less amount of vibration. The amplitude of vibration is very less around 2 to 5 micron. However for machining I require of vibration of at least around fifteen to fifty micron. So there is a mechanical horn or a concentrator which works like a amplifier and that has to be used to amplified. Now let us go to the next slide which shows how the transducer works.

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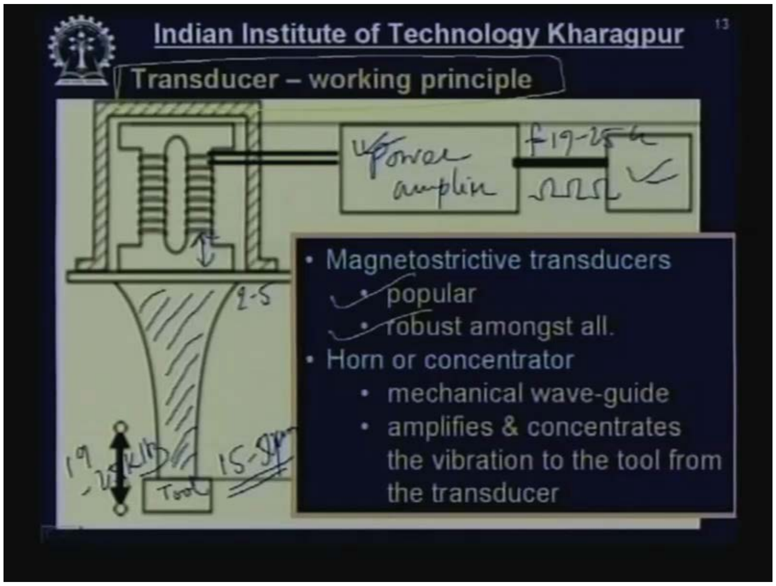

This is a magnetostrictive type transducer. This is very popular and robust and along with that transducer what I have here is what I have here is the horn. This horn basically amplifies the magnet a vibration. So this is my signal generator. So this is my signal generator this one and this is my power amplifier. So, these signals are typically of frequency of 19 to 25 kilohertz. These signals are generated they are amplified by the power amplifier and this is my magnetostrictive transducer because of repeated magnetization and demagnetization this will expand and contract. This expansion or contraction this will produce ultrasonic vibration. Here, it would be two to five microns but this mechanical horn will definitely amplify it to 25 to 50 micron. So, at the tool this is my tool at the tool I would have fifteen to twenty, fifteen to fifty micron of amplitude of vibration at around 19 to 25 kilohertz stop. There could be different types of horns.

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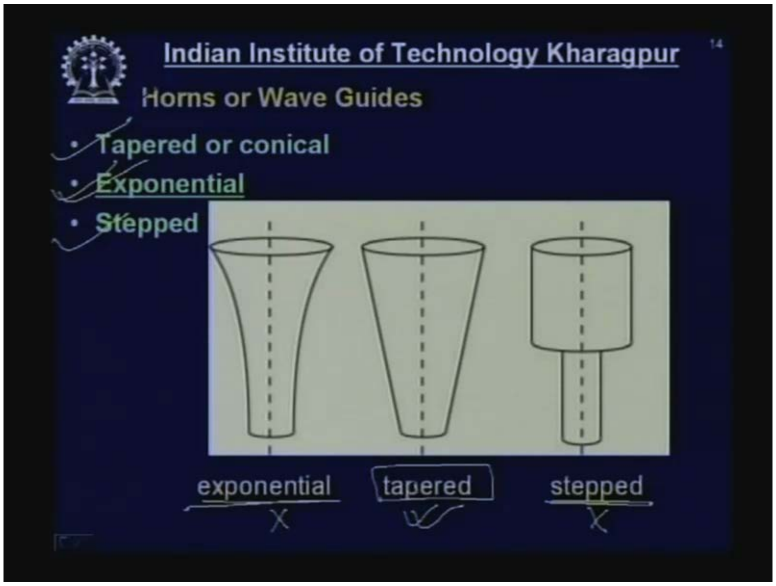

What is the function of the horn? The function of the horn is to mechanically amplify. We have already discussed so that it should be such that it can be it can function and at the same time, it can be manufactured very easily. One of the most efficient horn shape is exponential which is here but it is difficult to manufacture. Typically tapered and stepped are used stepped horn is most easy to manufacture, but typically tapered horns are use because this is a compromise between this one and this one. So this is typically used in machining in ultrasonic machining.

Now let us come to the modeling of ultrasonic machining process. We have already gone through abrasive jet machining process. There also we have non modeling. When you go to other processes like abrasive jet abrasive water jet machining electro discharge machining, electro chemical machining, they also will be delivering on mathematical modeling. Mathematical modeling in any nontraditional machining is very important because it gives you an indication what would be the effect on it gives you an indication on what would be the effect of process parameter on material removal rate and understanding that is very very important before one goes in to the shop floor for trying how different machining options. So, we will be starting with the very basic concept that is this is my grit material.

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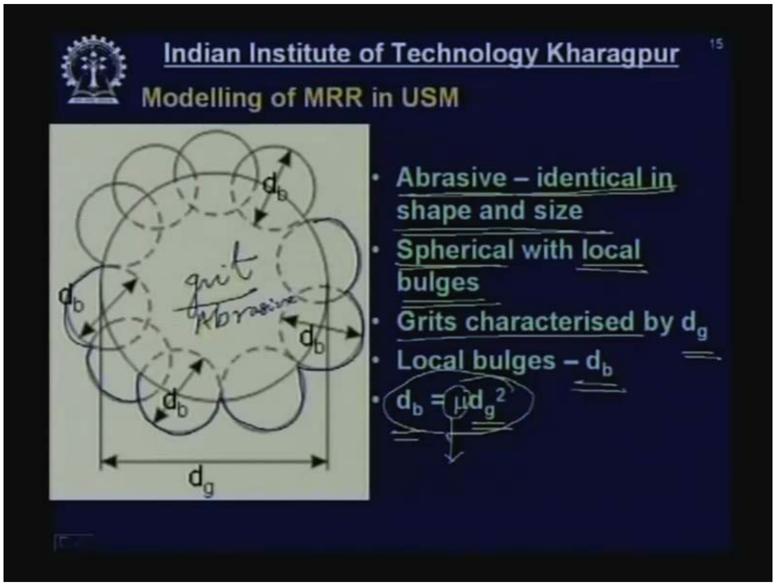

How? This is my grit or abrasive material. So abrasives, they are identically it is assumed they are identical in shape and size. So whatever we have schematically written here, this is my grit material or abrasive material. They are typically assumed to be spherical. but and more over they are identical in shape and size. Though they are spherical, there are local bulges on the abrasive where are the local bulges. It is assumed that through out the abrasive you have such local bulges. So your abrasive looks like a spherical thing but with local bulges. So, there would be such local bulges. How you characterize the local bulges? We characterize the local bulges by a bulge diameter and the grids are characterize by the grid diameter and once again it is assumed that the local bulge diameter is proportional to square of the grit diameter and this is my grit factor mu. So this decides the proportionality constant. Once that is done, now let us come to the process.

