Manufacturing Processes - II

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Lecture No. 37
Water Jet Machining and Abrasive water Jet Machining

Welcome to the Manufacturing Processes lecture. Today we are going to cover water jet and abrasive water jet machining. This is lecture number 37 belongs to module number 9 which is Nontraditional Manufacturing. I am doctor Soumitra Paul from Department of Mechanical Engineering, IIT Kharagpur. Now let us go into the instructional objectives.

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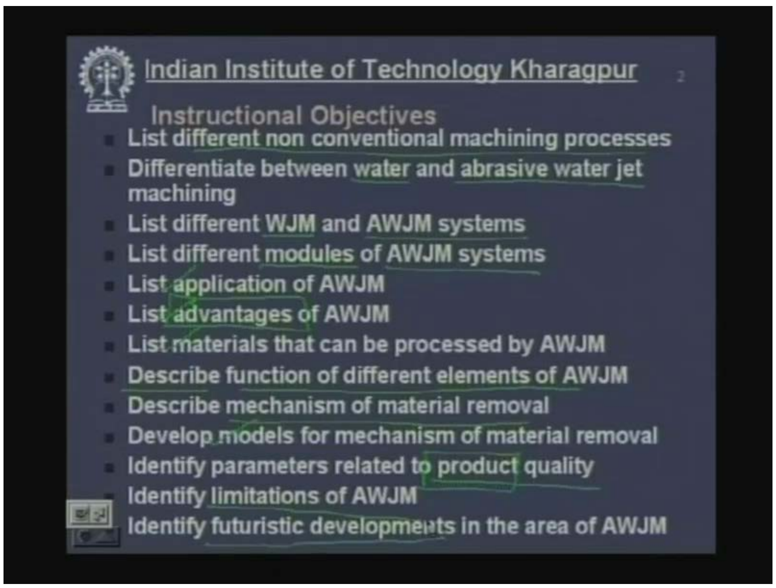

After going through these lectures, you will be able to list different non-conventional machining processes. Already we have covered some of them. If you remember the previous lecture and the lecture before that we will be able to differentiate between water and abrasive water jet machining. You will be able to list different things what are they? You will be able to list different water jet and abrasive water jet systems. You will be able to list what are the different modules within abrasive water jet systems. List their applications, list their advantages and what are the materials that can be processed by abrasive water jet machining process. Not only that, you will be able to describe the functions of different elements of modules which are required to build the abrasive water jet system.

Describe the mechanism of material removal process develop modules for mechanism of material remover. Identify parameters related to product quality. Whenever we undertake any manufacturing process, we are basically developing a product. So product quality is very very important. So you would be able to identify what are those product qualities and how the other abrasive water jet parameters affect them. You will be able to identify limitations of abrasive water jet machining. Any manufacturing process would have their advantages as well as limitations. So knowing the limitations are also very important. Moreover the futuristic direction of R and D in the area of abrasive water jet machining would also become clear once we cover this particular lecture.

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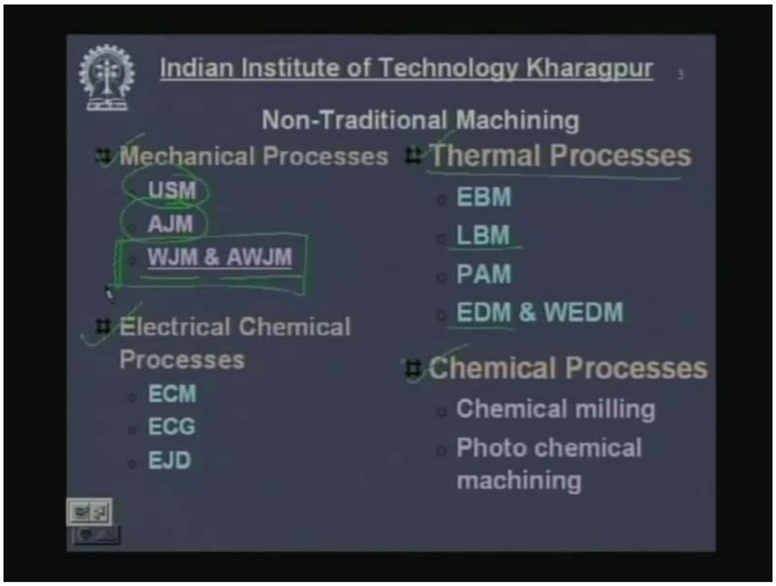

Now in non-traditional machining, the different processes can be grouped into different groups depending on what is the energy source. Already in the last lecture or the previous lecture before that we have identified that one such group is mechanical processes. One is thermal processes, electrochemical processes and chemical processes. Say for example; you may have heard about electro discharge machining, laser beam machining. They are the basic energy source which is relevant for the mechanism of material removable is thermal process. So, it is listed under that. Today we are going cover as I said water jet and abrasive water jet. They are the energy sources mechanical. Similar processes undergo mechanical process are ultrasonic machining and abrasive jet machining. Today, we will be concentrating as I said earlier on water jet and abrasive water jet machining.

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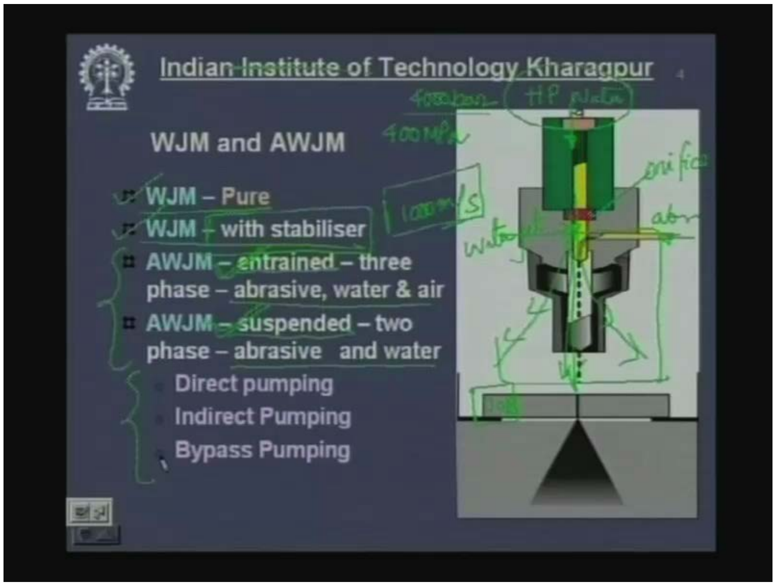

Now what is abrasive water jet or water jet machining? In both of them, very high pressure water so we require high pressure water. So this is the pipe which carries the high pressure water. How high would be the pressure? The pressure of the water would be as high as four thousand bar and you may question me how much is four thousand bar. Typically in a three storied building, if you have an overhead tank then in the ground floor you will get a pressure of around one bar. So four thousand bar is a lot of pressure. If you convert that into the stress unit, general stress unit four thousand bar is around four hundred Mpa. Most of the alloy carbon steels shear strength would be less than four thousand Mpa. So high pressure at four thousand bar is rather very very high. Then, what is done with the high pressure water? High pressure water is allowed to come out of a small orifice. How small is this orifice?

This orifice is really small. It is around 0.1 to 0.3 millimeter. So, the pressure energy of the water of four thousand bar gets converted into the potential energy. So once the water comes out of the orifice, the water jet is formed. So water jet is available here. What is the velocity of this water jet? If we use Bernoulli's equation were we will be going into in detail at a later stage. This velocity can be calculated as one thousand meter per second that means one kilometer per second. So, if you have to move from Kharagpur to Calcutta which is 120 kilometers at this particular speed it will take only two minutes.

So that is the nature of velocity that comes out in water and abrasive water jet machine. Now water jet machining can be divided into two groups. One is water pure water jet, another one is water jet with stabilizer. In pure water jet, this part of the schematic is not relevant. Water comes out and directly machines my job. This is my job. It directly machines it. How it machines? All of us have seen water falls. Just below the water fall, there is erosion of the granite or the rock. So, such low pressure water can also erode materials. This water can also machine jobs. However it cannot machine metallic alloys.

It can machine polymers. It can machine leather and stuff like that. The cutting ability of this water jet can be enhanced by adding abrasives through particular pipe.

So this abrasive mixes with the water comes out and this can also machine the job. Once again let us comeback to the pure water jet and with stabilizer. Pure water jet means it is commercially pure water. When it comes out, it flares it flares out because of increment of air from the atmosphere. As it flares out it cutting ability its amount of material it can cut definitely reduces. So we have to somehow control this flare. How do we control this flare? We add stabilizer, what are these stabilizers? These stabilizers are nothing but long chain polymers having higher molecular weight. So once we add those stabilizers with the water jet, the flare reduces. It becomes much more focus and we can use the total power of water jet for machining.

This is about water jet. The other part of the story is abrasive water jet. There are two different systems of abrasive water jet. One is called entrained abrasive water jet system and another one called suspended abrasive water jet system. Out of these two systems, entrained abrasive water jet is much more popular and widely used in the industry. Suspended water jet systems is also used however its penetration in the manufacturing market is not too high. In entrained water jet, it basically composed of it is basically composed of three phases, abrasive water and air. In suspended, it is composed of abrasive and water. Once again we will go later on into different variants of suspended water jet. Now what are the general experimental conditions?

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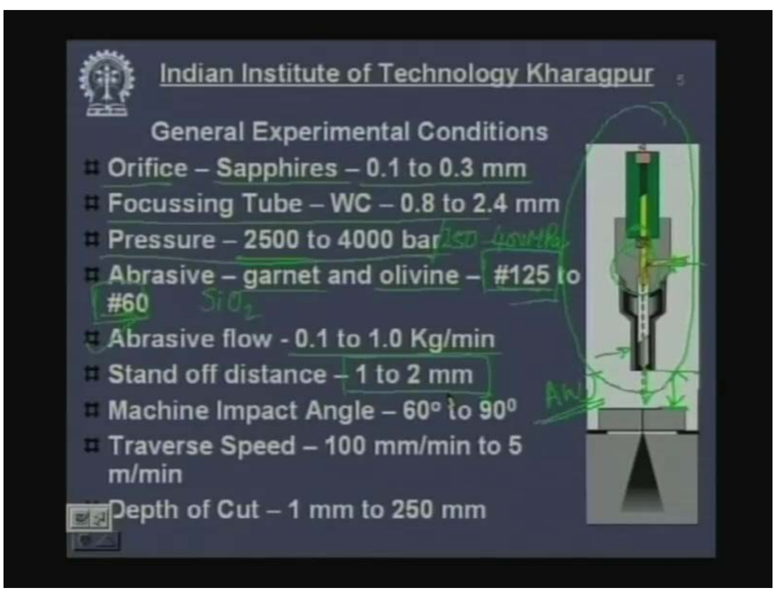

So what is this? This is a device. I have not yet named the device which issues high pressure abrasive water jet. This is called the cutting head. How it shows? I have explained briefly. Now there is an orifice which basically transfers the pressure energy of the water into kinetic energy of the water but generates the water jet. This orifice is made up of sapphire. Its diameter is around 0.1 to 0.3 millimeter. So, it is sub millimetric. In that the high pressure water is generated. After that, we have a mixing chamber. We will describe this one in future slides and you have a focussing tube. Within the focussing tube, the abrasives are added. So, this is my focussing tube. The inner diameter of the focussing tube is around 0.8 to 2.4 millimeter.

