Advanced Machining Processes
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Lecture 06

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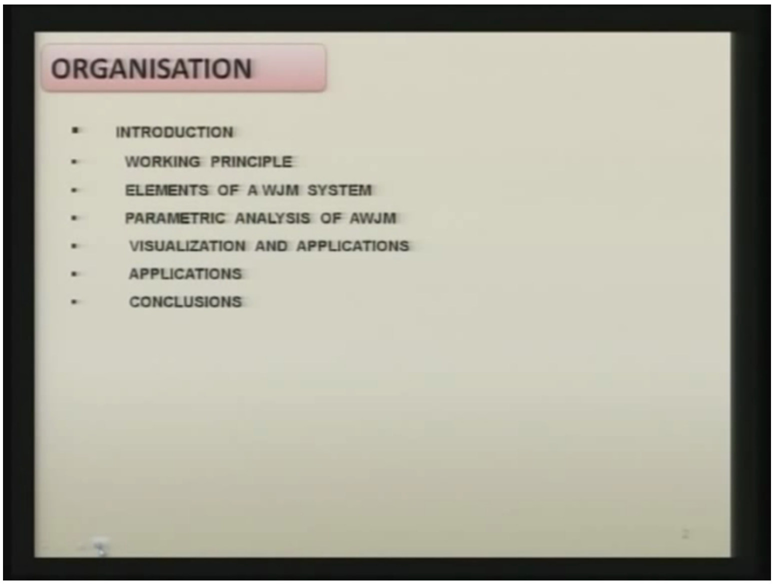

Today we are going to discuss about Abrasive Water Jet Machining Process that is also known as abrasive water jet cutting process, the organization of the todays lecture is as follows, introduction, working principle of abrasive water jet machining process, what are the various elements of abrasive water jet machining system then we will move to the parametric analysis, then some visualizations and how this abrasive water jet is moving within the work piece will be shown then finally the applications and conclusions will be discussed.

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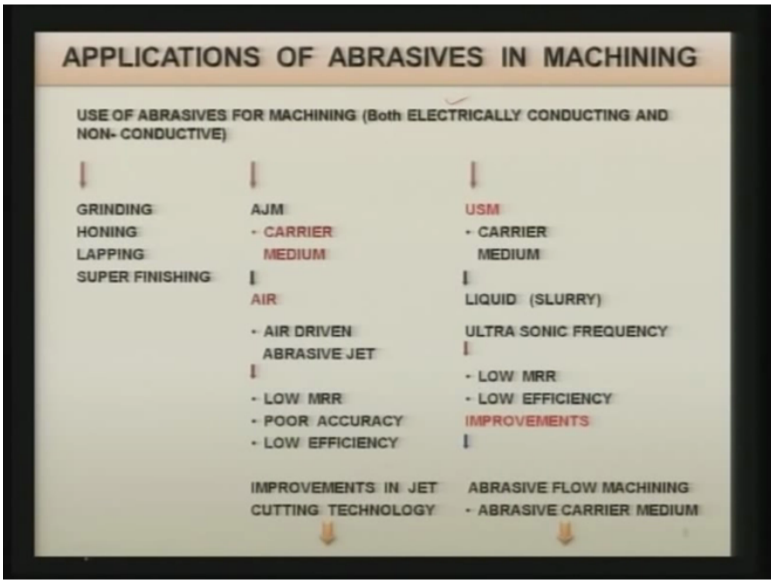

Let us see abrasive water jet machining set up, in introduction first before we really go for working principle of abrasive water jet machining, let us see some of the peculiar applications of this abrasive water jet cutting process and here I am trying to show you various processes which are based on abrasives or where you are using the applications of abrasive in cutting or machining processes on the left hand side you can see that there are the traditional processes which are based on the application of abrasives they are grinding, honing, lapping, super finishing and similar other processes.

One of the point to note over here is that all this processes are applicable for electrically conducting as well as electrically non-conducting materials and the advanced machining processes which are based on the application of abrasives include abrasive jet machining which we have discussed already here there is a carrier medium which is carrying the or moving the abrasive particles is the air which is easily available, cheap and not toxic so that is preferred over here.

Here the air driven abrasive jet when it is used in AJM process, the material removal rate is comparatively low, accuracy is not very good and efficiency of machining of AJM process is also low there are various venues of improving this abrasive jet machining process that we will discuss in the next slide on the other hand if you see ultrasonic machining process which is also based on the application of abrasives in cutting or machining of various advanced engineering materials.

Here the carrier medium is liquid and abrasives are mixed in the liquid say normally water and that water mixed with abrasives is known as slurry and the tool in case of ultrasonic machining is vibrating at ultrasonic frequency this process also gives material removal rate comparatively low, efficiency is also low some improvements have been made in this particular process to develop new processes specifically the processes which are used for finishing purposes that I will show you in the next slide.

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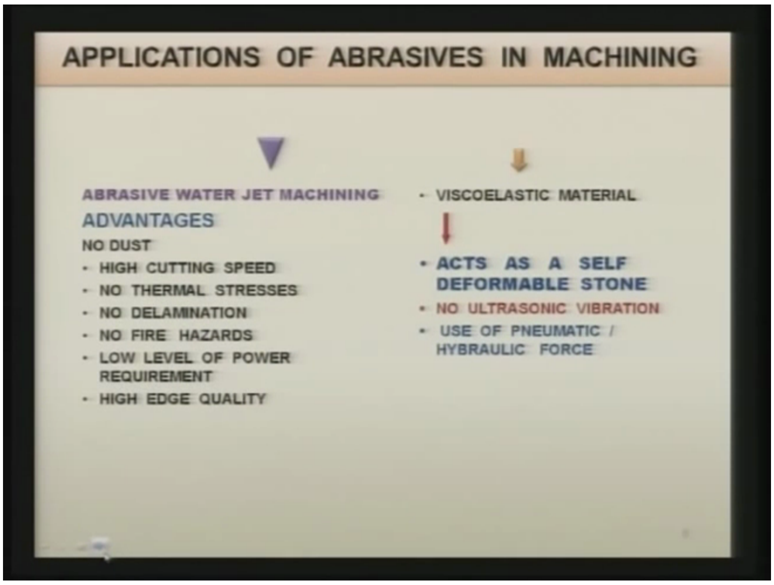

As you can see on the left hand side the improvement on the abrasive jet machining process is the result or as a result of improvement we have what is known as abrasive water jet machining process which has many advantages compared to specifically abrasive jet machining process, there is no dust in the environment, whatever material removal is there, abrasive particles are there all of them are within the water so environment pollution is minimized.

Compared to AJM it has very high cutting speed, there are no thermal stresses developed in the machine work piece because first thing is the whole work piece is completely in contact with the water throughout the machining process. Also the forces are comparatively in a localized area.

There is no delamination when you are machining the composite materials glass fiber reinforce plastic is one of the example, there are no fire hazards, low level of power requirement and quality of the cut edges is comparatively better on the other hand as an improvement over the ultrasonic machining process principle we can say that we are having a process called abrasive flow finishing process which is using viscoelastic material as the medium in which abrasive particles are added.

This viscoelastic material acts as a self-deformable stone which will discuss later in other chapter. Now in this particular case there are no ultrasonic vibration as we have in ultrasonic machining it uses normally hydraulic power unit for applying the force sometimes we can also use pneumatic power or giving the sufficient force for the movement of the piston so that it pushes the medium inside the working zone.

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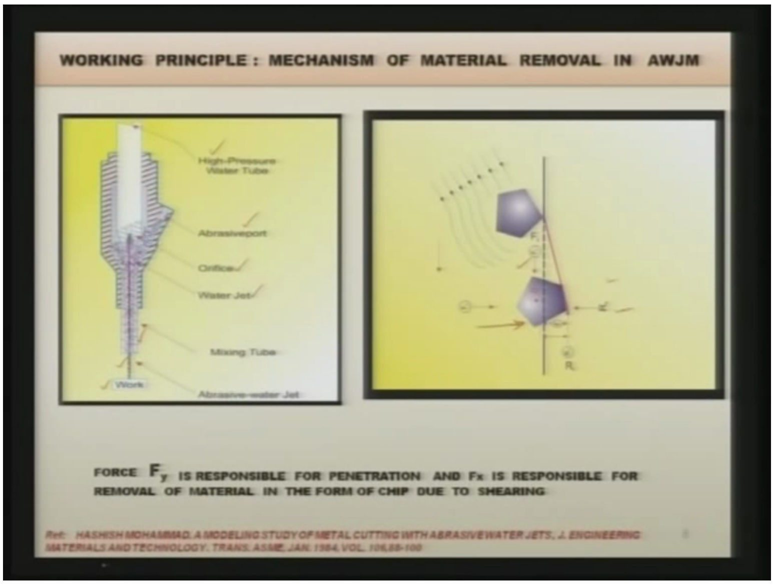

Let us understand the working principle of abrasive water jet machining, it should be water jet machining not C, as you can see here this is the schematic diagram of abrasive water jet cutting system, you can see there is a high power water tube through which the water at very high pressure is supplied and then on this side we have the abrasive port through which abrasive particles are supplied these abrasive particles may be alumina AL2O3, silicon carbide or some other abrasive particles.