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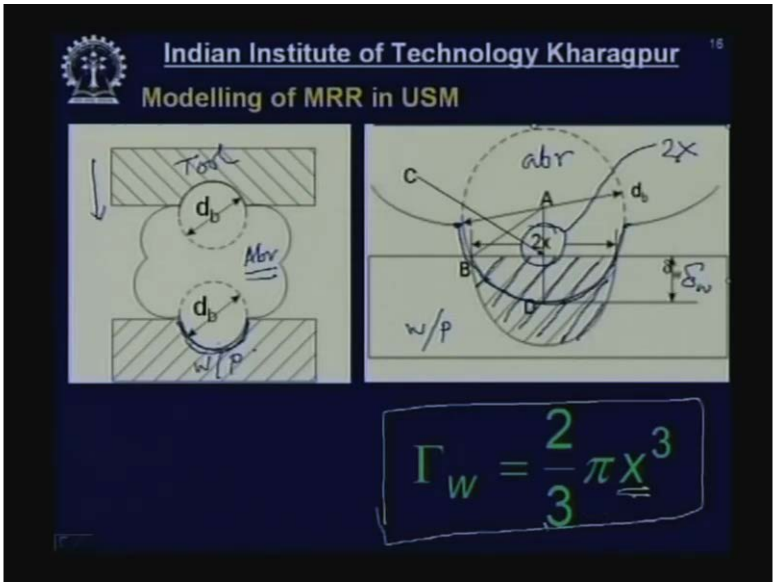

So what is there in the process I have a tool. This is my tool and this is my work piece. The tool is coming down because it is vibrating as it is coming down, it is getting indented by the abrasive particle and it is forcing the abrasive particle to indent the work piece. When the abrasive particle is indenting the work piece, it is basically interacting with the work piece through that local bulge on it. So let us draw that particular thing here in a magnified scale. So here what we have, this is my work piece. This is my abrasive particle and basically from this point to this point, to this point to this point, to this point this particular curve is nothing but the local bulge on it. As it interacts with the work feed, it generates a hemispherical brittle fracture zone.

How I characterize that hemispherical brittle fracture zone, I characterize that hemispherical brittle fracture zone by its diameter to x and by delta w which is the depth of indentation. Once I know 2x, I can definitely estimate how much is my material removal in a single impact or indentation. This is my amount of material removal in a single impact which is how much which is nothing but the volume of this particular hemisphere two third pi x cube where 'x' is the radius. Now I need to know, how much is my 'x' and how many times there is interaction these two I have to introduce. So let us go to the next one.

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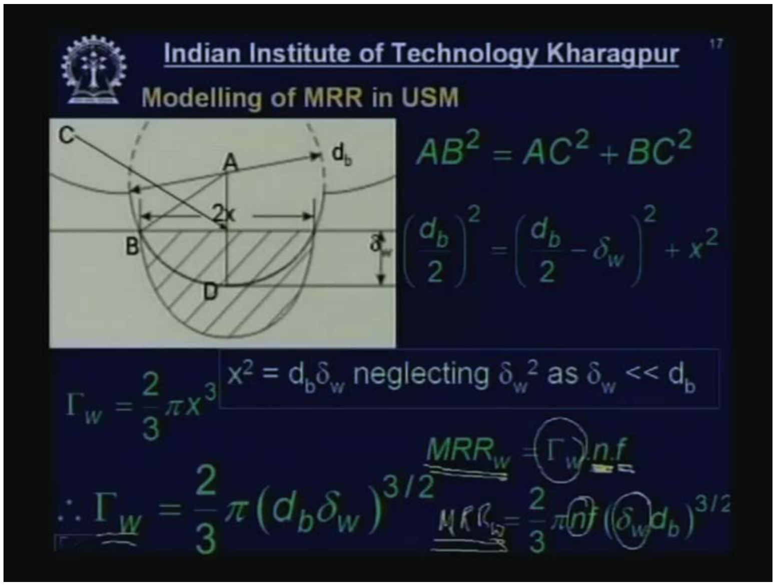

Here I am trying to find out a relation between ‘x’ and ‘dw’. For doing that, I have written a standard equation AB square that is this hypotenuse square is the perpendicular square AC square plus BC square the base square. Now I mean putting the value of AB AC and BC. How much is my BC? BC is my ‘x’ AC is nothing but the local bulge diameter by 2 minus the indentation depth and this is the local bulge diameter. Now we all appreciate that this ‘dw’ is very very less because this is the indentation depth. This diameter of the whole grit is possibly 100 micron. So ‘db’ this is your ‘dg’. So ‘db’ would be possibly 10 micron. So ‘dw’ would be very very less compared to other dimensions. So from that, we can definitely neglect how much is my ‘dw’ square and by neglecting it I can come up with the equation for amount of material removal in a single impact.

This was the previous expression. Two third pi x cube which is nothing but, the volume of that hemisphere and now instead of x, I can put because x square equal to db into dw delta w, I can put this particular expression. So it becomes two third pi db into delta w to the power 3 by 2. If you look at this particular expression if you look at this particular expression there is only one unknown which is ‘dw’. Now we have to see whether we can get a value of this unknown. But before doing that from single impact we can also get the material removal rate. How we can get that? Material removal rate would be nothing but amount of material removal in a single impact times number of grids available between the tool and the work piece and the frequency of impact. So frequency of impact is known, ‘n’ is unknown. So we have to find out ultimately this ‘n’ as well as the value of delta ‘w’. Once we can do that, we have an expression of material removal rate at the work piece. Now we are coming towards what exactly happens when the tool comes down. This is very important slide to understand what exactly happens?

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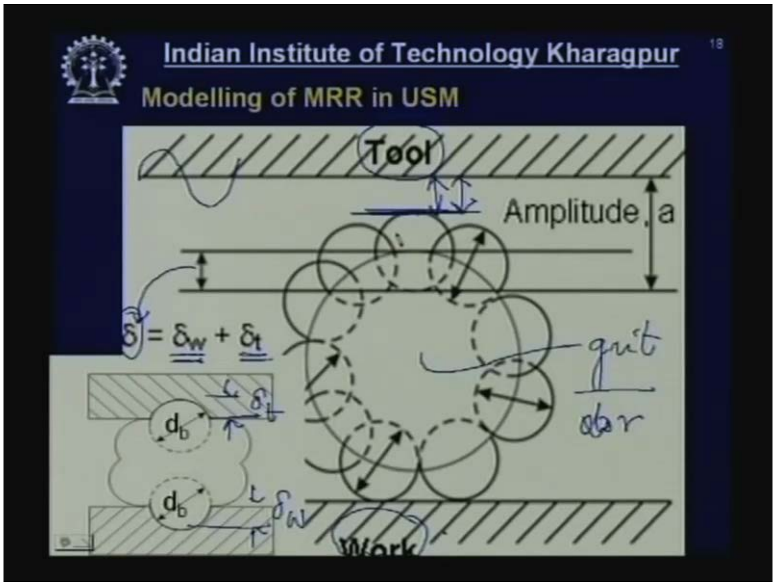

As we have already identified in this particular slide that, this is my tool this is already identified. This is my workpiece and in between I have a grit or an abrasive particle. Now this tool between the tool and the workpiece there is a separation. The tool is moving in this manner. So when it is coming down, it may not be in contact with the job contact with the abrasive particle. So it may if come down by some amount totally freely, then once it touches the abrasive particle then the abrasive particle will start indenting the tool as well as it will start indenting the work piece.

So the total indentation amount is this much delta which is delta w plus delta t how much is delta t. This is my delta t this is a side diagram which I have written wrong and this is my delta ‘w’. So total indentation is delta which is broken down into delta w and delta t however it is required to be understood that when the tool is coming down, it is not always in touch with the abrasive because of it depends on what is the size of the abrasive or gird abrasive particle of the grid diameter. So for sometimes it can come down totally freely. Now we need to understand whether we can model that particular process or not.