We have already discussed what kind of pressure we are using. The pressure of water is around two thousand five hundred to four thousand bar which is 250 to 400 Mpa. If you are converted into that unit, now what are the abrasives which are added here? Abrasives are nothing but silicon oxide or sand. Typically they are called garnet or olivine. Whenever we are specifying the material, we need to specify the size as well these are the size or abrasives which is used. This is mesh size 125 and this is mesh size 160. You have already come across. You have gone through the grinding lecture. So you know how much what do you mean by 120 mesh and what do you mean by 60 mesh? Now abrasives are being fetch. So I need to meter how much abrasing is being fed.

Generally abrasive flow rate is around 0.1 that is 100 grams to 1 kilogram per minute. Standoff distance: What is standoff distance? Any jet cutting process has stand off distance. This is the end of my focussing tube and this is my job. So this particular distance is my stand off distance and that stand off distance is generally one to two millimeter. You may ask me can I not have a standoff distance of 25 millimeter. Yes, you may have but when you have a standoff distance of 25 millimeter. You are going to waste your energy of the abrasive jet. The stand off distance you should be that much so that is there in no interference between the focussing tube and your material that you are processing but it should not be unnecessarily large. Typically in the industry stand off distance of one to two millimeter is used.

Next comes the question of impact angle. This is my impact angle that is the angle between my jet and the job. In this particular diagram the impact angle has been shown as 60 to 90 degree. It could have been inclined as well so inclined impact angle is typically kept at sixty degree to nine degree. Now what is the reason for inclining the jet if i need a cut along this particular direction then only I will incline the jet or else typically my inclination angle or impact angle would be 90 degree. Now traverse speed. If my jet if my jet is being issued like this, I would machine it in this direction. If the jet is stationary, I will only get a hole I am not interested in getting a hole I need to machine it, I need to slit it slot it.

So I have to give a velocity either to the jet or to my job. So that is called the traverse velocity or traverse speed. Typically in abrasive water jet machining, it is around hundred meter to five meter per minute, hundred meter hundred millimeter per minute to five meter per minute. Now how much is the depth of penetration. So what is this distance which is generally achieved in abrasive water jet machining? It can be as low as one millimeter. It can be as high as 1to 250 millimeter two millimeter in actual domain would be as least this much. So this is around 250 millimeter, so this is this long is rather long.

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Now let us go into how the system looks like. This is my photographic view of the abrasive water jet system. This is my cutting head. The schematic of which, you have seen already here. So this is the same thing. It is the photographic view. So through this the high pressure water is coming abrasive is added from this portion and abrasive water jet is coming out here and the yellowish substance that you can see is the job covered with water and abrasive. The whole this is nothing but the zoom view of this particular portion. So cutting head is this small. Below that you have your workpiece this could be your workpiece which you need to cut possibly along a complex contour. So, you need a CNC system. So this is the CNC system and this is the CNC table where the job is manual to get a particular contour. Any contour you want under the CNC control that you can get.

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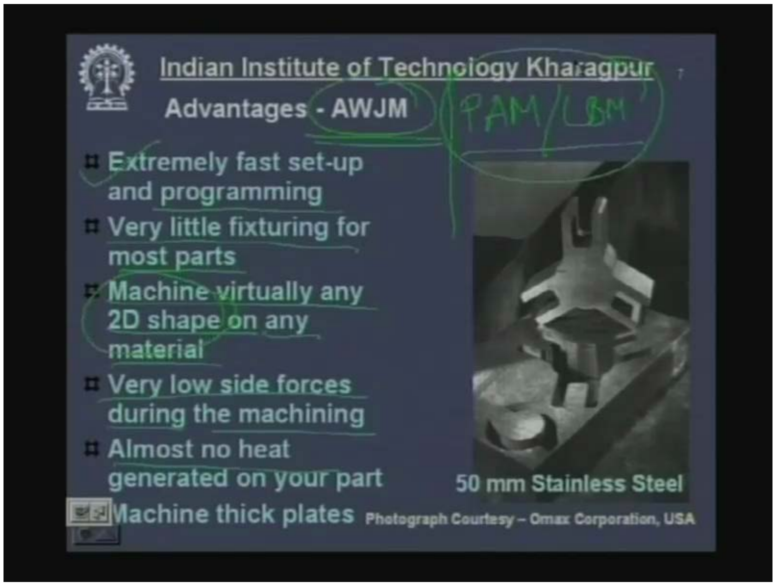

Now before going into the process description, let us go into advantages of abrasive water jet machining process. Compared to conventional machining processes as well as compared to non-traditional machining processes, it set up is extremely fast and as because most of the time a CNC is done, you can always do the CNC programming. So it is not going towards the hard automation but it is a soft automation you can even use it for batch production. There is no need that it has to be used under mass production situation. Very little fixturing is required as because most of the time, fixturing is almost nonexistent. It is a very good process technology which can be adopted for batch production scenario. It can virtually machine any two D shape on any material.

How can it machine any 2 D shape, because most of the time abrasive water jet system be having a CNC table along with it and because of its inherence properties, it can almost machine any material. We will come to that list after some time. It has very low side force. When it is machining an object, there is almost no side force. So you require very less amount of work holding device. So it can be implemented very very fast another great advantage of abrasive water jet system compared to other jet cutting processes like plasma arc machining or laser beam machining is that which is the last point. Almost no heat generated on your part. There is no thermal damage to the part even if your part is sensitive to heat, it can be machined. If it is made of plastic you can machine it. If it is made of glass fiber, you can machine it. There is absolutely no heat affected or thermal damage as compared to plasma arc machining or laser beam machining which is also a beam or jet process.

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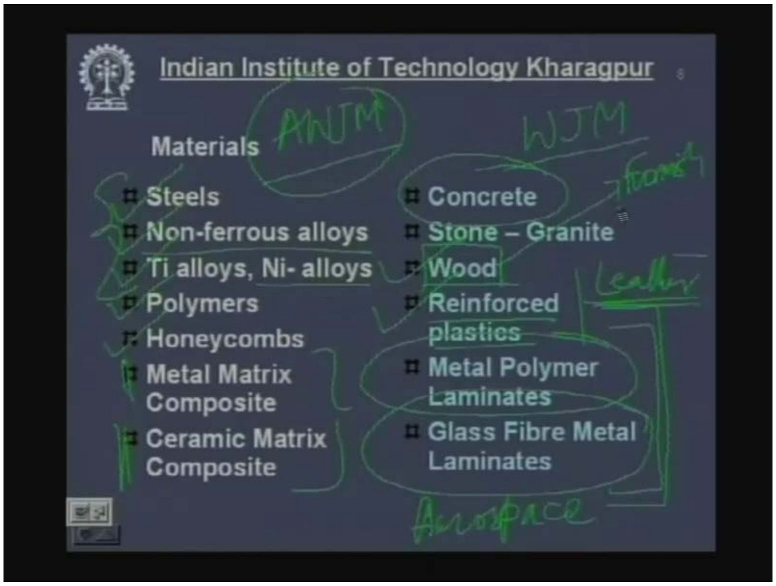

Now we were always saying that, it can machine any material. You go through this list you will be convinced. Now here they are in two different colours for a particular reason. Abrasive Water Jet Machining that is AWJM can machine steel. It can machine aluminium. Name any nonferrous material it can machine; super alloys, titanium super alloys, nickel alloys it can machine. Polymers it can machine. So it is it can not only the machine so called high strength alloys it can also machine polymers, honeycombs. They are very difficult to machine because the whole system distorts but they can be machined. Metal matrix composites and ceramic matrix composite. These are newer development. These have been developed possibly in last ten twenty ten twenty years. They can be very efficiently machined.

Now the other end of the spectrum is water jet machining. Water jet machine cannot be used for machining this abrasive water jet machine is required, then what for am I going to use water jet? It can be machined for reinforced plastics. It can machine wood. It can also to some extent machine. Say for example, leather and other kind of material, abrasive water jet machine can machine concrete metal polymer laminate glass fiber laminate. These two materials are very important materials for aerospace applications and they can be very efficiently machined by abrasive water jet machining. Water jet can machine wood, reinforced plastics, leathers. So in our leather industry, they do have lot of application. As they can move machine wood in our furniture industry, water jet does have lot of application. Now what are the applications?

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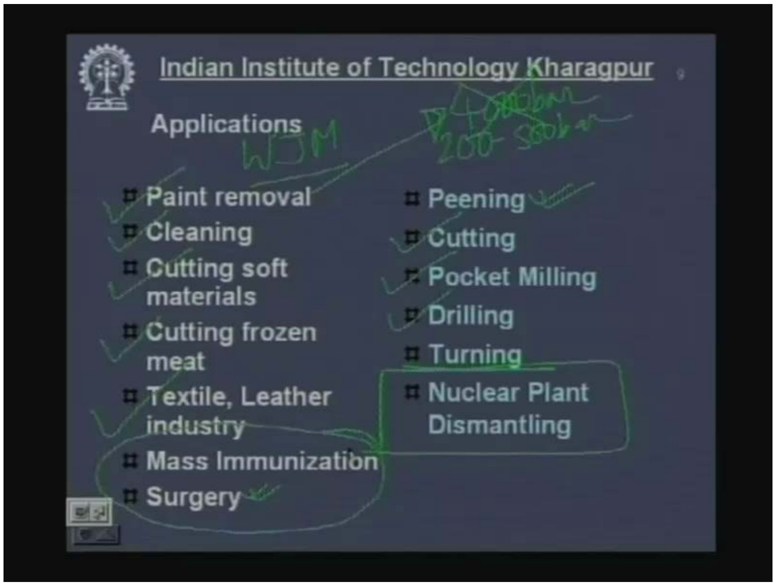

Once again they are in two different colors. So water jet can be used for cutting soft material only water jet not abrasive water jet cutting frozen meat. This may not be a very relevant application for our country, but otherwise it is an application. It can be used for machining textiles. It can be used in leather industry. It can be used for paint removal. However for paint removal, you do not require four thousand bars. You do not require such a high pressure. You require around two hundred to five hundred bar. Or else, instead of removing the paint, it will remove the material itself it can be used for cleaning.