Then there is a orifice through which the water jet is coming out at a very high velocity as we will see the velocity of the water jet can be as high as 800 to 900 meter per second depending upon what pressure is used then you have a mixing tube over here in this tube you can see clearly that abrasive jet is mixed with the water jet and both form abrasive water jet.

Now while coming out of the mixing tube we have here the abrasive water jet and the velocity of this abrasive water jet is very very high and such a high velocity when it hits the work piece over here the kinetic energy of the abrasive particle is responsible for removal of the material from the work piece and we can calculate the kinetic energy of individual particle by the formula half MV square where M is the mass of the particle and V is the velocity with which it is hitting the work piece.

Now when it hits the work piece it is not necessary all the time that it is hitting at a normal or at a 90 degree angle to the work piece as you can see on the right hand side the abrasive particle is hitting the work piece and it is moving at an angle other than the 90 degree to the work piece surface, now there are two types of the forces that are acting over here as you can see FX and FY.

Now here force FY is responsible for penetration that is acting in this particular direction so it is responsible for penetrating inside the work piece surface and FX is responsible for removal of material in the form of the chip due to the sharing action as you can see over here this is the FX force that is acting over there and there is a reaction force that you can see over here when it starts, when penetrates inside the work piece surface there is always resistance from the work piece surface for penetration and that is the reaction force.

Now these particular figures and some of the descriptions in this chapter have been taken from the paper written by Hashish Mohammad, a modeling study of metal cutting with abrasive water jets, it was published in journal of engineering materials and technology transaction ASME, January 1984, volume 106, pages are 88 to 100.

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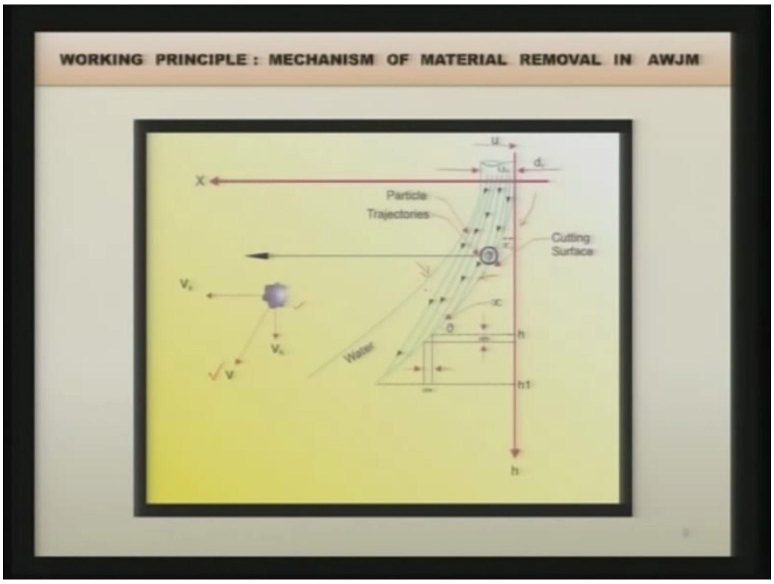

Now when the abrasive jet or abrasive water jet has penetrated inside the work piece surface, how or in what direction this jet is moving as it enters inside the work piece surface as you can see it is following a curved surface and if you see a particular particle now it has two velocities one is the velocity in the X direction another is the velocity in the Y direction or H direction and these are the components of the velocity V that is the resultant velocity.

And as I will show you in the next slide that the surface that you are getting after machining is not really a smooth surface rather it is serrated surface as you will see in the next slide. Now here this indicates the surface which has been cut over there so you can see these are the boundaries of the jet which it is moving along the particular path which you cannot predict easily however models have been developed to predict this particular path.

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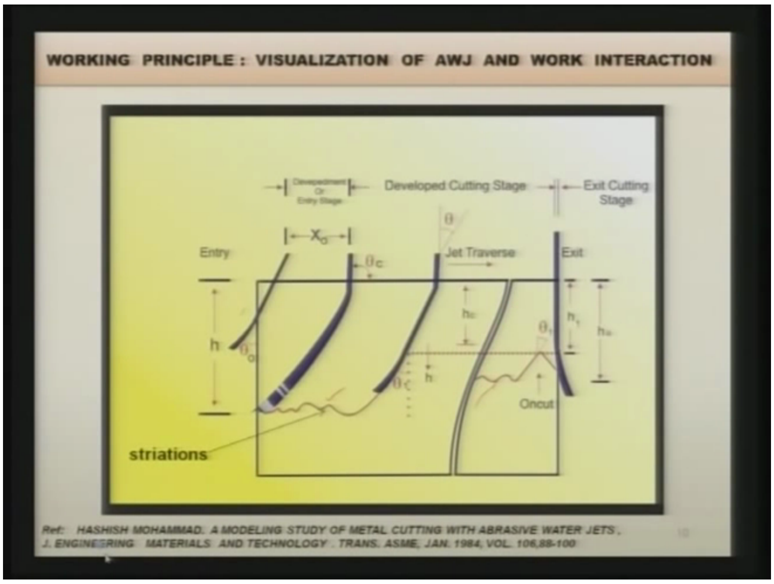

Now what happens really when it starts from one edge to another edge as you can see over here at the entry it cuts it and then starts exiting from the outside or least resistance path and then you can see in the beginning after entry stage it starts tilting or bending at a particular angle and striations in the surface are created as you can clearly see and whenever there is a blind cavity, this kind of the bottom surface is obtained and it is not acceptable in most of the application.

So for tool cutting it is a comparatively better process than for blind cutting, now as jet is moving you can see these striations are also being formed at the exit also this is more or less the same way as at the entry and you can see again the striations on the side of the exit of the jet again taken from the same paper.

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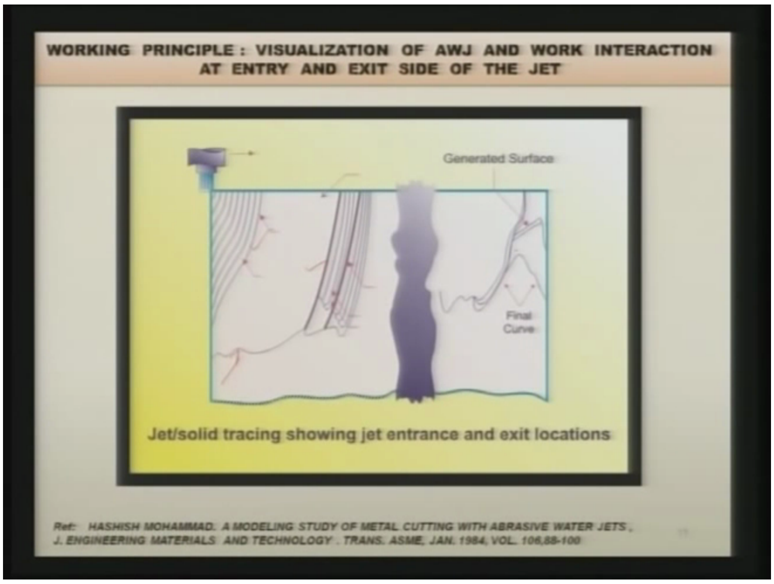

So this is really the kind of the surface that you are going to get, cut surface that you are going to get from the abrasive water jet cutting process now you can see these are the striations and these are the kind of the marks that will be seen on the cut wall of the work piece which you have obtained by abrasive water jet cutting and this is the kind of generated surface that you are going to obtain.