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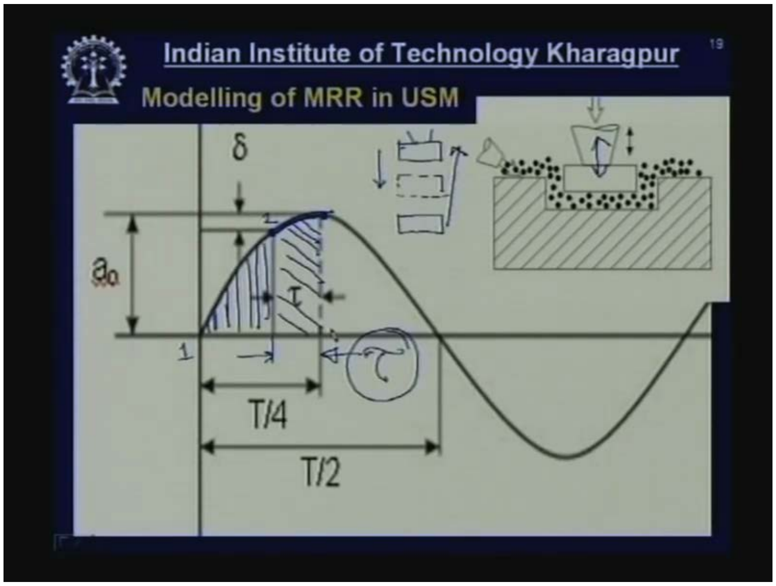

So this is my tool which is vibrating. So some part of the tool vibration. This is my tool vibration. This is sinusoidal vibration. Some part of the tool vibration this part. There is no contact between the tool and the work piece. There is no contact between the tool and the abrasive material. Only after it has come down to this much position, then only over this length of line only over this pan of time tau, there is contact between the tool and the abrasive particle. What happens beyond this till this particular point from point one to point two tool was coming down.

This is my tool. This was coming down but there was no contact. When it came here, then the contact was established. Then it indented the workpiece through the abrasive particle. Now as it starts going up, there is no contact between the abrasive particle and the tool. So, in ultrasonic machining contact between the tool and the abrasive particle is for a very small amount of time of the total cycle time t it is only in contact for a small fraction of time 'tau'. Now we need to understand how much is that 'tau' and what would be the interaction of the tool with the abrasive particle during such a small time 'tau'.

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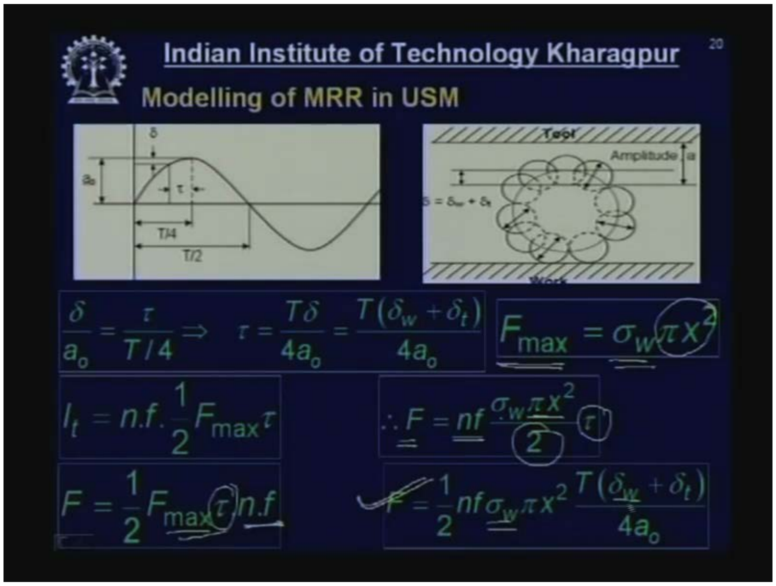

So what happens? During this interaction if we can draw it here, only during that interaction there would be a force. So this much is t by four. This is force ‘F max’ and this pan of time is ‘tau’ before that there is no force of interaction between the tool and abrasive because it is not in contact and when it is in contact, it introduce a total deformation delta which is once again a portion between delta w workpiece indentation and tool indentation. It has been schematically shown here in a single block. Thus I can write down the total. It can be written down that the total delta would be proportional to tau and the proportionality would be decided by what is my amplitude of vibration and what is my quarter period? Because once the tool reaches here beyond that there is no contact. So ‘tau’ can be expressed as t into delta divided by four into a 0.

Now how much is this delta? This delta is nothing but delta w plus delta t. delta w is the amount of indentation of the tool within workpiece and this is the amount of indentation of the abrasive within the tool. Now because of this indentation, there would be impulsive force I t and that would depend on how many particles are there? How frequently they are interacting with each and half into F max into tau. This is the total impulsive force, half into F max into tau for a single impact and this is the total force. Thus, the tool which was having a downward force ‘F’ that can be written as this I t which is nothing but half into F max into tau into n into f.

So in this particular equation once again there would be certain things which are known to us certain things which are not known to us. At this movement of time tau is not known to us fully, n is not known to us fully, but other than that things are known to us. What about F max? How much is the maximum force of indentation? Maximum force of indentation would be pi x square which is the area of indentation into the flow stress. So F can be written as nothing but ‘nf’. This ‘nf’ has come here into tau into tau into half F max. So half has come here and F max is nothing but sigma w into pi x square. So I have an expression for F here which depends on the flow strength and which also depends on how much is the indentation within workpiece and how much is the indentation within the tool. Now let us try to get a value for n. Here I have n try to get a value for n.

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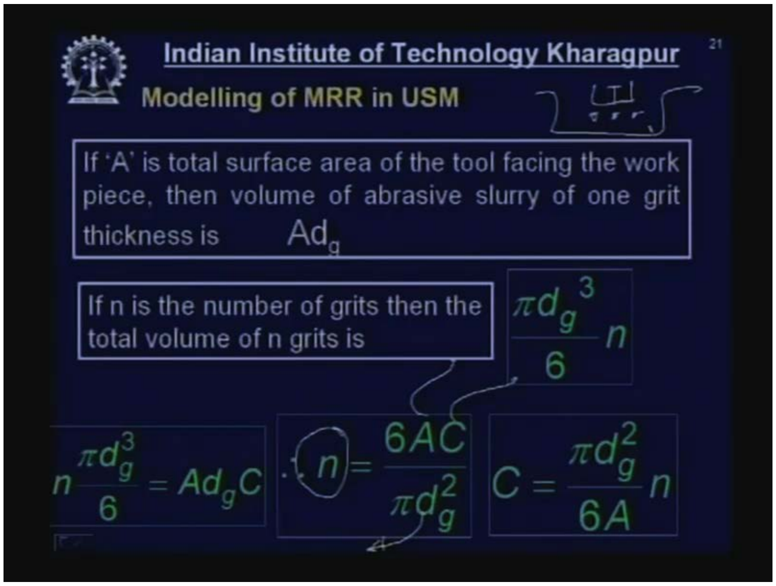

Between the tool and the work piece, there is some area this is this area. How much is that area that area is A in that total area 'A' there are a volume of 'A' into dg because this distance is assumed to be dg that is the grit diameter. So this is my total volume within that volume there are n number of grits. So what is the volume of the grids? Single grid volume is pi dg cube by six so it is nothing but pi dg cube by six into n. Now I have also a concentration number which designates what is the percentage of abrasives in that slurry.