Now there is another very important application of high pressure water jet or high pressure jet. It can be used for mass immunization. It can also used for surgery. I am not going into this because this domain is beyond the manufacturing. Now abrasive water jet machining can be use for peening for introducing compressive residual stresses. It can be used for cutting. It can be used for pocket milling, drilling. It can even be used for turning. Another very strategic application of abrasive water jet machining, is nuclear power dismantling. Now let us have a look at actual parts which have been machined by abrasive water jet.

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So these are few parts which I have selected. Now as you can see this is a very slender part having a less thickness and the length is rather high and there is integrating design. So abrasive water jet machine has machined this with such a good precision that integrated design has been kept. This one is a standard part with some holes these holes are typically of around three to four millimeter diameter. So abrasive water jet has machined it like this by trepanning operation. There is a circular part as well so this has been done using the circular interpolation. So this is from CNC part point of view are other complex part which can be machined using abrasive water jet.

These two parts shows what is the precision of the accuracy that you can achieve using abrasive water jet. This is basically a disk where some grooves have been cut and this one shows the same thing when it has been opened up you can see what is the level of precision that can be achieved with abrasive water jet machining. This one basically shows this this particular surface this particular surface which I am hatching. This is not vertical, this is slant. So abrasive water jet as I said earlier can be inclined, it can be made it can be inclined it can be made inclined by sixty degree up to sixty degree so that you can get an inclined surface. Now, we are gradually going into the composition of the abrasive water jet system.

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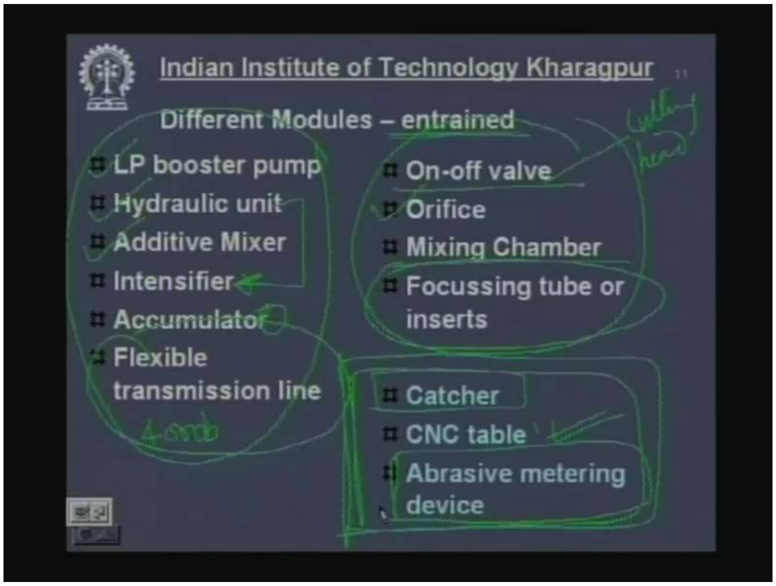

As I said earlier, that we will be mainly restricting ourselves to the entrained system because that is the most popular system. Now there are three parts here. This is one part. This is the other part and this is the other part. This particular list basically generates the high pressure water. So you have a low pressure booster pump, hydraulic unit, and additive mixture. This hydraulic unit drives the intensifier, you require an accumulator I will explain then you require a flexible line which can carry water at four thousand bar that water is brought to this particular unit. This is called the cutting head. This is called the cutting head. It is composed of on off valve which basically allows the water to come out of orifice or not to come you have a mixing chamber and focussing tube which basically focuses the water an abrasive together.

Once the water is available, it has already machined the job. Still it does have lot of energy, if you put your hand behind it your finger should be cutoff. So you require a system which catches the water that is the catcher. As I said initially you require a CNC cable and because you are adding abrasive, you also need an abrasive metering device. So these are the different modules which I described. Gradually we will go into pictorial description of them. So this part which I have discussed in the previous slide is here and

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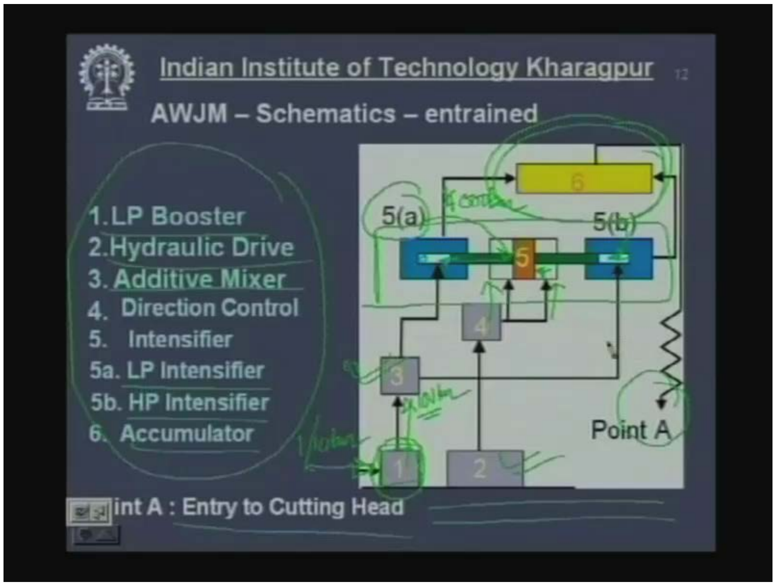

that is the pictorial description. So what are the things here? This is my number one LP booster pump- low pressure booster pump. This water is the plant water. Whatever water is available in your organization or a plant. This is possibly at one to ten bar depending on your municipal supply. This pressure is boosted using this LP booster pump to what value. This is typically boosted to around hundred bar then if required you can add additives why additives are added just remind you once again so that my water does not flare out this water goes into this part. This is the intensifier. Now intensifier is driven by hydraulic drive. This is my hydraulic drive.

What is this port? This is the direction control valve. At one time, it allows water to enter through this port. Now that the time, it allows the water to enter to this port. If water is entering to this port, it creates some pressure. So the cylinder goes in this direction and as because there is an area difference, I get a huge pressure of water at this particular port which is four thousand bar. Now this 5(a) is my low pressure intensifier which is this part 5(b) is the high pressure intensifier which is this part. 6 is accumulator this one. Now whenever this intensifier is reciprocating, what happens at this? Whenever it reciprocates, the velocity becomes zero. So there is a pressure drop. So, accumulator accumulates the water something like a fly wheel so that the energy becomes available all the time. Once from the accumulator, it comes out through this. This is entry to the cutting head. So this is my schematic description of the flexible tube which can carry water at such a high pressure.

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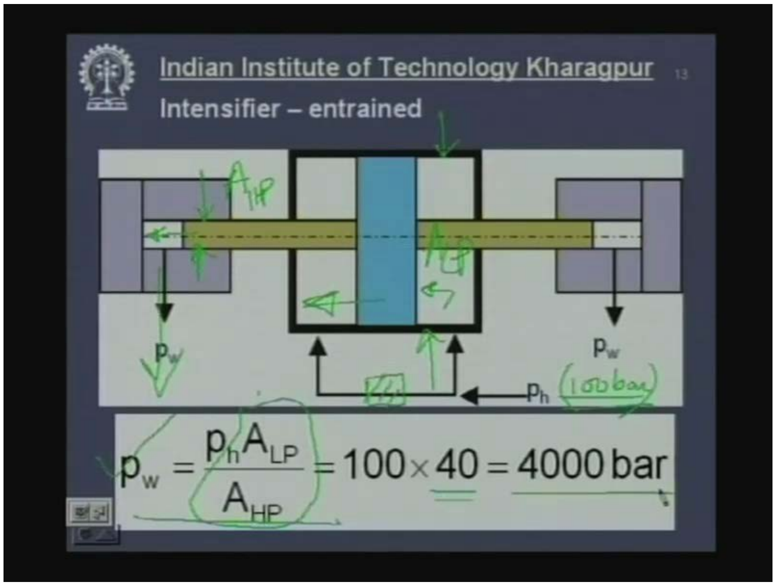

Now this slide explains the action of the intensifier in a better manner. So what do I have here? This 'ph' from where it is coming? It is coming from the hydraulic drive. What is this 'ph'? This 'ph' is 100 bar. Let us assume for this moment that there is the direction control valve and this direction control valve is currently allowing the water to enter this particular chamber. So what happens? This piston starts moving in this direction. So this one also start moving in this direction, from the force balance, very easily you can see the water which will be coming out of this, that pressure will be much higher. Why it would be higher because this area AHP is much less than this area which is ALP. Typically in commercial system, this area is around forty. So if this pressure is hundred bar the water which comes out of this will be 4000 bar that is the basic technology by which we generate such a high pressure. There are different variants of this technology. This is called a single acting intensifier. We have double active intensifier as well. So from the intensifier where does it go? It goes to my accumulator. From the accumulator, it goes to point A which is entry to my cutting head. Where is my cutting head?

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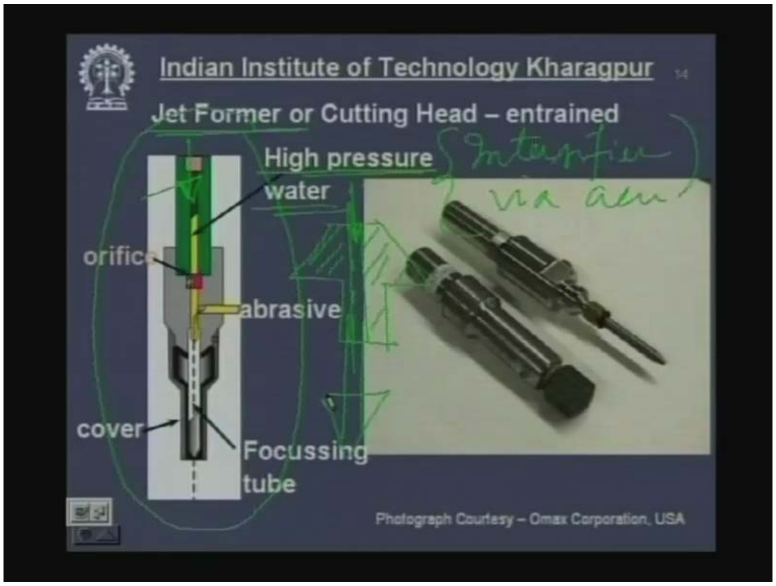

This is my cutting head, which is also called the jet former. jet former. We have already identified or discussed it but pretty hurriedly. So here I have high pressure water where from it has come it has come from the intensifier via accumulator so water is available here at four thousand bar. What is this? This is my orifice. How actually the orifice looks like? It looks something like this. So you have a central hole, a very small hole through which the water comes out which I have represented here by this one. So water on this side is issued from the orifice as a jet. Let me clear it once. So, water you received from the orifice as an abrasive water jet.