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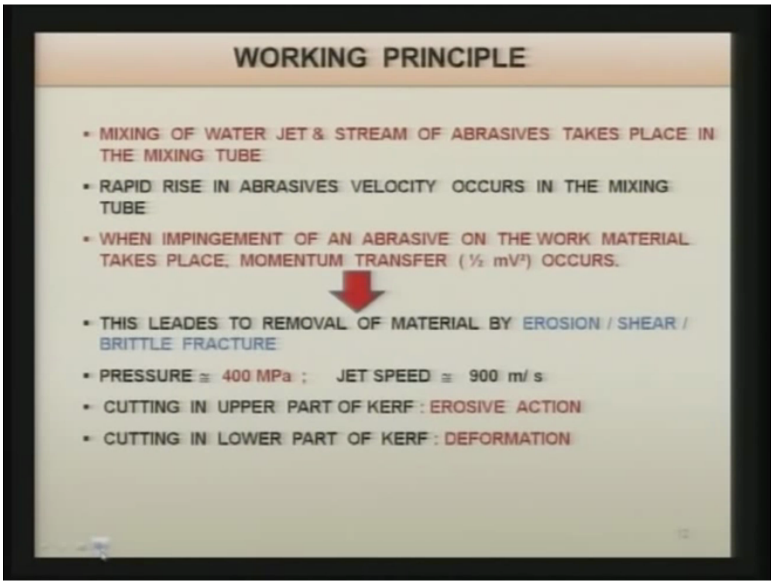

Now, mixing of water jet and stream of abrasives takes place in the mixing tube as we have seen in the earlier slide. Rapid rise in abrasives velocity occurs in the mixing tube after it is coming from the port, abrasive particles coming from the port and mixing with the water jet they come out of the mixing tube when impingement of an abrasive on the work material takes place momentum transfer occurs and that is given by half MV square. This leads to removal of material by erosion, shear or brittle factor.

It depends upon what are the properties of the work piece material if it is a brittle material then fracture may take place, if it is a ductile material then deformation, erosion and shearing are going to take place. Pressure is normally 400 mega pascal and the jet speed maximum jet speed that you can obtain, normally people have worked with is 900 meters per second which is very very high. Cutting in upper part of the kerf takes place due to the mechanism that is known as erosive action and then cutting in the lower part of the care take place due to the deformation.

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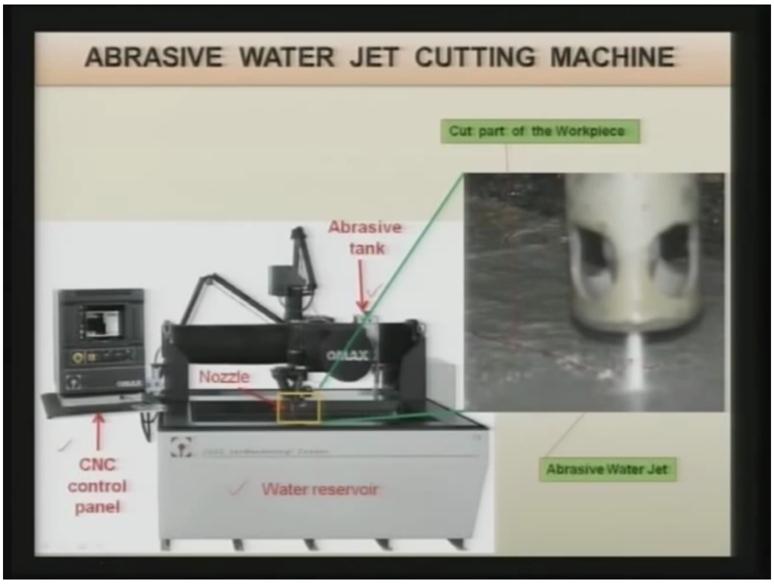

Now this is the actual abrasive water jet cutting machine which IIT Kanpur purchased, now the details of this particular machine can be seen on this site which is given over here. Here you can see the video also for this particular machine, now you can see the various parts over there this is the CNC control panel with the help of which you can feed different parameters, you can control various movements of the jet.

Here this is the enlarged view of the jet, you can clearly see the abrasive water jet visible over here and this is the cut part of the work piece that you can see here, this is the cut part of the work piece. Now here is the abrasive tank in which you fill the dry dehumidified abrasive particles and this is the water reservoir where whole of this tank is filled with water and here you will keep the work piece as I will show you in the next slide.

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Now you can clearly see various other elements of the abrasive water jet cutting machine, now this is the abrasive tank which is having dry dehumidified abrasive particles, now here is the nozzle and it is going to cut the work piece over there and you can see this is the water tank and this here you are going to place the work piece somewhere here.

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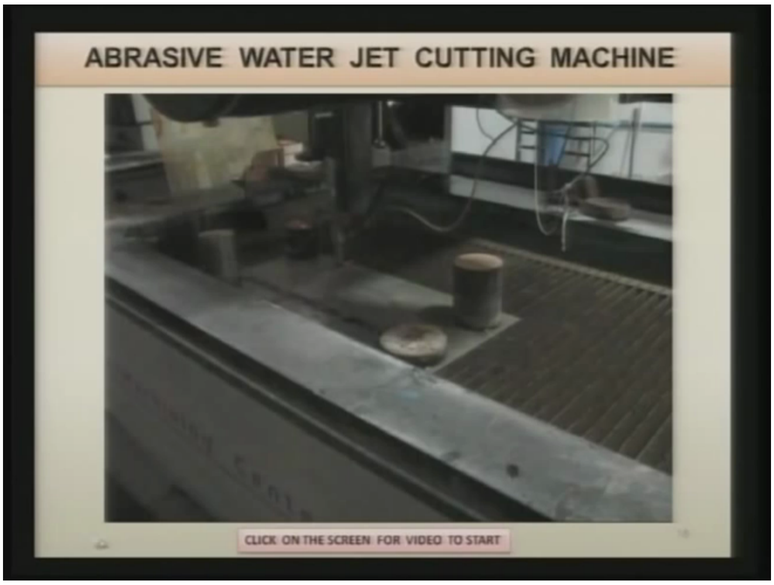

Now you can clearly see these are the work pieces which are being machined not very clear but here is the area where machining is going to take place, so these are the different views of the abrasive water jet cutting machine.

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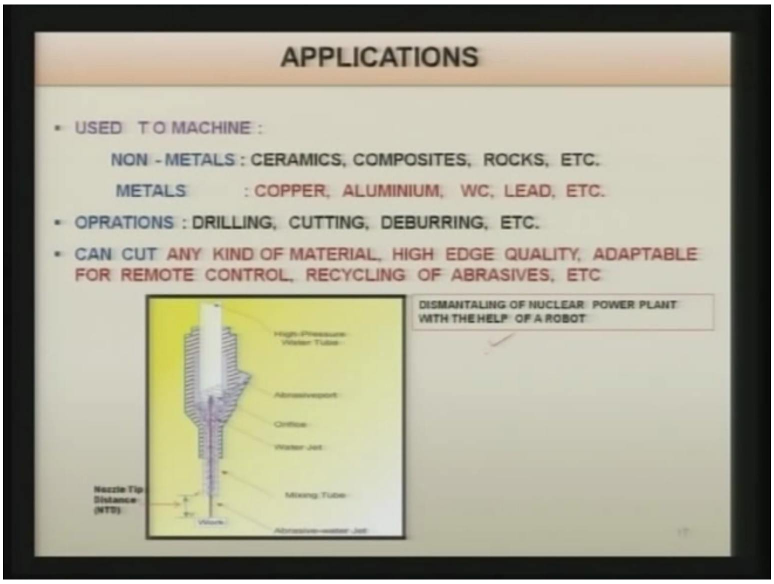

This we have already seen the important thing that you can see here once again is that the distance between the bottom of the nozzle and the top surface of the work piece that is known as nozzle tip distance or it is also called as stand off distance. Now it is used to machine metals as well as non-metals, non-metals materials are like ceramics, composites, rocks, etc.

Metals you can machine copper, aluminum, tungsten carbide, lead or even super alloys can be cut by this. Various kinds of operations can be performed like drilling, cutting, deburring, etc. It can cut any kind of material with reasonably good edge quality, acceptable (())(16:15 to 16:22 - inaudible)

Important applications of this abrasive water jet cutting is that you can use the robot and it can be used for dismantling of nuclear power plant with the help of a robot. This is very important application because in nuclear power plant human beings are not permitted to go there because of the radiation effect so for such kind of application where you can control the cutting operation with the help of the robot at remote places.