So if I multiply the total volume A into dg into concentration, I will get the total volume of abrasive particles. So by this expression, I can relate how much the value of 'n' is. I can also relate how much is the value of concentration number in relation to 'n', when I am supplying abrasive, this is known to me. C is known to me. When I am supplying abrasive to the work zone C is known to me this is known, 'A' is known to me even 'dg' is known to me. So number of particles adds between the tool and the work piece, how many particles are there that is also known to me. So in the previous expression I can replace the value of n.

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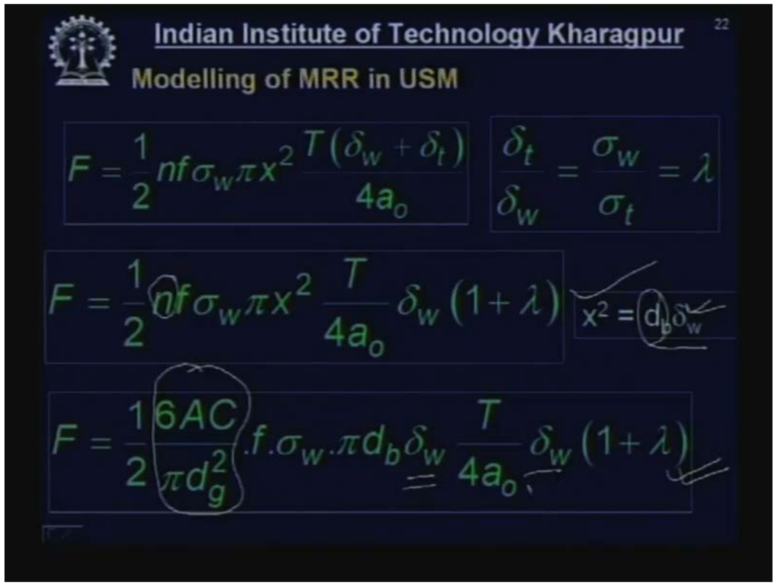

Now let us see how the expression of force is related to other quantities. Here I have 'n' which is number of abrasive particles available under the tool. Frequency is a quantity which we are setting on the machine that is also known. This is the flow strength of the workpiece which is known to me. One unknown is x and we have two more unknowns delta w and delta t, delta w is the indentation within the workpiece and delta t is the indentation within the tool. Now, let us see whether we can combine or find any relationship between delta w and delta t. Is there is? It is pretty much imperative that if my workpiece is very very strong, then delta w would be less so delta w and flow strength of the workpiece they should be inversely proportional.

Similarly if my tool is very very strong if my tool is very very strong definitely my indentation in the tool would be very less. So from that we can say the indentation within the tool indentation within the tool and indentation within the workpiece would be inversely proportional to the flow strength and thus we can define a quantity lambda which is nothing but the ration of flow strength of the work material and that of the tool material then what we have? We can take delta w as common and we can get this this particular equation. So here in the above equation we have three unknowns.

Now we have only two unknowns x square and delta w. Already we have an expression for x square x square equal to db into delta w db is the local bulge diameter and delta w is an unknown and from that we can get a modified equation like this where this 'n' has been replaced by this particular quantity as we have derived earlier. In this particular equation, everything is known expect delta w. So whatever expression was there in this particular slide that has been simplified here nothing more than that f and T frequency and time period they have taken together.

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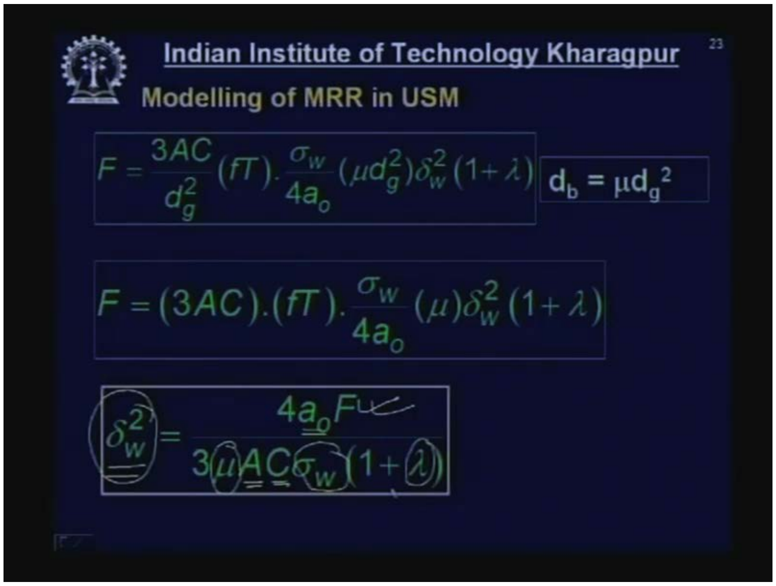

Instead of this d delta w into delta w instead of db. Instead of db we have put mu into dg square all this has been done. As you can see here, this dg square and this dg square cancels out. f and T basically they cancel out each other and give one. So I have the next expression which is something like this, three into AC this is basically one dg square and dg square cancels out giving my mu, delta w square still stays here and other things are already coming from the above step. Now from this expression I have an equation for delta w square, where on the right hand side all other things are known a0 is set what is the amplitude of vibration. Force how much force I am giving area of the tool is known grit parameters is known to me. Concentration is known, even work material flow stress is known. The ratio of flow strength of my work material and tool material is known so dw square I can calculate now.

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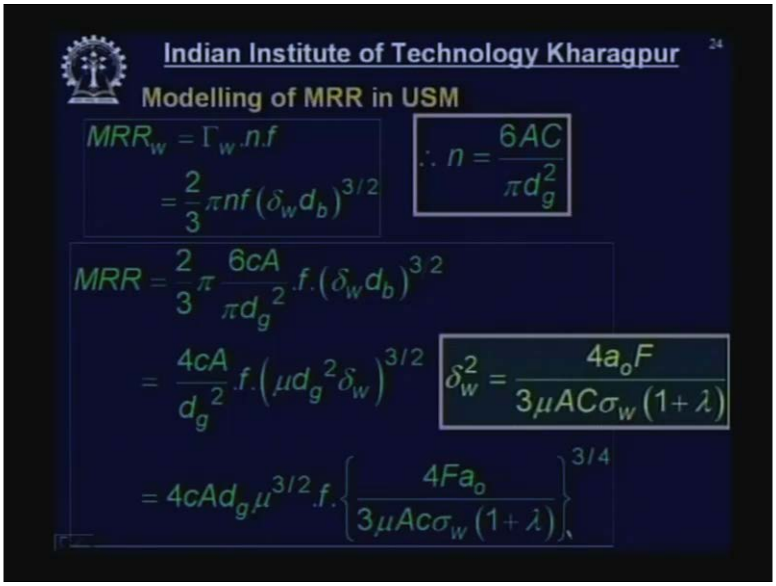

Once I can calculate dw square I can also get the expression for material removal rate. Earlier if you remember, we had a expression for material removal rate like this two third pi n into f into delta w into db to the power three by two. So, in this expression all I have to do is to put the value of n we would have to put also the value of delta w square. Once we do that we get an expression which looks like this.