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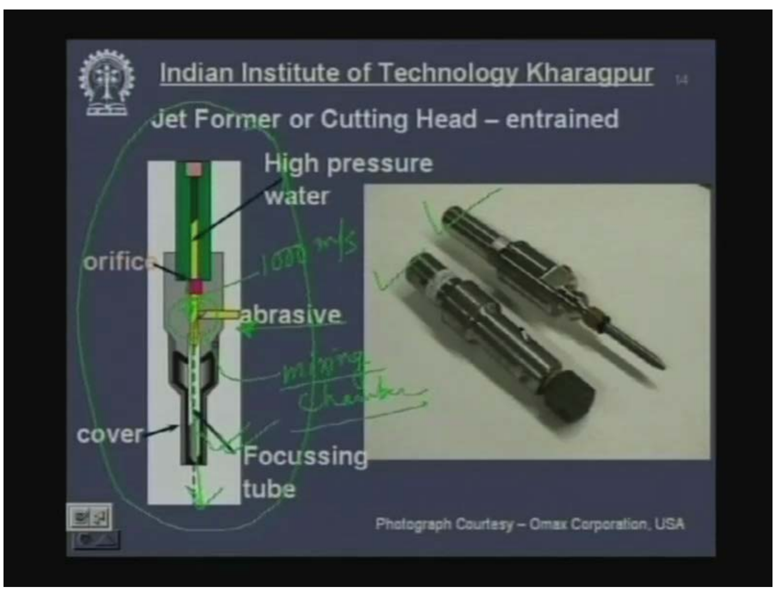

This water jet velocity will be very high, this much. Now these abrasives are being added their being added in a chamber which is called mixing chamber. If you remember correctly, this we have already identified under the list of modules. So what happens these abrasives are being added at a very low velocity. So once they are added, they interact with the water gain momentum come out of this focussing tube. This is called the jet former. This is the schematic of the jet former and here you will have two typical jet formers which are commercially available.

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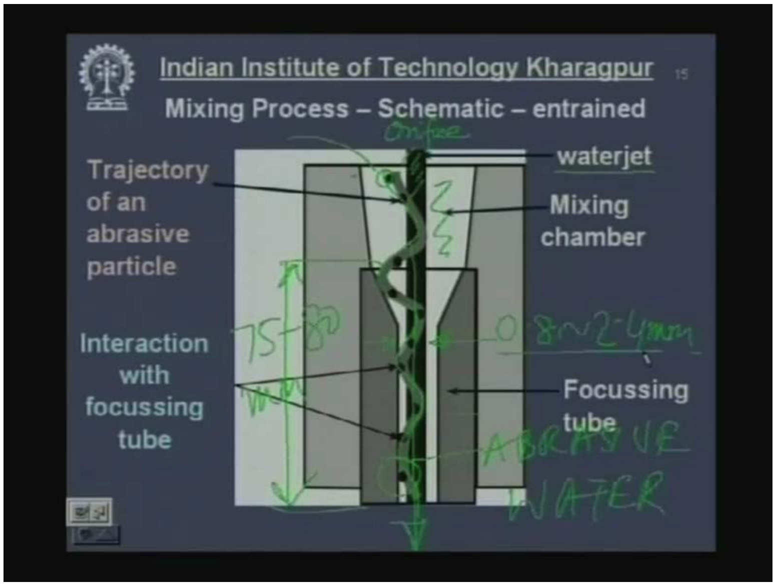

Now I have described in this, what it does. How the mixing process takes place? This is the water jet, this black part of it. So this is my water jet. Who has produced this water jet? The orifice has issued this water jet, this is coming. This particular part this particular part is my mixing chamber. So abrasives are coming here. This is one abrasive. So once it is added, it tries to enter their water jet, cannot enter whenever it tries to enter it comes out. So the mixing process takes place by a series of interaction with the jet and the mixing chamber and the focussing tube and gradually this comes out at the end of the mixing chamber, the velocity of the abrasive phase and the water phase. They are more or less same. So it depends on what should be the length of the focussing tube. Typically 75 millimeter to 85 millimeter length of the focusing tube is used. Already I have said, this is the inner diameter of the focussing tube which is 0.8 to 2.4 millimeter. It is chosen depending on what kind of application you are using. So this slide briefly describes the mixing process.

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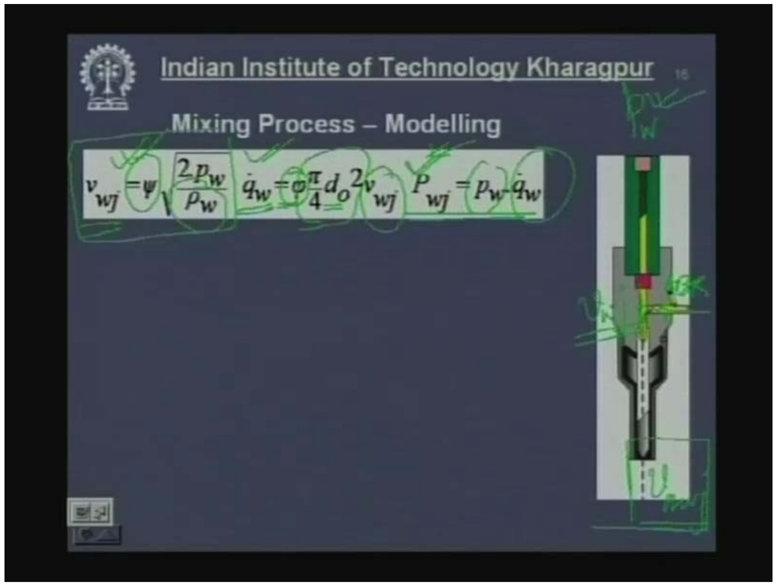

Now we are going to model the mixing process. This is the process description but my interest is can I mathematically model it? Yes we can do it. What would be my intention? My intention would be here is my pressure of water ‘pw’. Can I estimate ‘Vawj’ velocity of the abrasive water jet that is my intention. So that is called mixing process module. The first equation is basically a very simple equation, Bernoulli’s equation. Please concentrate here. What does it say? This equation says the pressure head. This pressure head is being converted into ‘Vwj’. See this is not Vwj, this is Vawj. So where is this Vwj? Velocity of the water jet which is coming out of the orifice so it is here. What it says?

The kinetic pressure head is being converted into kinetic head, so Vwj is root over 2 pw divided by rho w. ‘pw’ is the pressure of water ‘rho w’ as all of you know, it is the density of water. So what is this term? This is the velocity coefficient of discharge. All of you must have gone through field mechanics. So you know what it is? Now once I know the velocity of water, later on I will require this equation. So I have derived them. What then here what is this? This is the volume flow rate of water. How do I get it? Any volume flow rate through a channel is nothing but the area into velocity. So ‘Vwj’ area of any circular cross section is pi by 4 do square. So ‘do’ is the orifice diameter. Now who is this guy?

This guy is the coefficient of vena contracta. All of you know, whenever water flows through a particular orifice, there is vena contracta phenomenon. There is contraction as it comes out. So this is that particular coefficient. What is this? This is the estimation of the total power of the water jet which is pressure into volume flow rate. But our intension was to get Vawj. How to get that? Already we have done the job at least to some extent. We have got the velocity of water. Now after the water comes here what happens. Abrasive is added here. If you remember abrasive is added. So, water jet and abrasive interacts which has already been explained. How do I model it?

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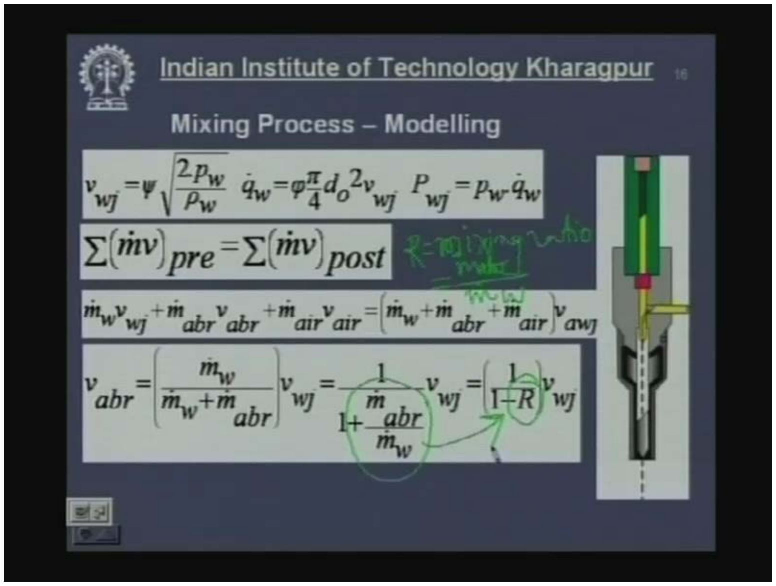

I model it with a simple assumption. What is that assumption? Assumption is the momentum before mixing and after mixing. Momentum here and sorry momentum here and after mixing, remains conserve. So momentum is conserved that can be written like this. Moment this is the momentum of water jet before mixing, this is the momentum of may abrasive phase. Before mixing, this is the momentum of air phrase and this part is after mixing one it is coming out of this particular position. Now here, the mass flow rate as such is less. So there momentum is almost zero. sorry sorry sorry momentum is almost zero. Here also the same for air goes zero. When the abrasives are being added, they are being added at a very low velocity, water jet velocity.

If you remember is thousand meter per second, this is very very low. So this term is also very small. So neglecting these terms what you can get? You can get the velocity of the abrasive water jet. So, this is my velocity of the abrasive water jet. This term was zero this is also very small so these two terms basically cancels out. So I have this one which is this into this and on the denominator, this term become zero. So denominator becomes mass flow rate of water plus mass flow rate of abrasive. By modifying this equation we get the final expression which is one by one plus R into vwj. Now all of a certain, I has introduced a term which is R. What is this R? This R is called mixing ratio. What is this mixing ratio? If you study this, this is basically mass flow rate of abrasive divided by mass flow rate of water. It is already here. I have tried to explain there as well. So this is my mixing ratio. This is an important parameter in water jet machining, abrasive water jet machining.