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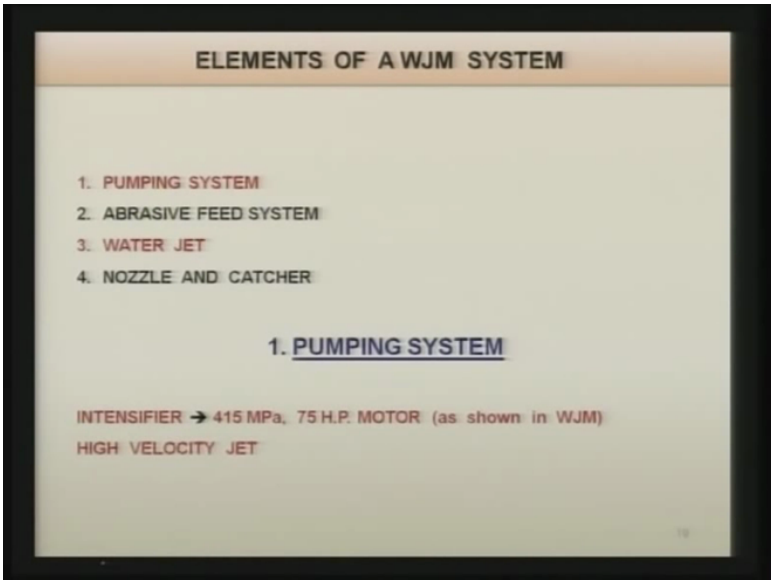

Let us see what are the various elements of abrasive water jet machining system, first one is the pumping system another is the abrasive feed system, water jet, nozzle and pressure of the water as high as 415 mega pascal or so for which the motor around 75 horse power is used. It gives a high velocity jet.

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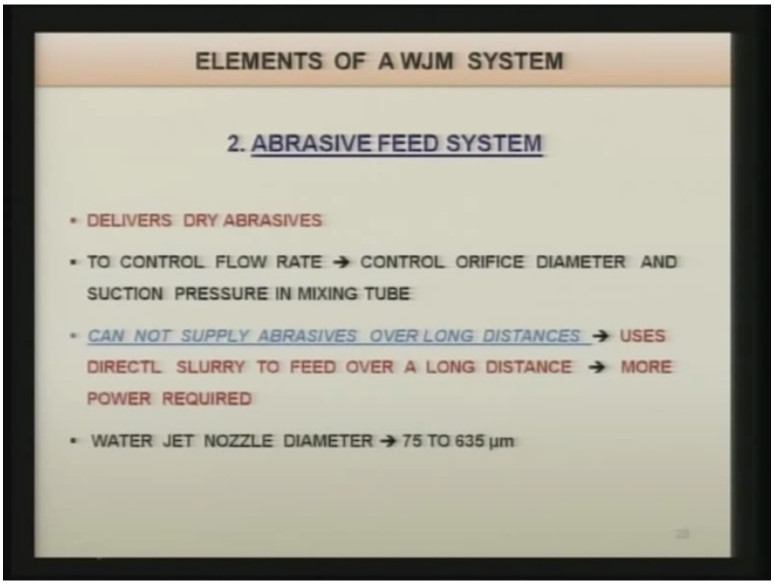

Another is the abrasive feed system we have seen in the figure of the system, abrasive water jet cutting system. It delivers dry abrasive particles to control the flow rate of dry abrasive particles, control the orifice diameter and suction pressure in mixing tube, you can change the orifice diameter. It cannot supply abrasives over long distances otherwise the kinetic energy or the velocity will slow down.

So what researchers have proposed or they are doing the experiments by using directly slurry to feed over a long distance they take the slurry over a long distance and then they directly feed the slurry over there and however it will require more power than the present systems. Water jet nozzle diameter normally vary between 75 to 635 micro meter.

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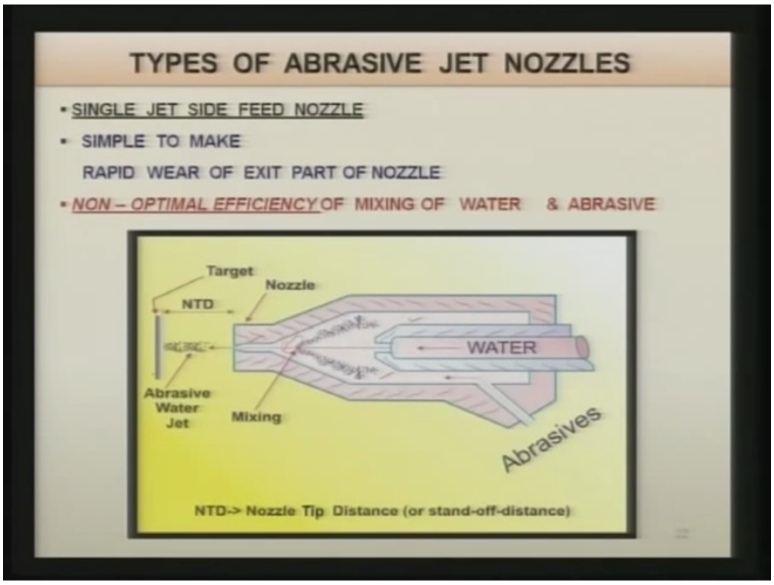

Now abrasive jet nozzles, their various functions of the nozzle in abrasive water jet machining, first one is mixing of abrasive and water jet as we have seen and then forming high velocity jet. Materials of the nozzle are tungsten carbide, boron carbide, sapphire or very hard materials and resistant for wear materials can be used for this purpose.

For high life of nozzle normally sapphire material is used but it is more expensive than other materials as listed over here. Now there are various kind of abrasive jet nozzles or abrasive water jet nozzles. Now first one is the single jet side feed nozzle it is simple to make but it rapid wear of exit parts of the nozzle takes place, it gives non-optimal efficiency of mixing of water and abrasive as we will see in the figure.

Now as you see in this particular figure abrasive is coming from this port as well as this port and water is coming from the central port and both of them are mixing somewhere here now after mixing they are going out and since you can see on the outer side abrasive particles are there and in the middle side water jet is there so abrasive particles are coming directly in contact with the nozzle surface, inner surface of the nozzle.

So wear of the nozzle will be more and you can see the distance between the bottom face of the nozzle and upper face of the work piece is the nozzle tip distance and when this abrasive water jet hits to the work piece surface, the removal of the material takes place.

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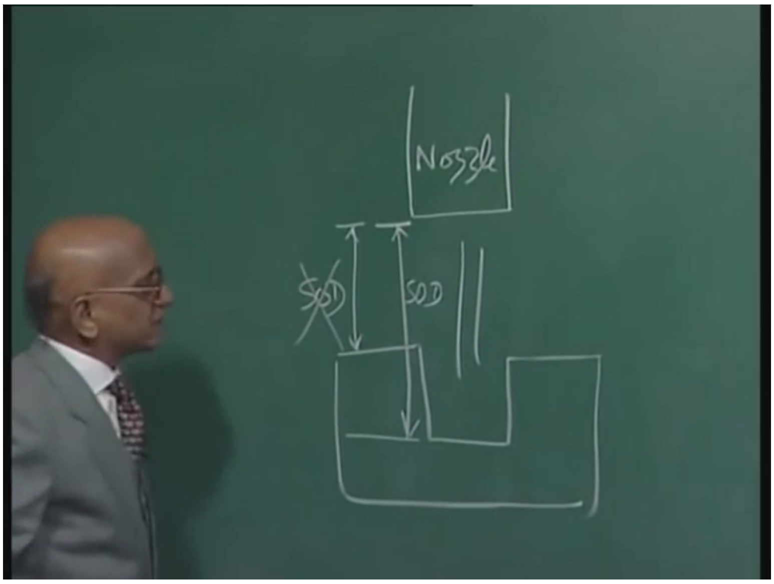

Here one point is to be noted that this stand off distance is not fixed always when the jet is moving inside and it has moved sufficiently below the work piece and here is the say nozzle, this is the nozzle then the stand off distance will be this one, not this one. So it has to be, this is the SOD no and so this has to be measured from the bottom face of the nozzle and the top surface of the work piece where it is removing the material this point should be carefully noted.