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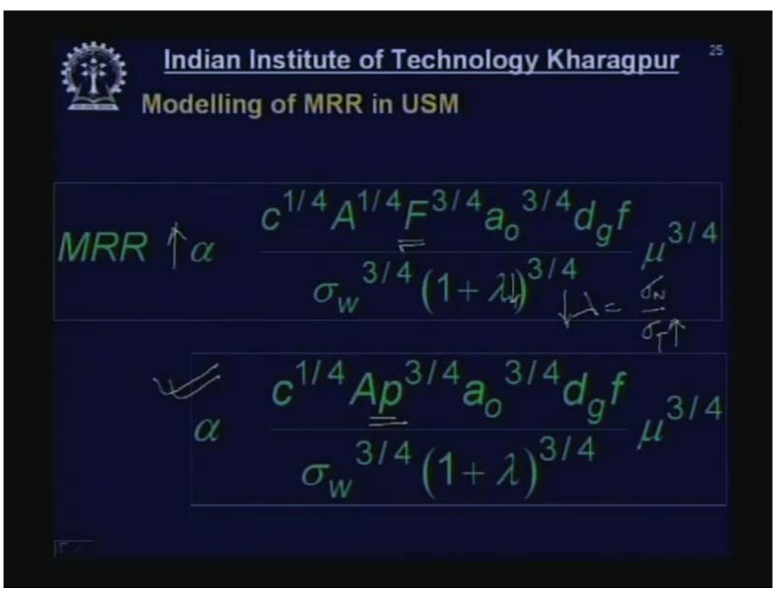

So in the next slide will simply that so the simplified equation for material removal rate is like this, what is there? If you look at the expression what does it suggest? It suggests if you increase ‘C’ concentration number your material removal rate is going to increase. If you increase force, your material removal rate is going to increase. If we increase amplitude of vibration, material removal rate is going to increase. If we increase frequency, your material removal rate is going to increase. If we increase grit diameter, you are going to get benefit. However, if your material work material that is strong if you try to machine a material which is strong, your MRR will reduce which is justified. I should be able to machine not so strong material faster it is law of nature. What is this lambda? This lambda is nothing but flow strength of the work material by flow strength of the tool.

If the lambda increases it means tool is becoming easy to machine which should not be the case material removal rate will reduce. So, I should have a lambda which is very very small. How can I have that? I can have a lambda which is very small when my tool material is very very strong. When this is strong, this goes down as this goes down material removal rate increases. This block of expression is nothing but in replacing force by the pressure, instead of machining downward machining force we have converted that quantity into pressure. So in this way, we can study the effect of process parameter on material removal rate.

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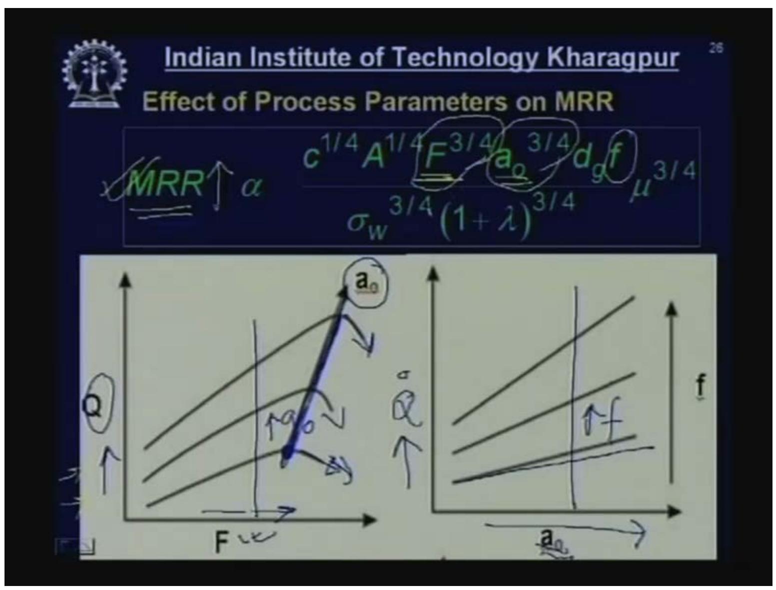

Now let us see whatever we have modeled, whatever experimental data is available in the domain, do they match or not? We can always develop a mathematical model but having said that there are assumptions in the mathematical model. In today’s mathematical model, what was the assumption? There were a lot many assumptions. First of all we were assuming all the grits are having the same shape and size. They have local bulges the local bulge diameter or radius they are all same, when they are indenting the work piece it is removing a hemispherical duct a brittle fracture zone. So there are quite a lot of assumptions, but despite those assumptions we need to see whether our model can capture whatever we observed during experimentation. So, in these two slides we are going to study that. So what do we have here? We have material removal rate on my 'y axis' against machining force.

What is my experimental observation? Experimental observation says as I increase my machining force or downward force, the material removal rate increases. But beyond a particular point, it starts dropping. What is this 'ao'? Similarly keeping my force constant, if you increase 'ao' there is increase in material removal rate. Now let us see whether this is captured into my model for material removal rate. This is my expression for the model material removal related a material removal rate relating to all the process parameters. See here, if we increase force there is increase in material removal rate. So my model is able to capture my actual experimental observation if I increase 'ao' there is material removal rate increase and them my model is capturing that but beyond a particular force there is reduction as you can see beyond this line, there is a reduction in material removal rate which my model does not capture.

Why is it so? Because beyond a particular force, the tool would not be able to force the abrasive materials towards the workpiece it would always been contact and beyond a critical force, such contact between the tool and the abrasive particle reduces the material removal rate. On the other side, what we have? On the other side also, we have a similar thing this is once again material removal rate this is a zero. As you increase a zero material removal rate increases. This is very well captured in the equation as we have seen. At the same time, at the same a 0 if you increase 'f' there is increase in the material removal rate which as you can see is very easily captured here by these three terms. So whatever experimental observations we have put in this particular slide, they are very well captured in material removal rate. However there are phenomena's which our simple model cannot take into account. Let us go to the next slide.

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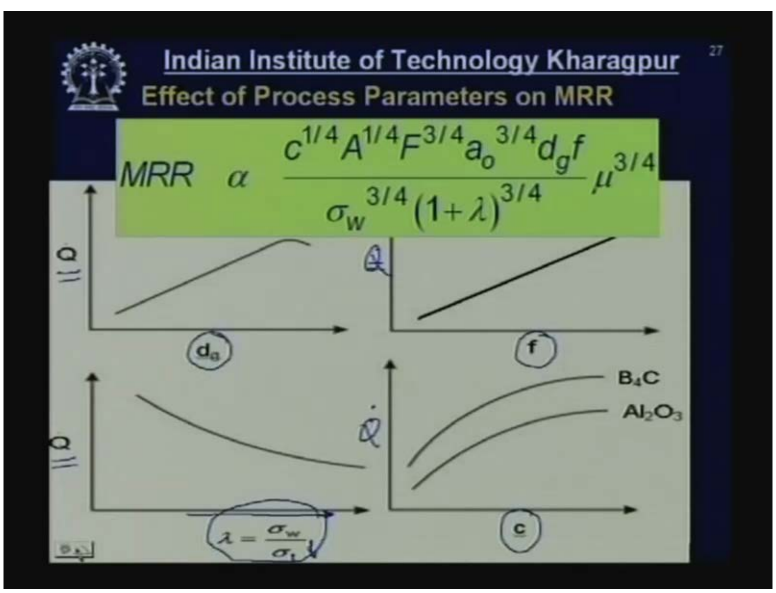

In this slide, what we have we have once again material removal rate at four different places. Here also I have material removal rate. They are varying against ‘dg’ that is the grid diameter against frequency against concentration and against the ratio of the strength of the work material and the tool material. As you increase the ration lambda that means as your tool is made up of not so strong material what happens? Material removal rate reduces because instead of material remove removing the work material tool material is removed is that captured in the expression that is very much captured. See lambda is in the denominator as you increase lambda this whole quantity increases. So the material removal rate decreases. This is very well captured in the expression. Now let us come to ‘dg’.