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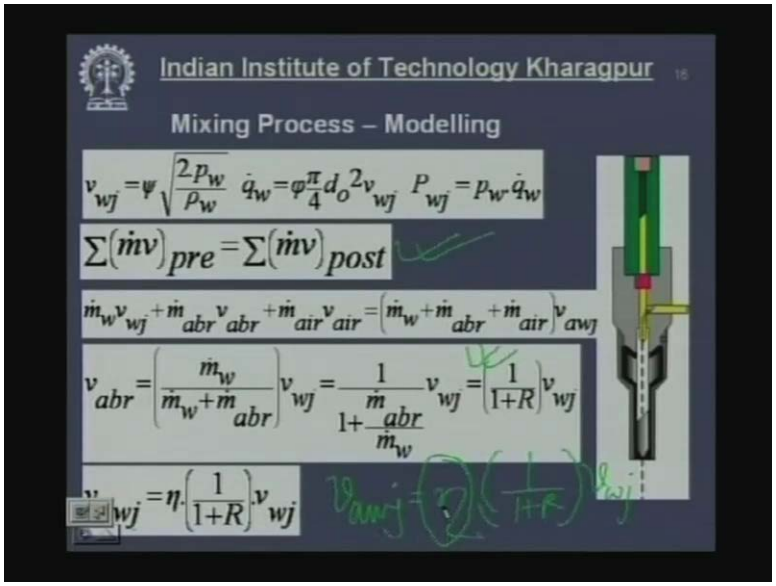

Finally we have assumed that momentum is conserved. But, actually momentum does not get conserved. So the abrasive water jet velocity as given here Vawj is expressed as eta times one by one plus R into Vwj. So what is the difference between this equation and this equation? I am introducing a term 'eta'. This coefficient takes care of loss of momentum. Why the loss of momentum takes place? You have already seen the mixing process is highly a process full of collisions. During such collisions, there is some loss of momentum.

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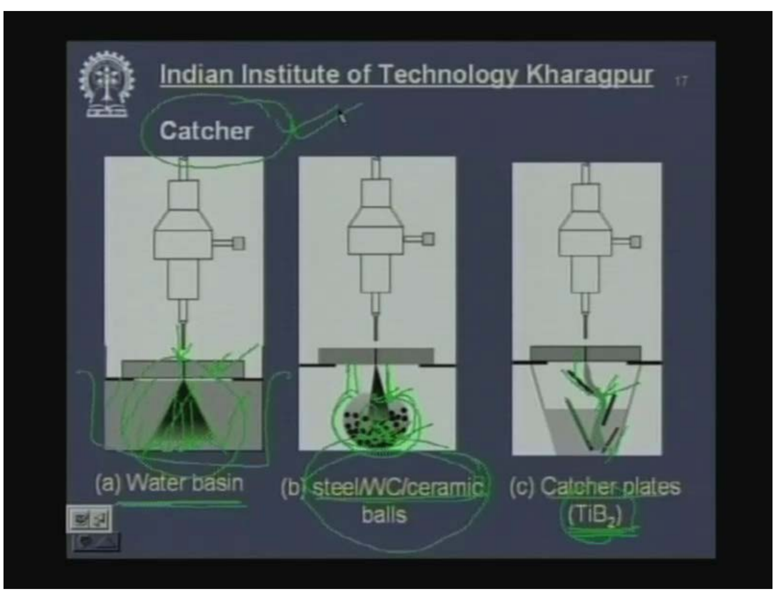

Now mixing has occurred. This is my jet coming out. It has machined my job. Still there is sufficient energy of the water jet or abrasive water jet. This energy so much I can say from my practical experience, it can cut through human flesh. This energy of the abrasive is so much. So what do you have? You move this spent abrasives. They need to be restrained somehow. So that, they do not damage your workshop, your machine tool as well as most importantly you are. So we have module called catcher, which basically restrains that abrasive water jet velocity. We have water basin catcher is the simplest of all.

You put a tank in that tank, put lot of water. So the abrasive water jet interacts with that water and looses its energy but the water tank is a very bulky thing. You can have a small picture kind of thing. In that, you can have steel tungsten carbide of ceramics balls. Why because these are wear resistant balls. They can interact with this ball and loose their unutilized energy or you can have plates. So that, it interacts with the plate and in the process looses its energy but all this plates this balls should be wear resistant. So titanium diboride plates are used. Ceramics or steel balls are used or else, water basin is used for restringing the spent energy of the abrasive water jet and this is called a catcher.

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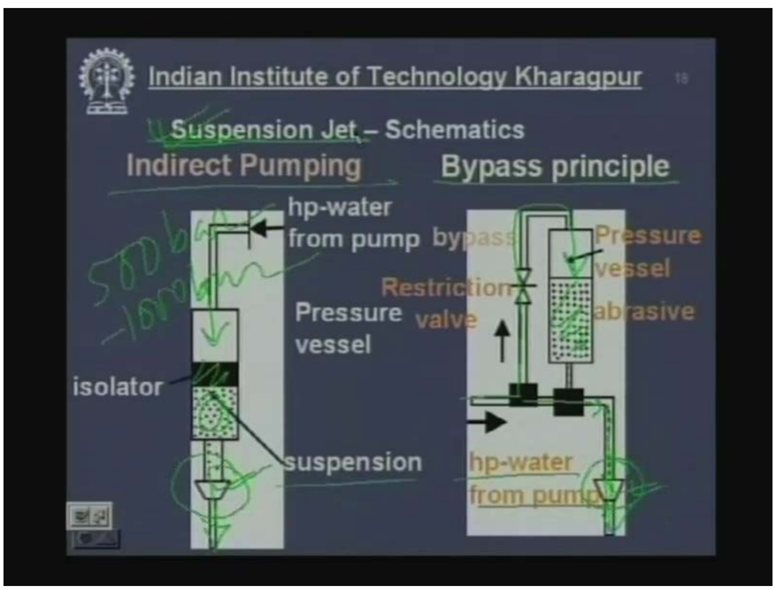

Now before going into the mechanism of material removal, let us come back to another kind of abrasive water jet which is suspension jet. There are three different variants. One is indirect pumping, one is bypass principle or bypass pumping, another is direct pumping. As I said, suspension jet is commercially not that popular as the entrained jet entrained abrasive water jet which we are discussing that is for here in suspension jet typically the water pressure is not that high. It is around five thousand five hundred bar to one thousand bar in indirect pumping you have a slurry premix slurry, where the water is directly pump using an isolator.

So the abrasive water jet comes out here. In bypass pumping, you have a premix slurry the water comes here through a bypass valve as well as it get mixed up and then in comes out through the orifice as because the orifice is handling both water and abrasive phase. The wear strength of this orifice are to be very high. They are they are to be made of ceramic having tungsten carbide orifice is not sufficient. In abrasive water jet machining, orifice does not handle abrasive entrained system. It only handles water. Still we use sapphire orifice. As I said this suspension system is not very popular because it has been introduced much late as compared to entrained system.

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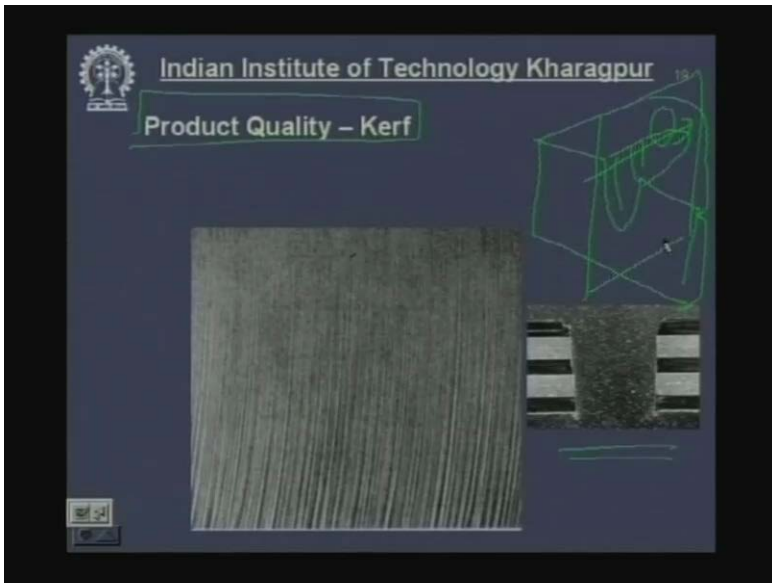

Now before going into the mechanism of material removal, one very important thing is the product quality. So, let us concentrate on product quality. Whenever you manufacture, we manufacture to get a particular product which should be a useful thing to the society. Now this is the scheme this is the photographic view of the kerf. What is the kerf? Say for example; this is the kerf that I have machined. My jet was here and is being even a velocity like this. So this is the front view of the kerf and this view is a longitudinal view. So as if, I have cut it with the plane like this. So these are the two views. This is my front view. This is my longitudinal view. So what we can see in the front view, the first thing that you can observe is that I intended to cut it normally but it has cut in a taper. So I need to characterize this taper. This is an important deviation. If I do not know how much is the taper I cannot control my quality. Another very important thing in my longitudinal section is that

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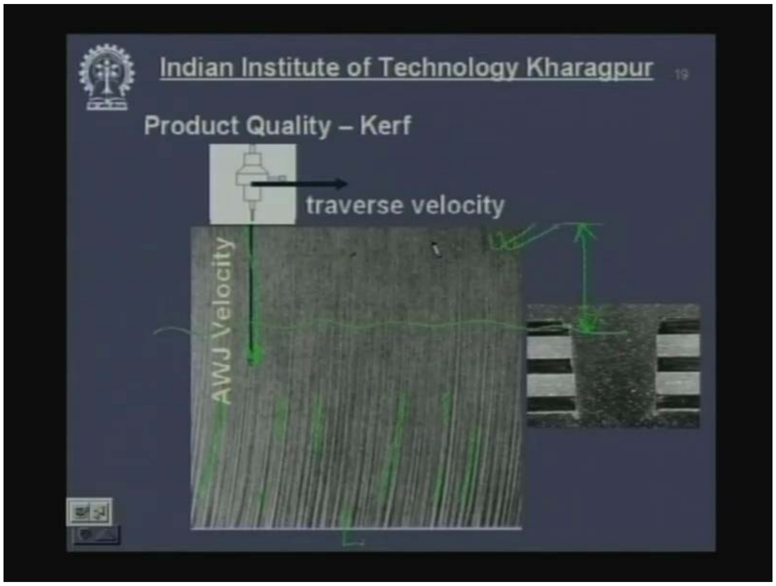

This is my cutting head. This is my traverse velocity which is being given to the cutting head. The water jet is coming out in this direction. So, this is the schematic and this is my longitudinal section. What can you see in the longitudinal section? In the longitudinal section, the upper part this part is rather smooth. The surface is very good but the lower part you have lot of mark. Can you see them and they are periodic. So, the mechanism of material removal would be different now if you require the surface to have a smoothness, then you have to set your parameters accordingly.