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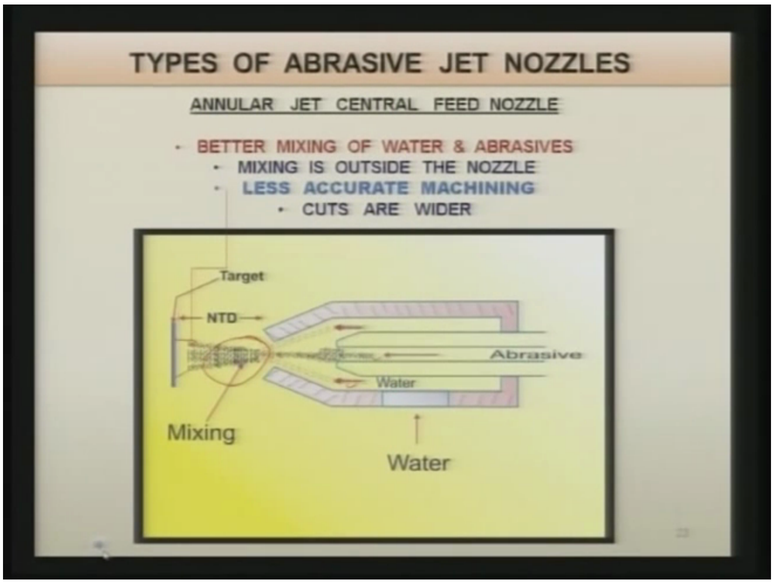

Another one is known as annular jet central feed nozzle, it gives better mixing of water and abrasive but in this particular case mixing is outside the nozzle it is less accurate or it gives less accurate machining as compared to the earlier one in this particular case cuts or the kerf width is higher compared to the earlier one.

As you can see here clearly that water is coming from the sides and abrasive is coming from the central port now both of them are mixing here outside the nozzle and you can see the divergence taking over there because of this divergence of the jet, abrasive water jet the accuracy of the cutting reduces compared to the earlier type of the nozzle. Now because of this, this is less accurate.

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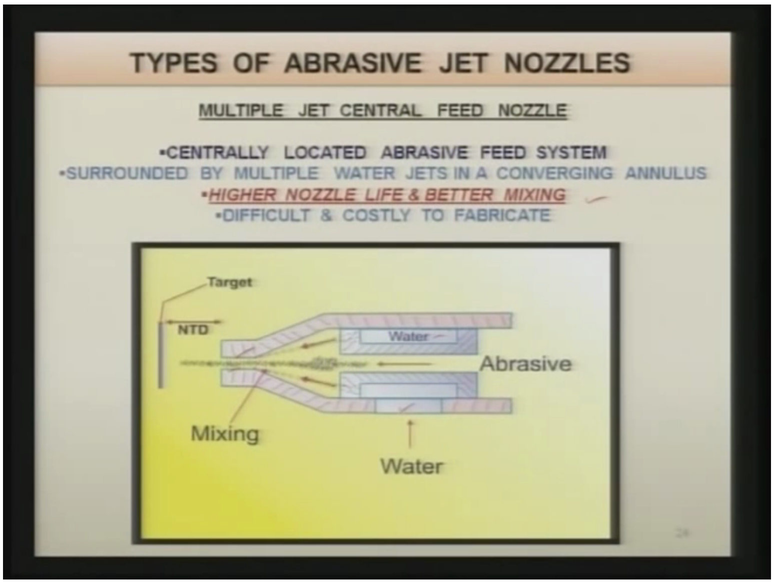

It is surrounded by multiple water jets in a converging annulus it gives higher nozzle life and better mixing, this is very important I will just explain it with the help of the figure. Now it is difficult to make and costly to fabricate now in this particular case you can see it gives higher nozzle life and better mixing if you see this particular figure, here water is in contact with the sides of the nozzle or inner surface of the nozzle not the abrasive particles are not directly in contact with the inner surface of the nozzle that is why the life of the nozzle is higher compared to other types of the nozzles.

And mixing is also inside the nozzle and it gives better mixing compared to other nozzles as you can see here nozzle tip distance is shown over there and water is coming from this annular side from all around it and that is why it is known as multiple jet central feed nozzle.

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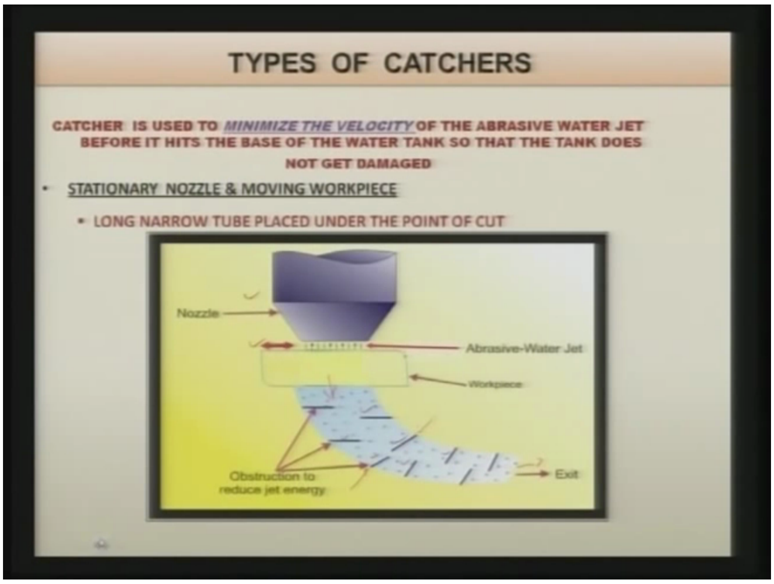

Types of catchers, now if you see here the abrasive water jet is coming at very high velocity after cutting the work piece if it hits the table on which you are going to machine the work piece then it will penetrate inside the table also and it will damage the table immediately that is why what is done is that before it really hits the table or the container or the tank of the water base, the velocity of the abrasive water jet is reduced to the minimum possible value so that the impact with which it hits the table or the bottom of the water tank is close enough not to damage it that is why the catchers are being used.

So catcher is used to minimize the velocity of the abrasive water jet before it hits the base of the water tank so that the tank does not get damaged now you can see here this is the nozzle and abrasive water jet is coming out of it, it is cutting the work piece then there is a tube in this tube you have the two types, you have the obstructions on all around it and when this water is coming inside this it hits these obstructions over here and its velocity reduces continuously before it is really out from the tube and this obstruction are there to reduce the jet energy. Here in this particular case nozzle is stationary and work piece is moving so that is shown, movement of the work piece is shown here, here nozzle is stationary.

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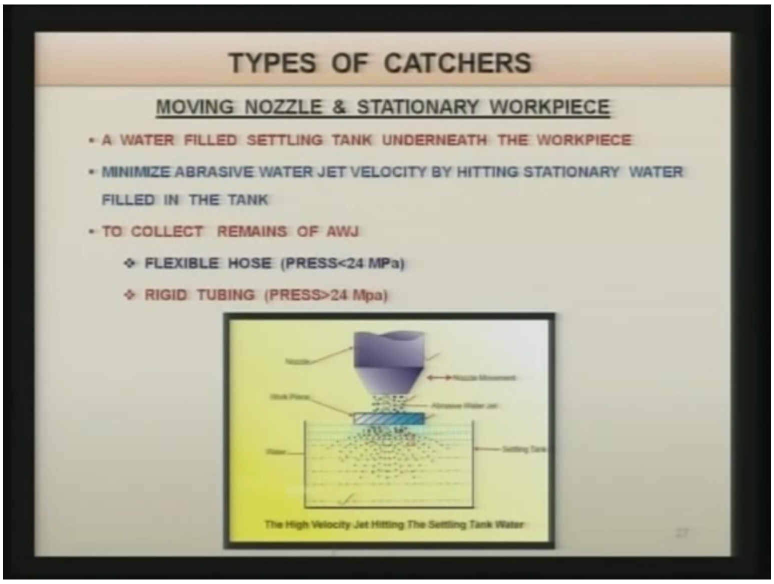

Now in the second type of the catcher, nozzle is moving, work piece is stationary. A water field settling tank underneath the work piece is there it minimizes abrasive water jet velocity by hitting stationary water filled in the tank. To collect remains of abrasive water jet they remain, the tank filled with water is used for this purpose.

You can use the for movement of the water you can use the flexible hose, a pressure is less than 24 mega pascal, you can use the rigid tubing a pressure is greater than 24 mega pascal, now here you can see clearly this is the nozzle and the jet is through cutting the water jet is coming in the abrasive water jet is coming in the water tank and this is the tank filled with the water and abrasive and water jet when they hit the water stationary in the tank their velocity reduces considerably before it reaches to the bottom of the tank.

