Advanced Machining Processes
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Module - 02
Lecture - 05
Abrasive Water Jet Machining Process

Okay welcome to the course on advance machining processes. Today we shall about abrasive water jet machining process. So this is one type of advance machining process, mechanical type of advance machining process. So already we had discussed abrasive jet machining and here today we are going to discuss abrasive water jet machining process.

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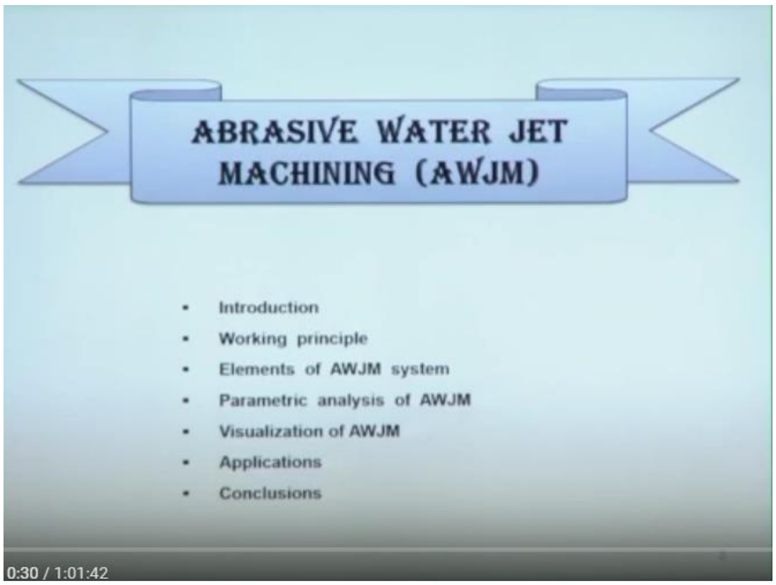

So before starting of that process we shall discuss use of abrasives in different mechanical type machining process. So this is the outline of my presentation. So first we shall discuss about the about abrasive water jet machining and then we shall discuss about the working principle of abrasive water jet machining process and different elements of abrasive water jet machining process and then parametric study, how this finishing parameters and machining parameters are effected by, affected on abrasive water jet machining process and we shall discuss after that that visualization of abrasive water jet machining under camera okay and then we shall discuss about the applications and process performance of abrasive water jet machining and finally we shall conclude about this process.

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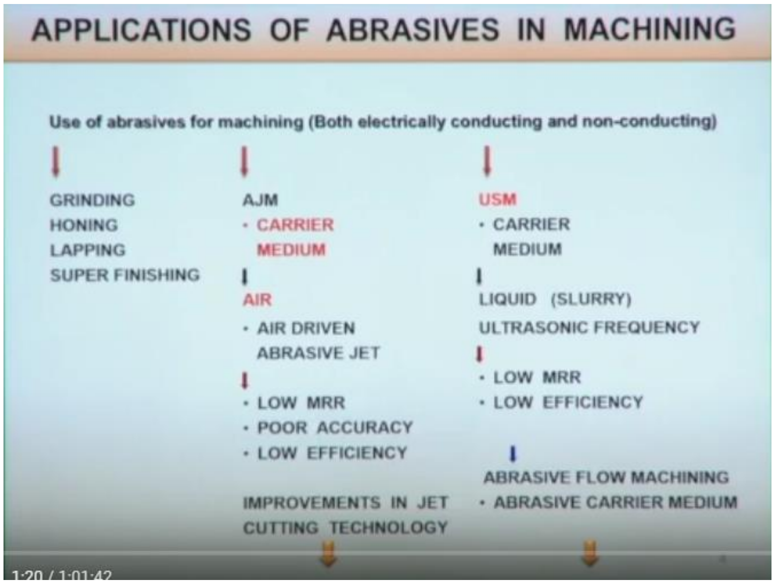

So first introduction. So here we are going to discuss about different applications of abrasives in machining process okay. So already we had discussed this abrasives it can be used in conventional machining process, conventional finishing processes, and also machining process like in grinding, honing, and lapping operation. So these 3 are actually conventional type finishing processes okay.