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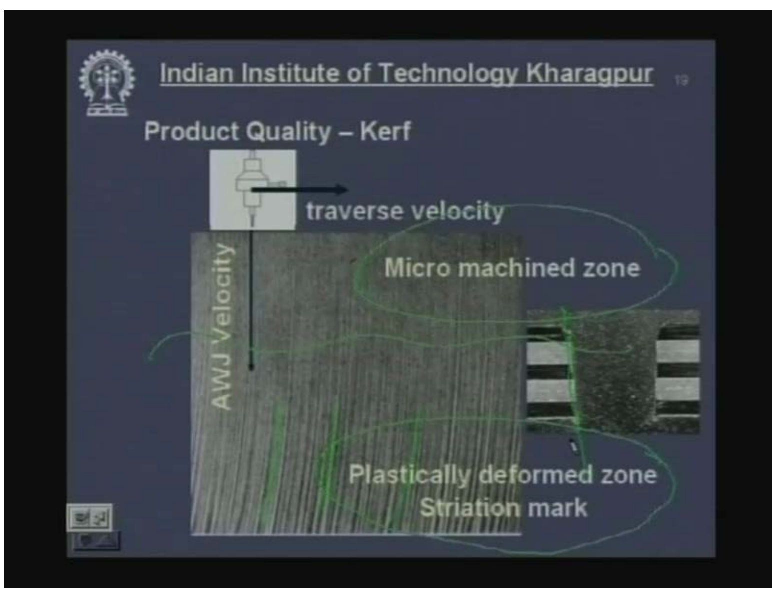

Now this upper part is called micro machined zone and the lower part is called plastically deformed zone is particular one and you can see this mass. These are called striation mark. So what is the important conclusion of this slide? You have taper. You have smooth micro machined zone you have plastically deformed zone having striation mark depending on what is your requirement, you have to set your parameters accordingly.

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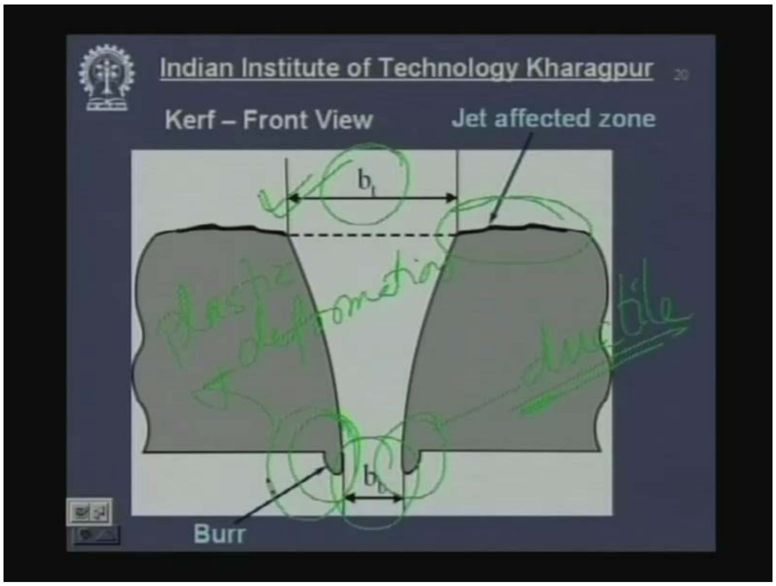

Now this is a schematic of the front view. Not only you have taper as it seen here, you also have two more things jet affected zone and bar formation. This bar formation is typically important whenever your machining ductile materials like titanium alloys, steel something like that. If you are machining glass, it will not be there. If you are cast iron it will not be there. These bars are typically formed because of plastic deformation. Now these particular slides also show one more thing. What does it shows? It shows the top width of the kerf and the bottom width of the kerf and they are different and they needs to be characterized in abrasive water jet machining process.

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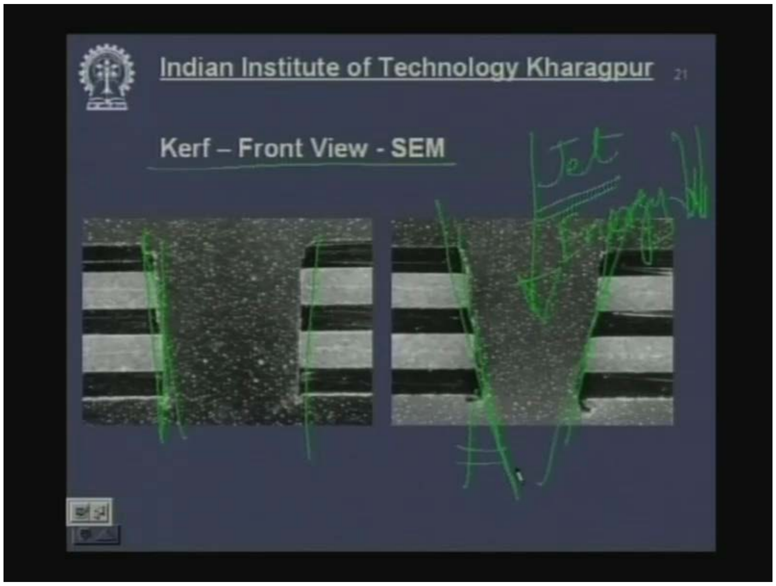

Now you are coming to the front view of the kerf, this you have already seen. Here also, depending on what was the process parameter setting, the tapers are different. If you look closely this taper and this taper are different. What could be your conclusion? Your conclusion would be possibly the jet. While machining this was not that energetic energy part of it. Its cutting ability was low. So it has given you more tape. Moreover another important thing to see is you have bars. So when you are cutting with a machining with a abrasive water jet have having less energy, it will form bars. Here the bar formation is less. Now you can also see a cut from the back side.

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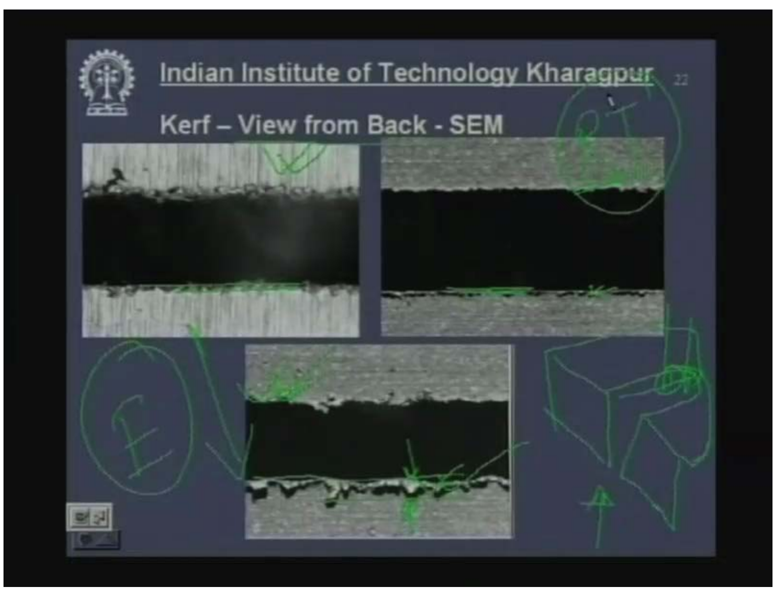

Let us see how does it look like? So what is this? This was my jet. It was cutting in this direction. I am looking from the bottom. So view from the back. So what is there? Here again, the back side looks different. Here it is very good. Here to some extent, bar formation is there. Here not only there is bar formation, there is another important thing what is it? See there is variation. So much of variation in the definition of the geometry. So once again what could be the reason? The energy content of the cutting ability was low in this one and was definitely much better in this. But, there are issues which have to be kept in mind. If you are using abrasive water jet for something called rapid tooling, then you should not have such bars. Rapid tooling would definitely be covered in some other in rapid prototyping, if you have a subject like that.

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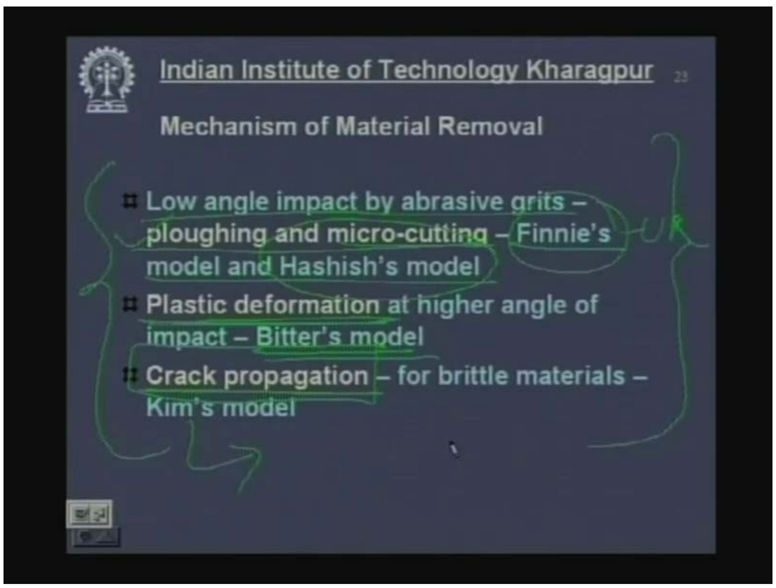

Now let us come to mechanism of material removal. All the time, we are seeing it is getting removed. Why it is getting removed because of erosion. Basically there are three distinct mechanism of material removal. One is low angle impact by abrasive grits. This causes ploughing and micro cutting. Very similar to grinding phenomenon, but grinding with loose abrasives. This has been studied by Finnie, a person from UK has studied it long back and it has been adopted by Hashish within abrasive water jet phenomenon. There is plastic deformation. Already I have shown you, at the bottom of the kerf, you have plastically deform zone rather than machine that has been studied by Bitter, then if you are machining glass of ceramics, not only they would be micro machine, sorry micro cutting would be there or plastic deformation would be there.