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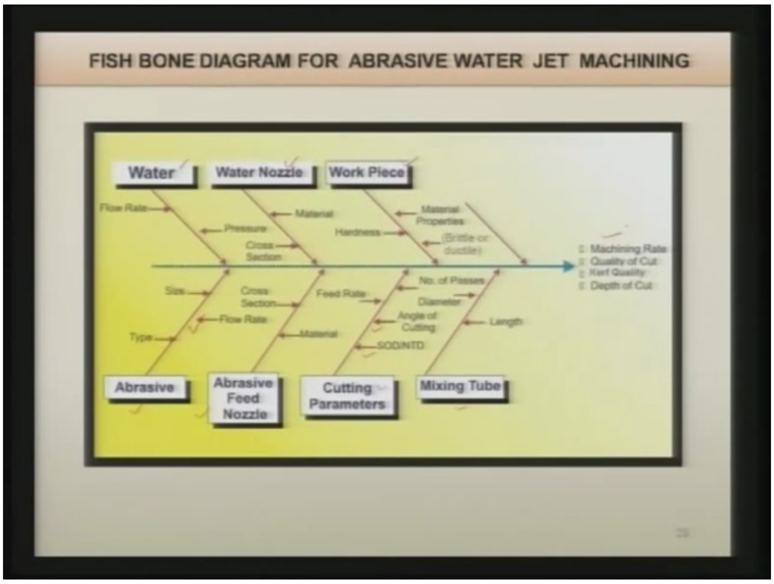

Let us have some parametric analysis of the abrasive water jet machining process, before we discuss it let us first see what are the various parameters involved in abrasive water jet cutting process. Now first of all water is there the pressure of the water and the flow rate of the water both are the parameters for this particular process then there is a water nozzle.

Material of the water nozzle is important as we have already seen and the cross-section of the water nozzle it can have a circular cross-section, it can have rectangular cross-section also then the hardness of the work piece is very important parameter, other material properties are also equally important then the work piece whether it is brittle or ductile that will decide the material removal rate and the mechanism of material removal rate also.

Then you have the abrasive particles size of the abrasive particles what is the absolute size or mesh size of the abrasive particle is important whether they are coarse or they are fine and type of the abrasive particles whether it is silicon carbide, alumina or other type of the abrasives.

Then flow rate of the abrasive is another important parameter then abrasive feed nozzle what is the cross-section of the abrasive feed nozzle and the material of the feed nozzle because it is not very hard than the nozzle itself will wear out slowly and you cannot control accurately the abrasive feed.

Then there are the cutting parameters like feed rate number of passes, angle of cutting and stand off distance, these are the cutting parameters which affect the performance of the abrasive water jet cutting process and then the mixing tube diameter of the mixing tube and the length of the mixing tube both are important cutting parameters the output responses which are normally measured and based on which the performance of the abrasive water jet machining process is evaluated are the machining rate, quality of the cut edges, kerf quality and depth of cut.

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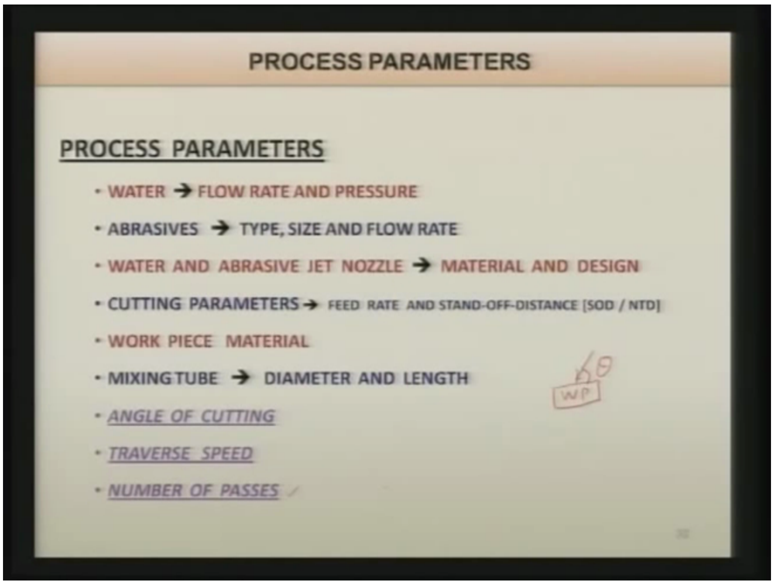

Let us see again the same thing water, we have seen flow rate and pressure, abrasives, types size and flow rate, water and abrasive jet nozzle material and design, cutting parameters are feed rate and stand off distance, work piece material mixing tube angle of cutting, traverse speed and number of passes these three are very important now what angle the jet is hitting the work piece surface.

This is the work piece surface and what angle the jet is hitting that will decide the mode of removal of material and it is very important, so this angle is important which it is making theta with reference to the surface to the work piece. Now traverse speed is another very important parameter, this as I will show you in the next slide is the relative movement or relative velocity between the work piece surface and the abrasive water jet and number of passes.

As we already know say in case of traditional machining processes say turning if the thickness of the material to be removed is much larger than not in one pass rather in many pass, same way if the thickness of the work piece to be cut over here is very large than in place of single pass you can use multiple passes for cutting the through cutting of the whole work piece.

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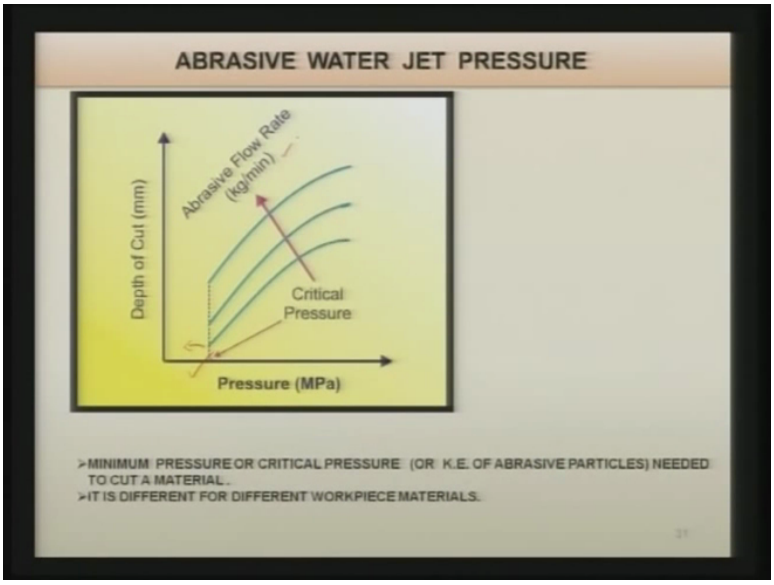

Now let us see the effect of pressure on the depth of cut, as you can see in this particular figure there is a, here is a point which is written as critical pressure, this is the minimum pressure or minimum (())(30:40) has got certain strength and unless the kinetic energy of abrasive particle crosses that it cannot penetrate inside the work piece surface that is why you can see there is no cutting in this particular zone that is the before the critical pressure is reached.

And as the critical, as the pressure is increasing, the depth of cut is also increasing but beyond a certain pressure this is not a linear relationship this is a non-linear relationship and it tries to stabilize beyond a certain pressure. Now also if you see here as the abrasive flow rate increases the depth of cut is also increases but again this is also not a linear relationship so you can see here that minimum pressure or critical pressure or kinetic energy of abrasive particles needed to cut a material is there and it is different for different work piece materials.

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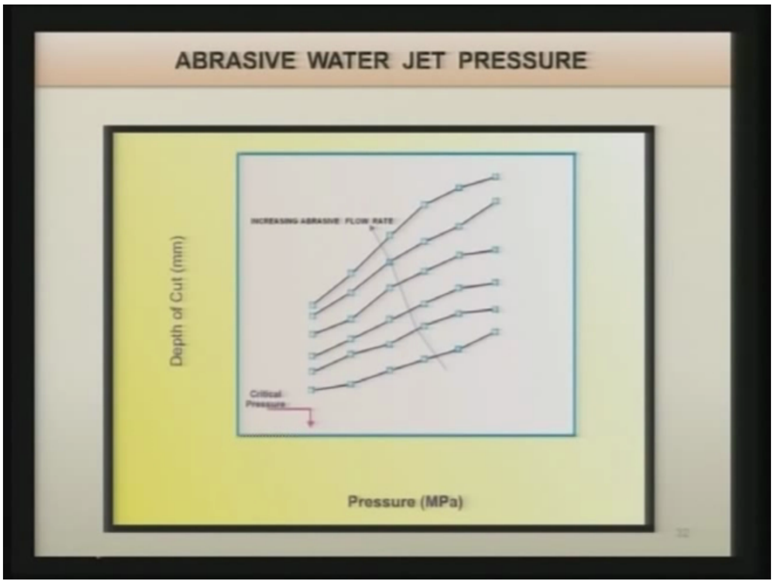

Same thing is shown over here with the various experimental points as the pressure is increasing the depth of cut is also increasing and as the abrasive flow rate increasing, the depth of cut is also increasing.