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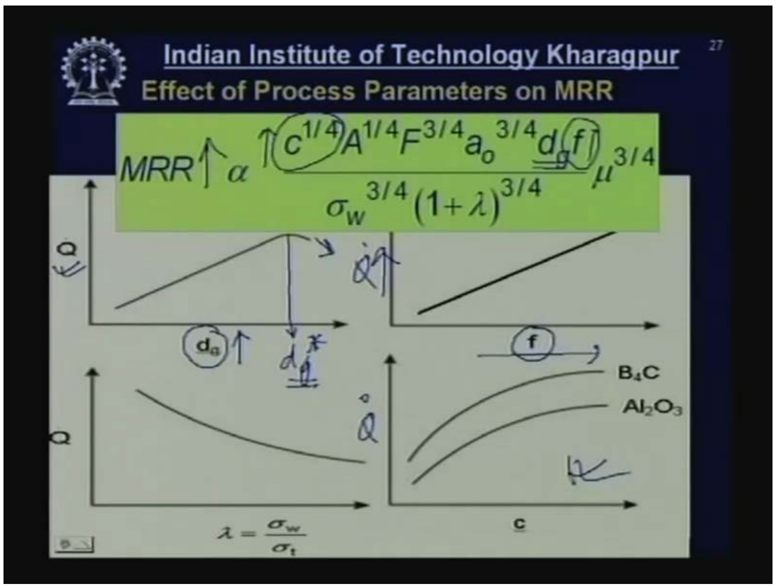

What happens to ‘dg’? As you increase dg, the grid diameter you observe that material removal rate once again increases and this is also well captured but there is a point beyond a particular dg star value it drops. Because if your amplitude of vibrating is not increased along with dg star along with dg a point will come beyond which material removal rate cannot increase because they are not getting enough power so that they can remove more material. This is against frequency which is very well captured against Q’s that is if as we increase frequency material removal rate increases and this is very well captured in our model. Now comes the concentration; as you increase concentration you expect to get more material removal rate which is also very much evident from our experimental observation but there is a strick.

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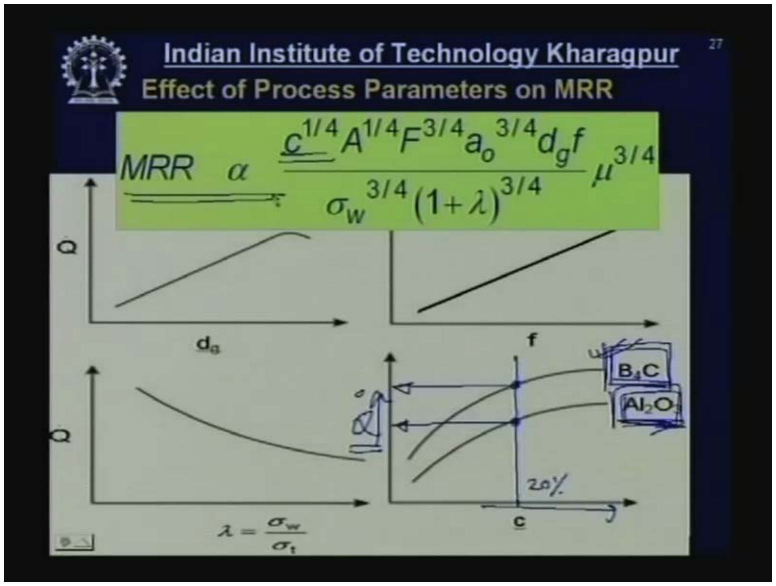

This is my material removal rate. As you increase concentration material removal rate increases fine that is also there in my model, but depending on what abrasive material you are using you have different material removal rate say this is twenty percent concentration. If you are using alumina, you are getting a particular material removal rate. If you are using boron carbide, you are getting another material. Typically, this is decided by what is the sharpness of the abrasive particles. Do the abrasive particles undergo disintegration during indentation? If they undergo disintegration, which is once again decide by there viability and strength then they would not be very efficient in continuously machining. So what abrasive particles you are using that also definitely affects your material removal rate which is not captured in our model. Having said that our model is a very simple model, but still it captures most of the phenomena which occurs in ultrasonic machine. Now let us come to the applications.

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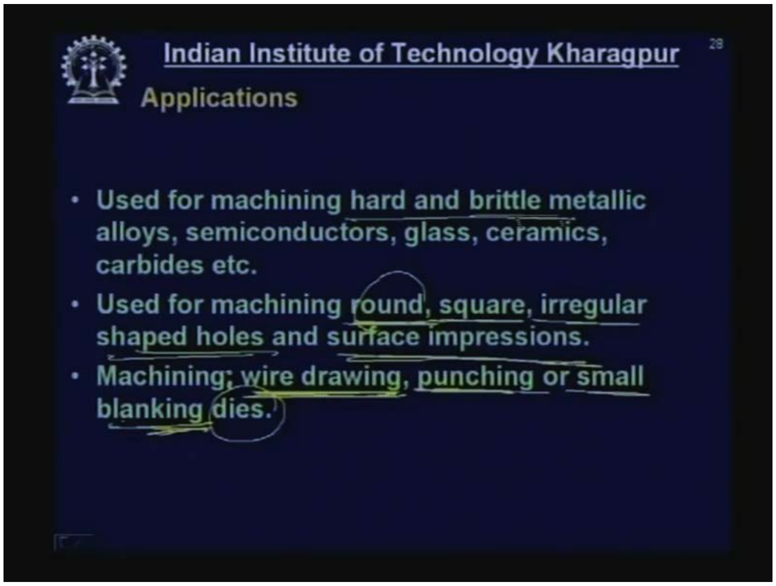

Till now what we have done? We have described about the material removal rate, what is the material removal mechanism in Ultrasonic Machining. It is mainly because of brittle fracture. After that we have tried to identify all the process parameter, basics of the ultrasonic equipment and we have also developed the material removal model. Now let us try to see one of the applications in abrasive water in USM in ultrasonic machine. So these are applications of ultrasonic machining USM. They are typically used for hard and brittle materials for machining hard and brittle materials, semiconductors because they are also brittle glass and ceramics and carbides. USM is never use for steel because it is a ductile material. So, once again it is used for machining hard and brittle materials.

This is also machined for use for machining round, square, irregular shaped holes and surface impressions. They can be used to machine dies. What kind of dies? Wire drawing dies, punching dies, small blanking dies. So, they are used for machining wire drawing dies punching dies and small machining dies. They never use for machining large dies. They are used for small components for integrate shapes and if they are brittle in nature. What are the limitations?