There could also be crack propagation which has been studied mainly by Kim. So, if you are interested in doing your research you can refer to the work of these guys for a better understanding. However these models are very sensitive to the choice of parameters. So they are very involved model. Their base is in science, but to the shaft floor guy you require a much more easier model which will come,

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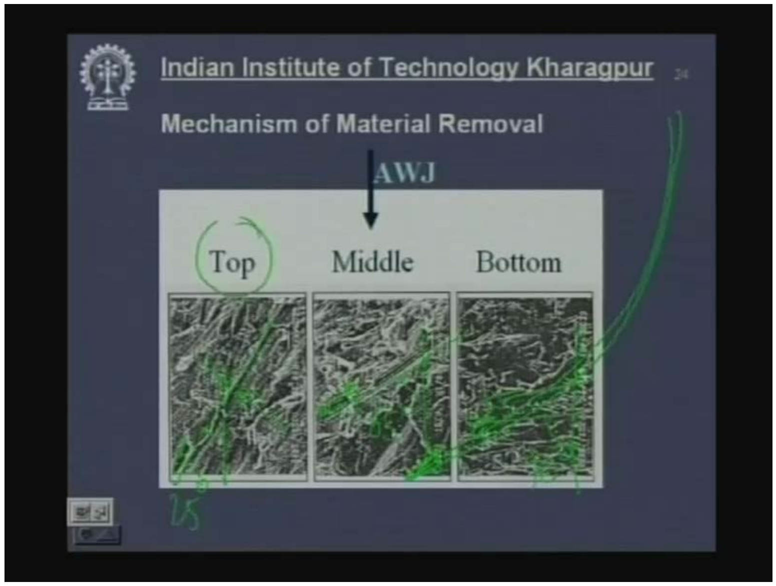

Now these few slide shows what is the evidence of micro cutting can you see? This is the top of the kerf. Here you have a micro cutting in this direction. What is the angle? Angle is possibly 25 degree. As you go to the middle, the jet looses its energy the angle is much higher possibly around 65 degree. At the bottom, abrasives are flowing like this so the angle is almost 90 degree. So as the abrasive jet penetrates, as it penetrates, it changes its local impact angle as it looses its energy. But, there is clear evidence at least in this particular slide that there is micro cutting, there is ploughing that is side deformation

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and in the next slide, I can give you the evidence of cracks. This is the special material I will not identify this material for some reason. This is the special material which has undergone cracks. Can you see that? This is the brittle material. It is a complex material which has undergone cracks, because it is brittle. So we have got evidence of micro cutting. We have got evidence of plastic deformation and for brittle materials we have also got evidence of tracks. You have cracks here. You have got fracture here. So all this leads they occurs in case of brittle materials.

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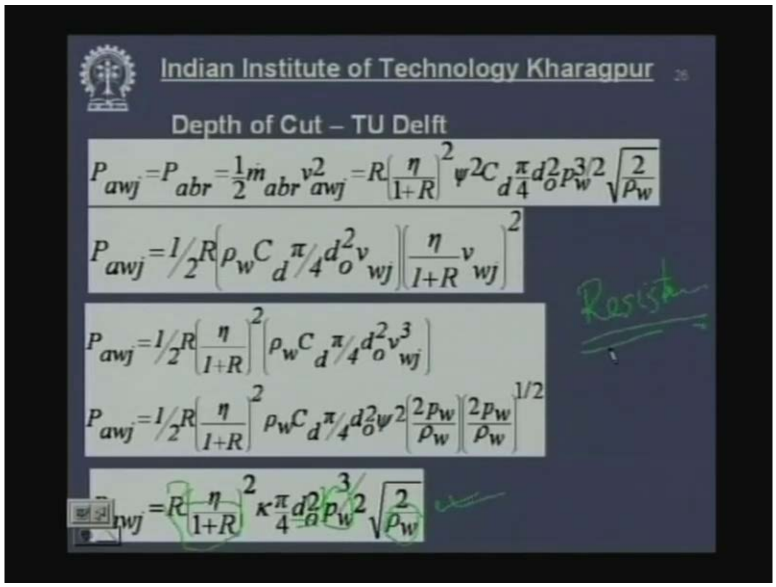

Now let us come to a model, which is rather simple. It is not so involved as in as proposed by Finni or as proposed by Bitter and others. This model has been developed by TU Delft. What is the model? The model is very simple. They try to estimate how much is the power of the abrasive water jet? Once they estimate that, they divide that by the resistance of the material. If these two quantities are known you can find out, what is your material removal rate or what is your depth of penetration? So what does it say? This is my power of abrasive jet 'awj' first assumption. The power of abrasive water jet is equal to the power of abrasive. Water phase does not contribute towards any cutting.

When you are cutting materials like steel, concrete, metallic alloys, ceramics. If you are cutting leather, that is a different thing but we are trying to develop depth of cut model for abrasive water jet. So these two things are same. The abrasive water jet power is equal to the abrasive power. Water phase does not contribute. What is that? ?That is nothing but the kinetic energy of the abrasive water jet half mv square. So this is nothing but half m dot abr into va awj. Already we have derived the equation for this one. Ultimately we will come to this particular equation but we are deriving it one by one. Now mass flow rate of abrasive. Earlier I have introduced a term called 'mixing ratio' what was that? That was m dot abr divided by m dot w, ratio of mass flow rate of water sorry abrasive to mass flow rate of water. So if this is R how much is this. This is nothing but R into this that is what I have written here.

So this half stays there of R into this R comes here. What is mass flow rate of water mass flow rate of water is density into its volume flow rate. You can you you can all let it see this is my area of the orifice this is my velocity of the water jet and what is this? This is the coefficient of this chart of that particular nozzle. So this gives my half m dot abr this part of it ‘Vawj’ already we have derived this equation. So this is nothing but eta by one plus R into Vwj square. This was in a different form. But, it is a very small derivation which you can always incorporate. So at this stage I can derive what is this. Let us go further.

Now what I am doing is that I am adding I am basically assembling these two velocities. So the velocity power becomes three, area of the orifice stays here. ‘Cd’ stays here. ‘rho’ of the water stays here and this ‘eta’ plus eta by one plus R I have taken it outside and by doing a very simple simplification, you can arrive at this particular equation. What does it say? It says power of abrasive water jet is related to power of water. Basically, it is related with the power of three by two. It is true. It is also related to the orifice diameter with a power of two. It is inversely related to ‘rho w’ with a power of half. It is also relates the complex manner with the mixing ratio. So with this equation, I can estimate how much is my power of abrasive water jet. Now I need to bring the resistance part that is offered by the material that comes in next slide.

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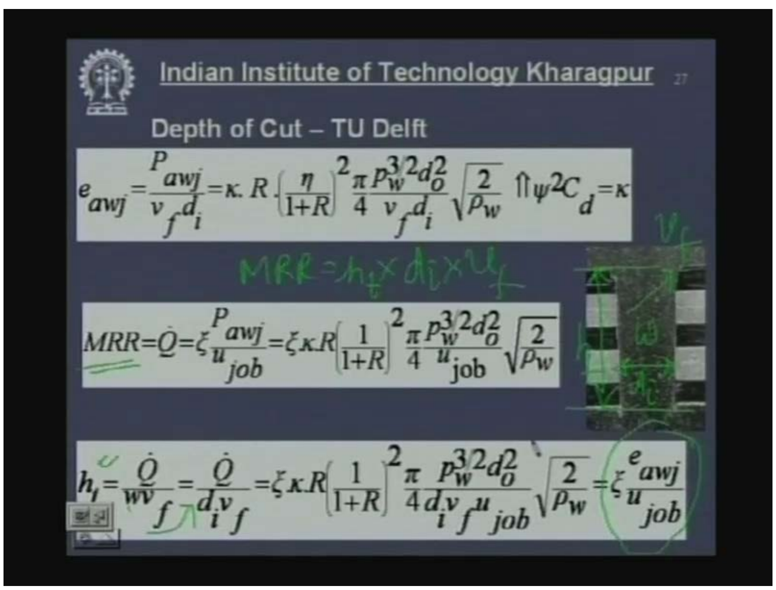

So what I am trying to predict is this one. This is my depth. Why do I need to predict it? Because, for a given set of parameters if I can predict it I can easily machine it or else I do not know what should my parametricity so this is very very important. So what do I have here this particular equation basically tells you what is the energy density. It is nothing but power of the jet divided by how much area you are generating. This is the width of the kerf which is the inset diameter of the nozzle diameter which was identify earlier as around 0.8 to 2.4 millimeter. Is it not? So this is ‘di’. How fast I am machining it. I am machining it at a rate of ‘vf’ thus I am generating an area which is ‘vf’ by di

So this one is nothing but the how much is my energy density. Now next step next step says how much is my material removal rate how fast I am machining how do I get it? I simply divide the power of the abrasive water jet by the resistance of the material. What is this u job? u job is the specific energy of the material. Generally, it has been seen for metallic alloys like aluminium steel, it is somehow empirically related to our Young's modulus. Typically, it is E by fourteen provided you specify it in appropriate units. So this is what the cutting ability and it is how much the energy I required. So, if I take the ratio, what do I get? I get the material removal rate. Once I expand it, it takes a form like this.

Now if you look closely, I have introduced a term zeta. Why I have introduced a term zeta? I will come to that after sometime. So after material removal rate from material removal rate now I am trying to get 'ht'. How much is my 'ht'? This is my 'ht'. What is my width w or di? How fast am I cutting 'Vf'? So how much is my material removal rate? 'ht' this much into 'di' into 'Vf' that is what is written here, ht into w or di into Vf. Now w is replaced by di. So simply you will get a final equation which is like this. Now whenever we machine, whenever we manufacture, what would be our intension? Our intension would be how fast can I machine? To what extent, can I machine is it not and moreover my product quality should be as good as possible.

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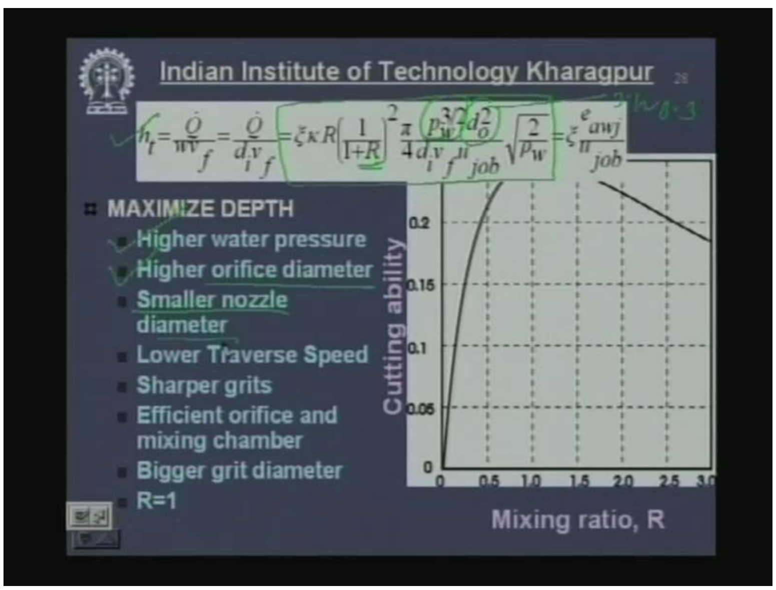

So our next intension at least one of them. How to maximize depth of cut? Any practicing engineer, any manager would be interested machining as fast as it possible. Because, it is quite often directly related to your productivity. So what is my objective? My objective is to maximize my depth. How can I do it? This is my equation. Once again, this is my equation. So you need to concentrate here. So first what it says? Increase water pressure. Does it say the same in the equation? Yes, look here. Your 'ht' is related to water pressure. If you increase water pressure, your depth of penetration is going to increase higher orifice diameter 'do' orifice diameter as I said is 0.1 to 0.3 millimeter. So, try to use as large as possible, but there is an implication of using higher orifice diameter. As you increase the orifice diameter, it also affects the material. Sorry mass flow rate of water, which indirectly affects R. Smaller nozzle of diameter. What is smaller nozzle of diameter?