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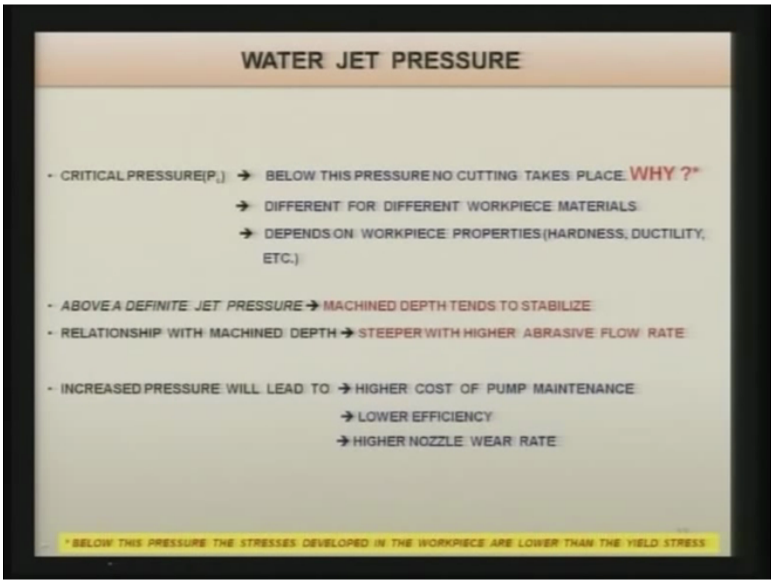

So the same thing is given here as the explanation that below the critical pressure no cutting is taking place different for different work piece material it depends on work piece property. Above definite jet pressure machine depth trends to stabilize relationship with machine depth is steeper with higher abrasive flow rate, increased pressure will lead to higher cost of pump maintenance because if the pressure is very high then the maintenance of the pump becomes more expensive because of more wear and tear.

It gives lower efficiency at very high pressure, higher nozzle wear rate is also observed with very high pressure, below the critical pressure the stress is developed in the work piece are lower than the yield stress that is why you do not get any removal of the material.

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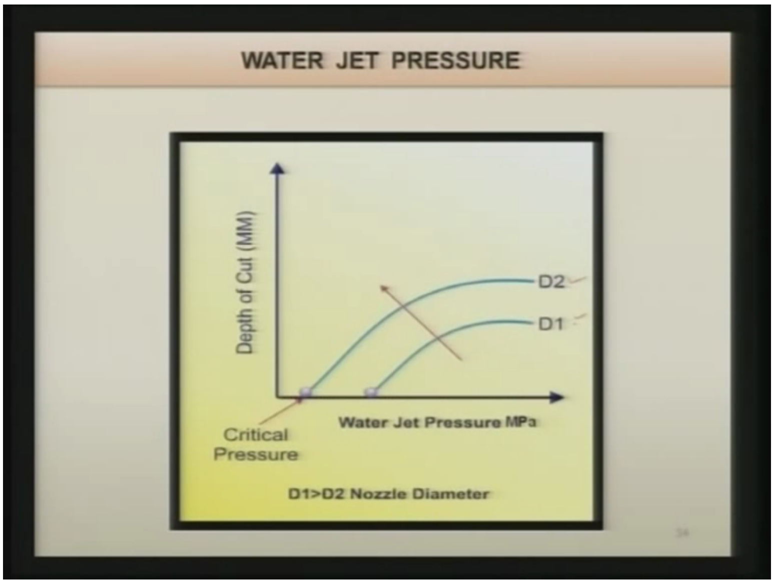

Here it shows the effect of the water jet pressure on the depth of cut, it initially increases and afterwards it tries to stabilize it now you can also see that this is the nozzle diameter D1 and D2 now if nozzle diameter is larger then the depth of cut also decreases as you can see over here it is because if the same power is there then the pressure of the water, abrasive water jet coming out is smaller and that is why the depth of cut is also smaller.

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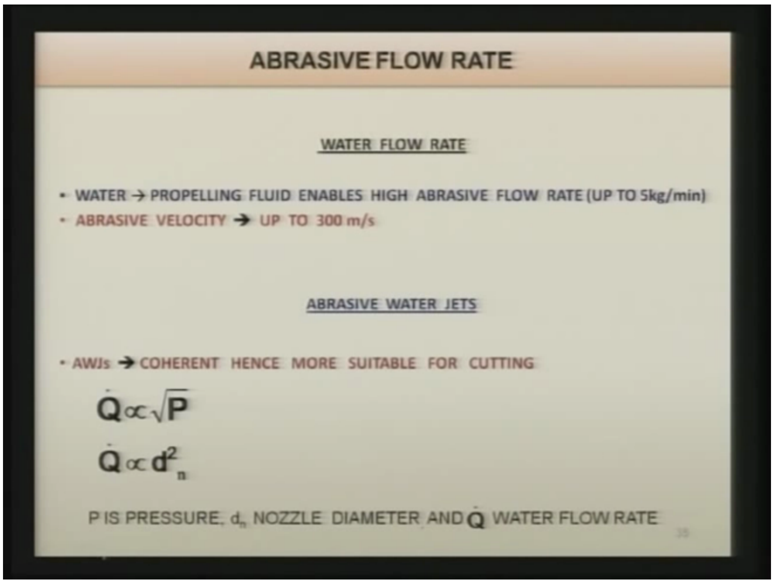

Water flow rate, water is the propelling fluid that enables high abrasive flow rate and the flow rate you can have is as high as 5 KG per minute. Abrasive velocity normally is 300 meter per second, abrasive water jet are coherent hence more suitable for cutting and this are much more coherent as compared to the abrasive jet machining process, now here you can see here the water flow rate is directly proportional to the under root of the pressure P and it is directly proportional to the square of the diameter of the nozzle that is DN square.

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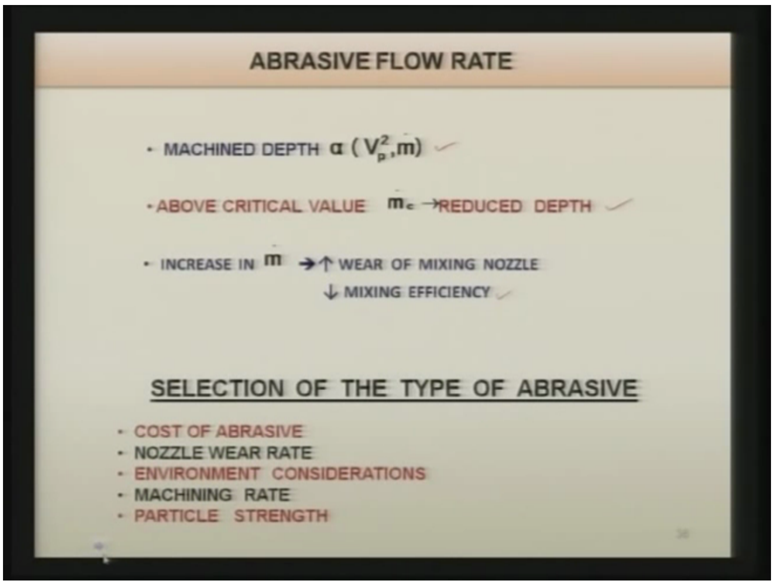

Machine depth is proportional to the velocity of the abrasive particles as well as the mass flow rate of the abrasive particle that we can see here above the critical value of the mass flow rate of the abrasive particles the depth of cut starts reducing. Increase in mass flow rate leads to the wear of mixing nozzle, higher wear of the mixing nozzle and reduced efficiency mixing efficiency that is why there is always an appropriate or critical amount or critical value of the mass flow rate of the abrasive particle.

Selection of the type of the abrasive, cost of abrasive it depends selection of the type of the abrasives depends on the cost of the abrasive, nozzle wear rate, environment considerations and machining rate and finally it also affects, it is also affected by the particle strength.