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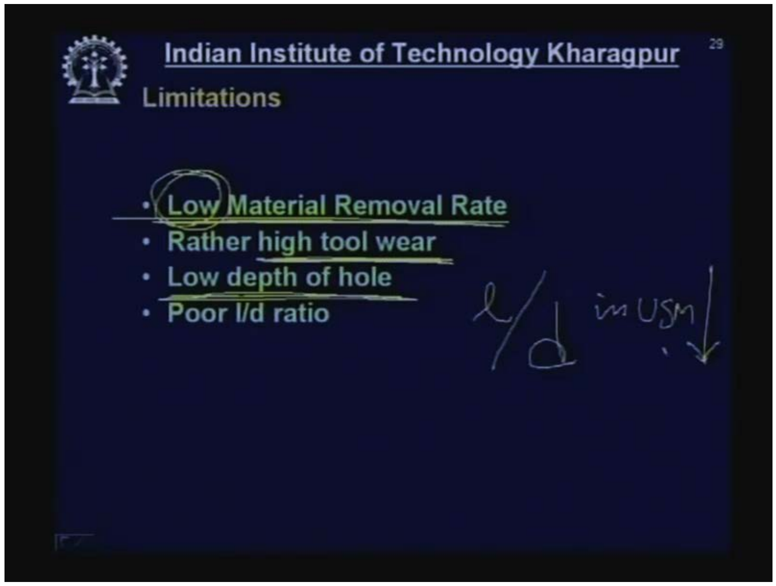

Typically the major limitation of USM is there material removal rate is very poor, low material removal rate, high tool wear rate. So quite often you have to machine your, you have to re-machine your tool. The depth of the hole that USM can produce is rather low so l by d ratio in USM is poor. Poor l by d ratio; so that comes these two points are basically interlink. So these are the limitations of USM. Now let us come to the question answer part in this particular lesson.

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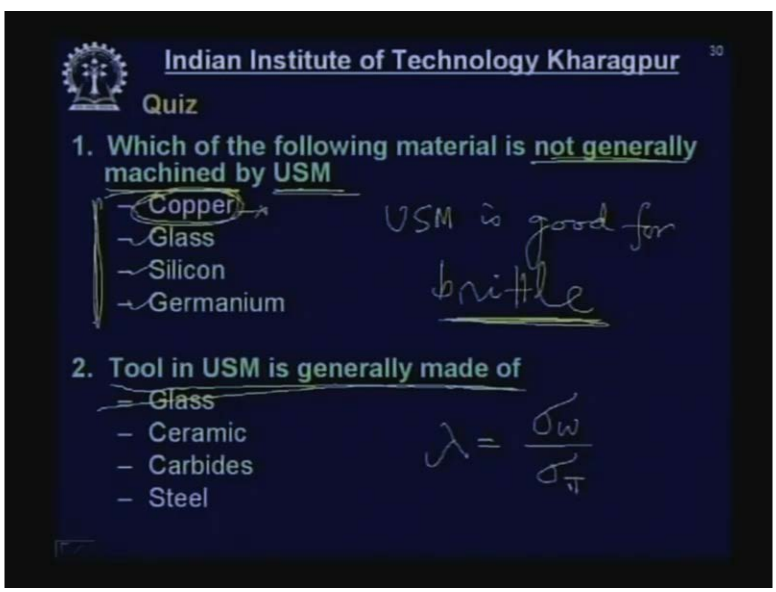

In each and every lesson, we have a quiz part we also have solve problem part. So in today’s lesson, we have a quiz quest four quiz questions which are like this. Which of the following material is not machined by ultrasonic machining? It is not generally machined by ultrasonic machining. We all know USM is good for brittle material. So in this particular list, if there is any material which is not brittle that has to be discarded and that would be our answer glass is a brittle material, silicon is a brittle material, germanium is a brittle material. So our answer is copper which is a ductile material and not machined by USM. Let us go to the second question. Tool in USM is generally made of we all know there is a quantity like lambda. What is that quantity that is the ratio of strength of the work piece and tool material? How does it affect us? That affects us in two ways.

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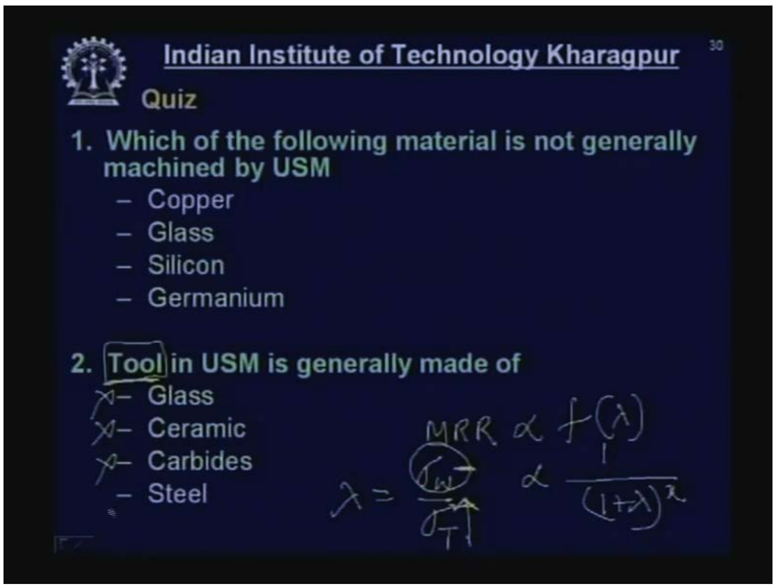

Material removal rate; if you remember correctly is a function of lambda and in that function lambda appears at the denominator. So lambda should be as less as possible. How can I make lambda less? Lambda can be made less by it can be reduced by reducing either this one. We do not have any control on what kind of work material and machining so I have tool material which is strong? More over in USM machining occurs because of brittle fracture so tool should not be made up of brittle material. So, glass is not the answer because it is brittle, ceramic is not the answer because it is brittle. Carbide is not the answer because it is brittle. So, my answer is steel which is a ductile material. Let us go to the next one.

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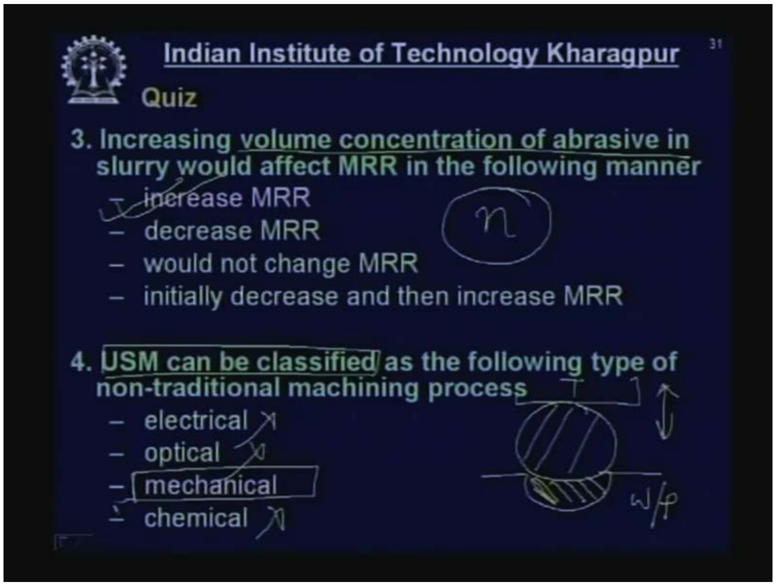

Increasing volume concentration of abrasive in slurry would affect MRR in following manner. As we know if you have volume concentration of abrasive increases, the number of particles available at the machining area increases. So that will definitely need to increase in material removal rate. USM can be classified as what kind of non-traditional process. In USM, there is an abrasive which is being driven by the tool. Tool is vibrating and it leads to indentation of the work material. This is work piece and this is the brittle fracture hemispherical. So, it is not an electrical process. It is not an optical process neither the mechanism of material is chemical. It is because of brittle fracture, so USM is a mechanical non-traditional machining process. Now let us come to the last part of the lecture which is solved problem.