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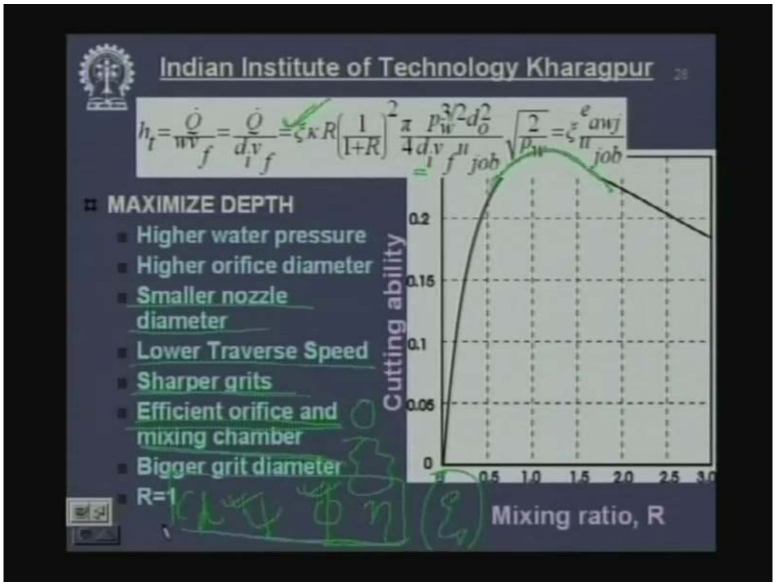

This is, if this 'di' is less, definitely your material removal would be much higher. Your 'ht' would be much higher because this is in the denominator. So this is the same thing, smaller nozzle diameter so 'di' is in the denominator, lower traverse speed definitely if you machine at a less speed you will be able to machine. You will be able to penetrate more. This is my nature of the curve, then sharper grits. I have never talked about the shape of the grit definitely you can understand if you take a blunt knife, you would not be able to cut a vegetable. If your knife is sharp, it would be able to cut it much easily. Your efforts require would be less.

Similarly grit can be totally spherical or it can have irregular shape or it can be sharp. This zeta basically incorporates that sharpness of the grit. Efficient orifice and mixing chamber. We have talked about quite a few coefficients one is this. Phi, psi, eta and zeta. This talks about the material sharpness. What are these? These are the velocity coefficient. This is the contracta 'Cd' was there which was discharge coefficient. If your orifice and nozzles are efficient and these values would be very near to one. So that is also required.

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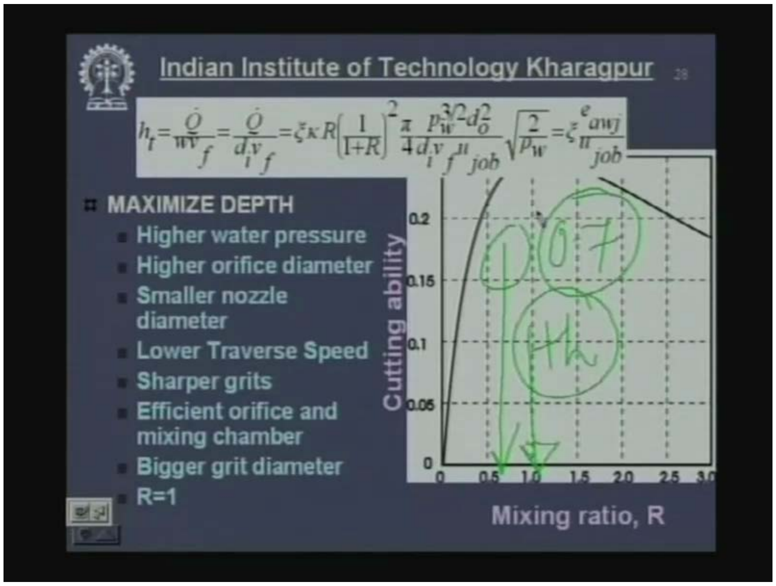

Grit; bigger grit diameter. Bigger grit diameter is not reflected here. However it has been seen for the same energy level. If your grit diameter is higher, then also this tends to be higher and you get a higher penetration. Another very interesting thing, what should be my mixing ratio R 1? Generally, it is never said go on increasing abr mass storage of abrasives no. If you differentiate this equation, with respect to R you will see a value of mixing ratio of one the maximum cutting ability is etching. However, this is theoretical model. Practically it has been seen it is not an one. This is theory, practically somewhere around zero point same seven value or R this occurs.

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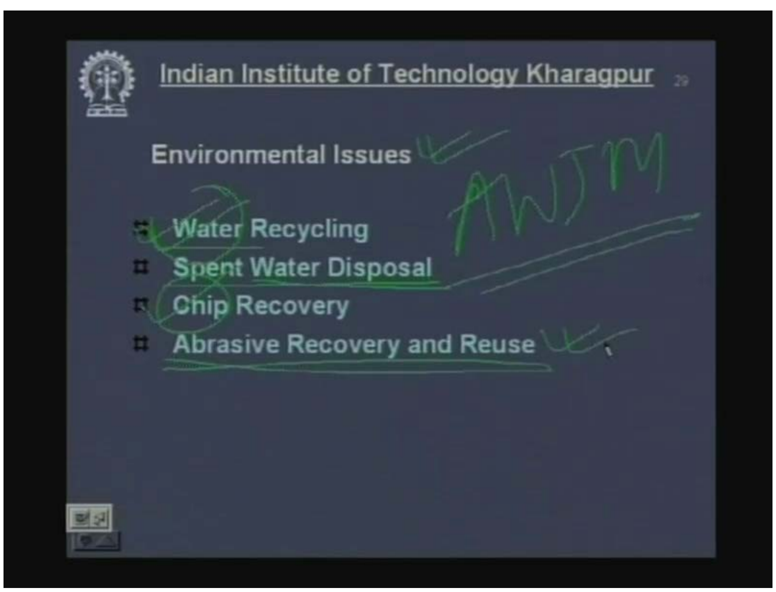

Now let us come to the limitations, I would not say the limitations but environmental issues of abrasive water jet machining. You are using water. So you need to recycle them we should not use any manufacturing process which ultimately pollutes our environment because we need to preserve our environment not only for us, but for our future generation. We should not dispose the water here and there. So, this also includes economic cost. Chip recovery is an issue. Whenever we are machining chip and water they are getting mixed up, we should through them and pollute the environment. Still I would say abrasive water jet machining is rather a friendly process or environmentally benign process but there is also the issue of abrasive recovery and reuse.

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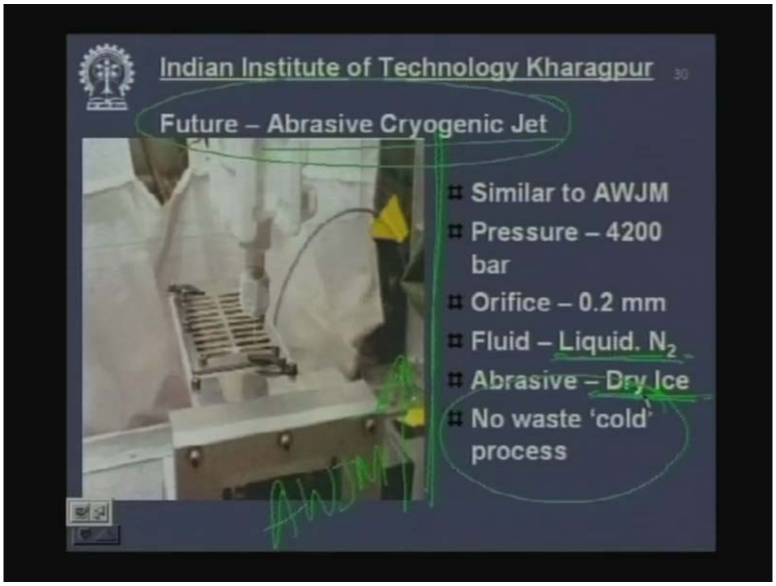

It helps us in reducing cost as well. Now, this is the future of abrasive water jet machining. This is not called abrasive water jet, rather abrasive cryogenic jet. Instead of water, liquid nitrogen is used. Instead of abrasive, dry ice or carbon dioxide is used. You do not have any waste after you have machined. Absolutely, no waste is there. So possibly this is the future where abrasive water jet is gradually move in towards. The water is replaced by liquid nitrogen and the abrasives are that of dry ice.

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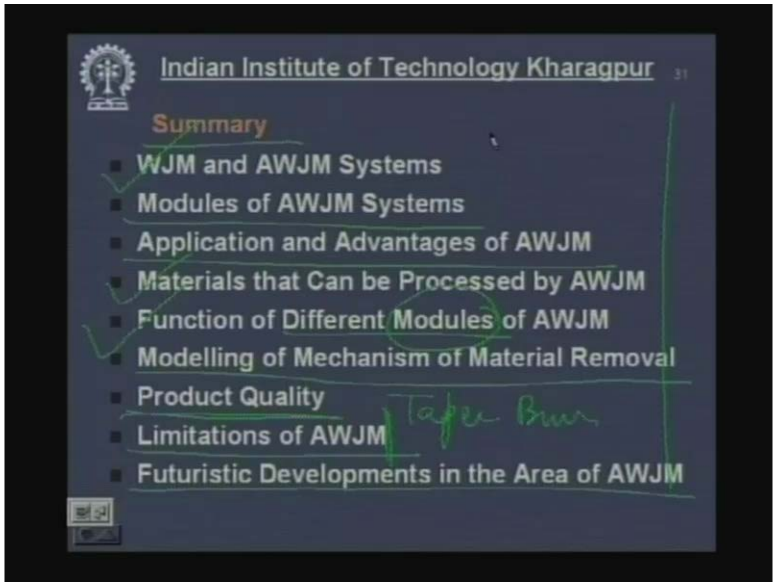

Now let us come to the summary part of it, what we have learnt today. We have learnt about abrasive water jet machine as well as water jet systems. Different modules of abrasive water jet systems, applications and advantages of application water jet systems, their materials, functions of different modules, not only identify module but their functions modeling of mechanism of material removal. This is very important because once you have the have the model, you can tryout that model to say parameters. You also know the product quality issue taper is there, bar formation is there. If you remember the limitations of abrasive as such there is no limitation but there are some environmental issues which are to be looked into and future direction in the area of the abrasive water. Before I end, I mention that after this you have four solved problems and you have four quiz questions. Please go through them and if there are any queries in the very fast life the email address is given, you can always come back to me.

Thank you with that I end my lecture today.