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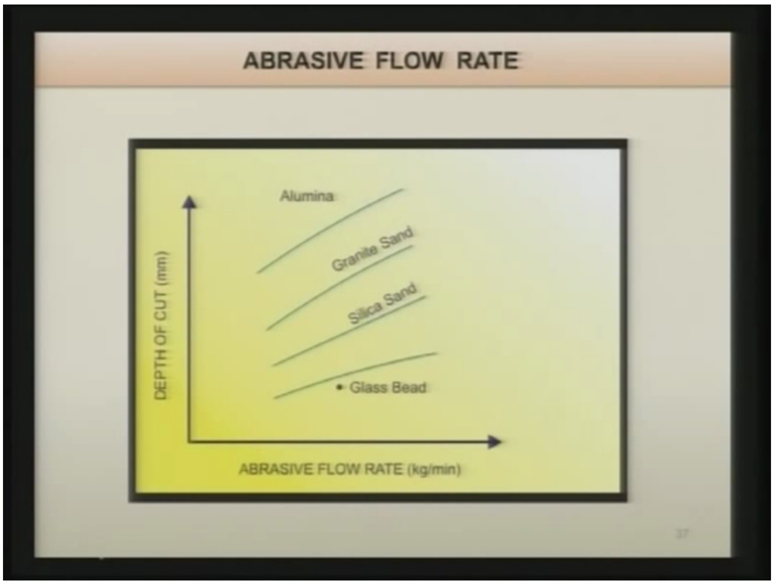

Let us see the effect of abrasive flow rate, now as we can see here as the abrasive flow rate is increasing the depth of cut is increasing in different kind of the abrasives glass bead is there, silica sand, granite sand or alumina. Now one thing we can see here that depending upon the type of the abrasive the depth of cut is different in different cases.

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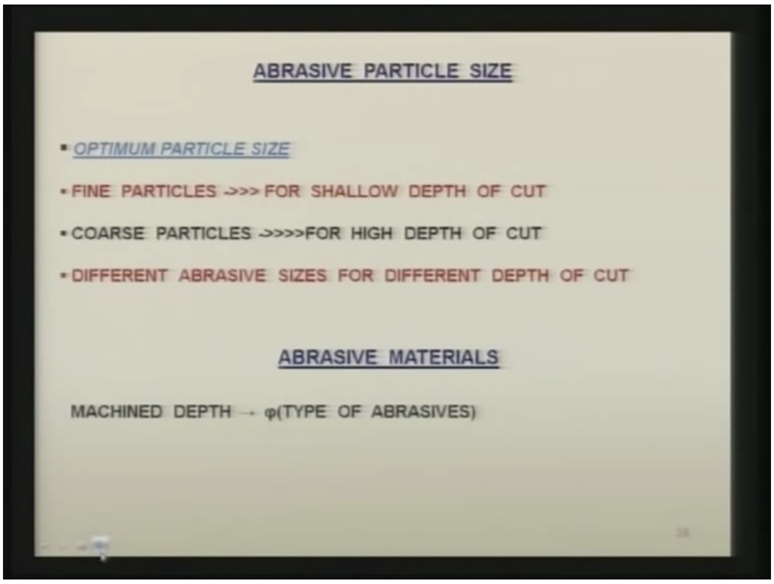

Now abrasive particles size, there is always an optimum particle size for a particular application which includes the work piece material also. Fine abrasive particles are good for shallow depth of cut and coarse abrasive particles are good for high depth of cut. Different abrasive sizes for different depth of cut are also proposed by some of the researchers however in practice it seems to be a little difficult task. Now abrasive materials the machine depth is function of the type of the abrasive also.

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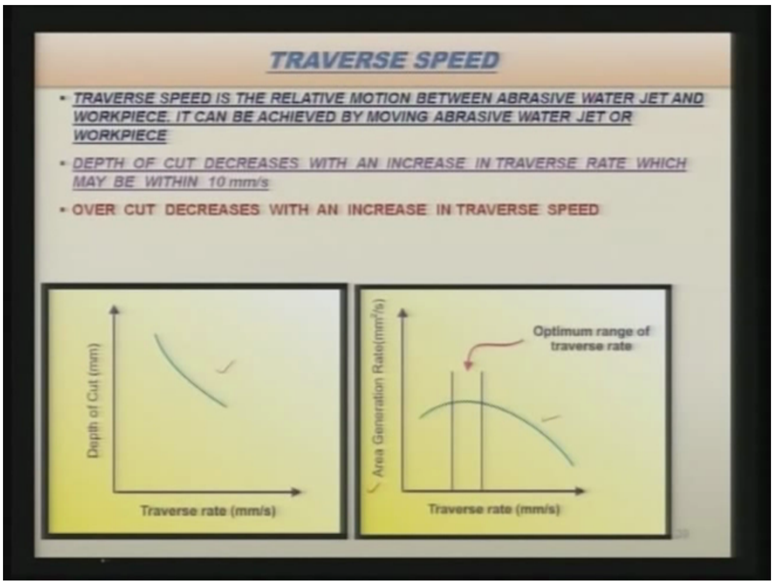

Now traverse speed is the relative motion between abrasive water jet and work piece, it can be achieved by moving abrasive water jet or by work piece. If you see the relationship between traverse speed or traverse rate and depth of cut this is the kind of the relationship that we obtained that as the traverse rate increases the depth of cut decreases.

If you see here as the traverse rate is increasing the area generation rate is increasing and there is the optimum area generation and beyond which it start decreasing, now depth of cut decreases with an increase in the traverse rate which may be within 10 millimeter per second.

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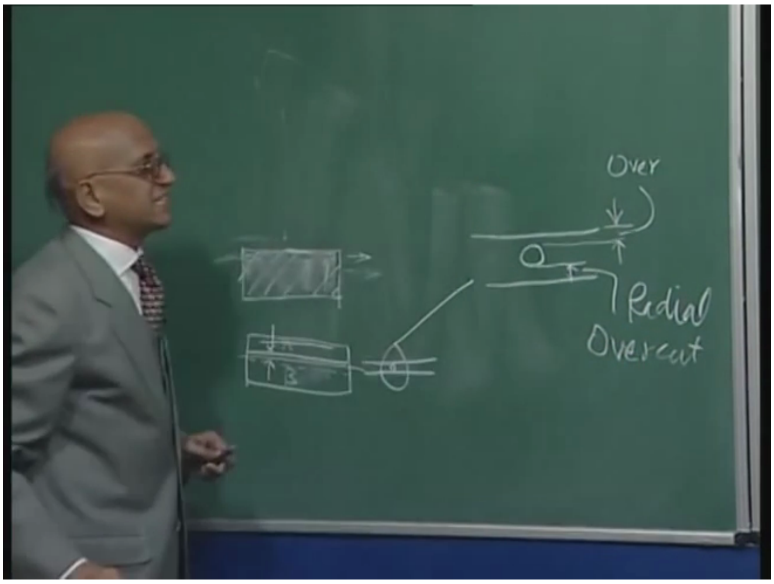

Now let us understand this what is the traverse rate, suppose this is the abrasive water jet and this is the work piece to cut the whole length of the work piece either the work piece can be moved in this direction then the jet abrasive water jet will remain stationary or if the work piece is kept stationary and then the jet can move along the surface of the work piece.

So the relative motion between abrasive water jet and the work piece decides what is going to be the total depth of cut in a given time because suppose we are considering this particular area then depending upon for how long the jet is here it will keep penetrating if it is for very long it will keep penetrating deeper and deeper, if it is for a very short period then it may penetrate only upto this length and go out so the traverse rate is very important in deciding the depth of penetration or machine depth.

Another thing is when you are cutting this say if you take the top view of this particular work piece it is cutting like this now if you see this area which has been cut over here, now I take the cut area from here say suppose it has been cut in two pieces then one of the surfaces that has been created will be like this so whatever is this area of the cut surface because similarly there will be this is say this is cut surface of this part A similar cut surface will be for part B so whatever is this area generated and this area divided by the time taken that will be called as area generation rate.

So you can see here that the area generation rate in terms of millimeter square per second this particular relationship is follow, so this is the area generation and the traverse rate that we have just seen. Over cut decreases with an increase in traverse rate, if this traverse rate is increasing with an increase in traverse rate if this traverse rate is increasing that means the jet is moving very fast so this is the kerf width, now when this is the kerf width, I remake it here and suppose this is the size of the jet then if I take the enlarged view of this then it becomes like this and this is the jet size then whatever is this difference that is known as over cut or if you want to take say you can call it as radial over cut, if you want to take diametral over cut then this plus this, so twice that.