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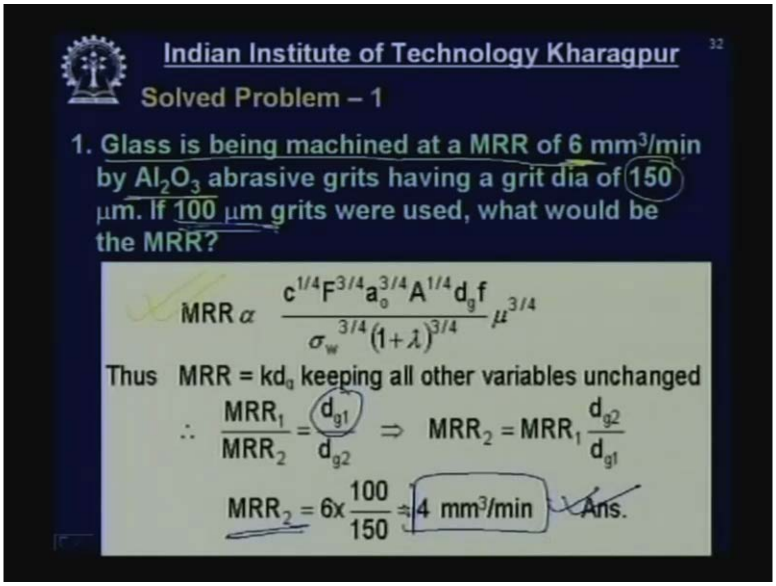

What it says? Glass is being machined at MRR of six millimeter cube per minute by alumini abrasives with a grit size of 150 micron. If I reduce the grit size to hundred micron what happens? This is my expression for MRR. From that, we can write every keeping every thing else constant MRR is nothing but proportional to dg. So from that I can say as because it is proportional if I reduce it by 100 micron, MRR will be also reduce and I will get a MRR of four millimeter cube per minute in this.

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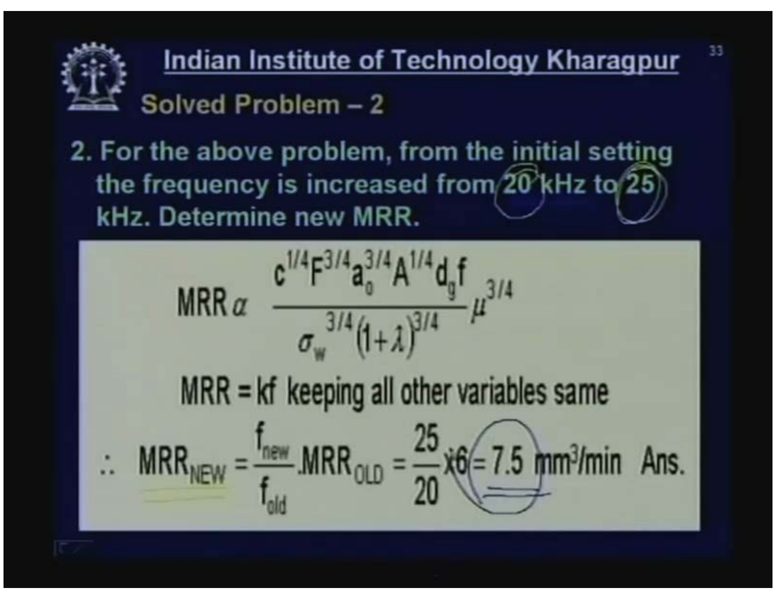

In the same problem, frequency was 20 kilo hertz which has been increase to 25 kilohertz. In the previous problem, the frequency was 20 kilohertz. It has been increased to 25 kilohertz. Once again keeping everything constant, MRR is proportional to the frequency. So from that we can say, as you reduce as we increase frequency MRR will increase and the same way so it becomes 7.5.

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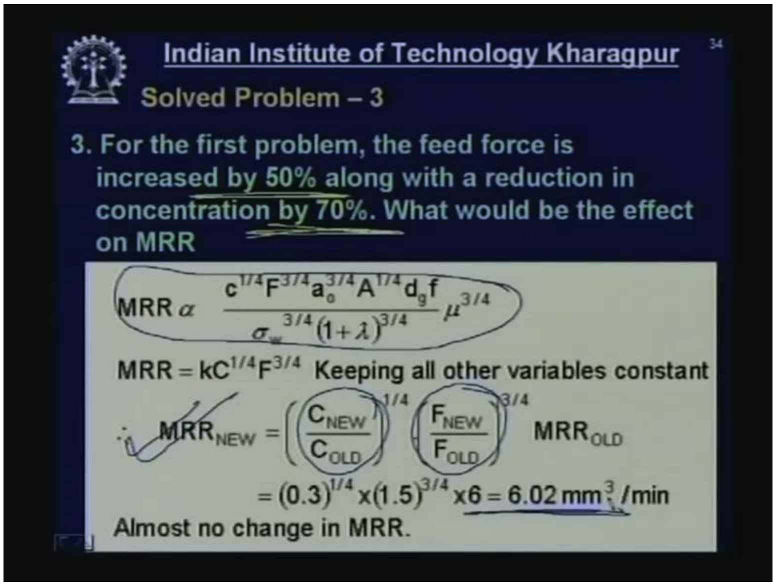

In the third problem, is a continuation of the first problem one can say, the feed force as well as the concentration they have been changed. Feed force has been increased by 50 percent. Concentration has been reduced by 70 percent. So keeping all other quantity constant, MRR expression which is such a complex expression can be written like this where it is a function of concentration and function of feed force and we see there would not be any change in material removal rate. It was 6 micron 6 millimeter cube per minute and it remains almost 6 millimeter cube per minute. Now let us come to the summary of today's lecture.

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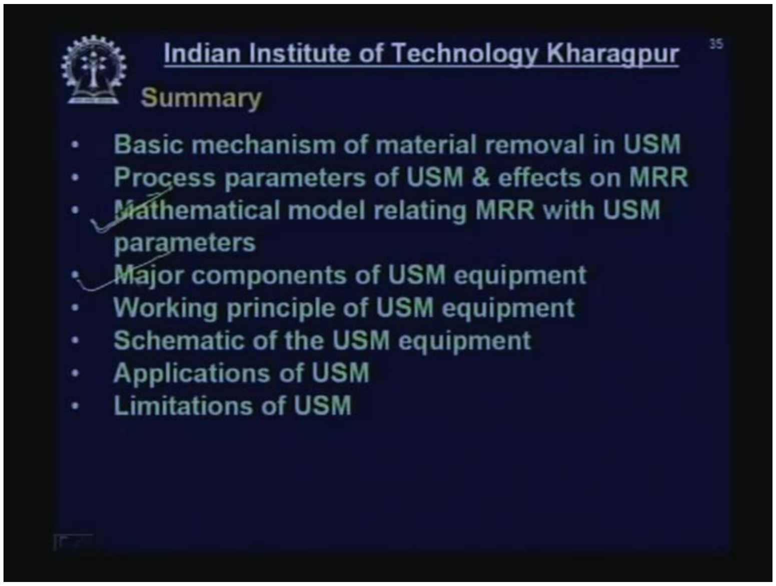

In today's lecture, we have discussed about the basics of ultrasonic machining. We have identified the process parameters in ultrasonic machining and we have also studied their effect on MRR both experimental as well as theoretical. We have developed a mathematical model relating we have developed a mathematical model relating the process parameters with material removal rate. We have discussed about the major components and working principle of the USM system. We have discussed about schematics of a USM. Once you go through this lecture, now you can draw the schematic of ultrasonic machining. You also know at least three applications of ultrasonic machining and you also know three limitations of ultrasonic machining. Other than that, we have also solved three problems and you have interacted with some quiz questions. So with that we end today's lecture.

Thank you.