So grinding, honing, and lapping. So in grinding actually abrasive particles are bonded together and in honing and lapping in lapping operation this abrasive particles, loose abrasive particles are used. Honing also, it would use honing stick. There abrasive particles are bonded together okay.

So other than these process there are other super finishing processes also where abrasive particles are used.

So after that this abrasive particles are used in abrasive jet machining already we have discussed. Here carrier medium is the air or any inactive gas also we can use. So generally air is used because it is cheap and so it is cheap and easily available so air is mostly used and in abrasive jet machining this disadvantage is that here material removal rate is low and surface finish and machine deficiency is low in case of abrasive jet machining process.

So already we had discussed in abrasive jet machining there is a divergence of the flow. So when it comes, when this abrasive jet comes from the nozzle so and it comes to the atmosphere okay so at that time because of the friction in the air so this divergence of this jet so because of this divergence this kerf generated in case of abrasive jet machining is high okay. So we get lower efficiency and lower accuracy of this process.

So there are different improvements in jet cutting technology. So we shall discuss in abrasive water jet machining so there are different improvements are there. So after that these abrasives, loose abrasives are used in ultrasonic machining process. So there we have used slurry as the carrier medium where base medium was deionized water or water also we can use and abrasive particles are mixed in that water and this tool actually it vibrates with a ultrasonic frequency and because of this impact of this abrasive particles on the workpiece surface with a high velocity okay so this small craters are generated.

So here slurry is the liquid and tool vibrate with ultrasonic frequency. In ultrasonic machining also we can see that material removal rate is very high because machining is done by small abrasive particles. So here also in ultrasonic machining process efficiency is very less.

In another process where we use abrasive loose abrasive that is called abrasive flow finishing process.

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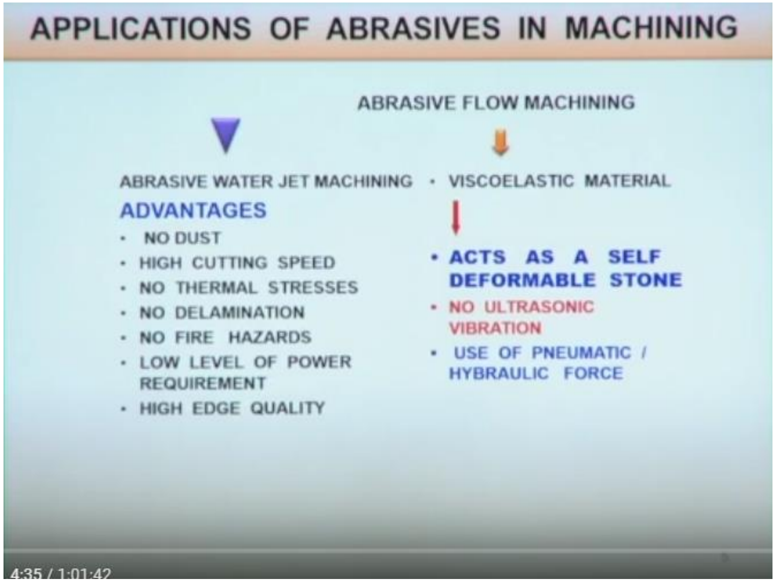

In abrasive flow finishing process this viscoelastic base medium is used. So it acts as a self deformable stone and here there is no ultrasonic vibration of this tool like in ultrasonic machining process. So use of pneumatic or hydraulic force to reciprocate the media from top media cylinder to the bottom media cylinder okay so while flowing this media through this cylinder and you have to move the fluid through the finishing zone and like that polishing is done in abrasive flow finishing process.

So in abrasive water jet machining process also loose abrasive particles are used, so there are different advantages of abrasive water jet machining process. So there is no dust because this abrasive water jet machining it is done in water environment so water mixed with abrasive particles comes from the nozzle for machining okay. So that is why because of this water is the base media is used here so there is no dust but in abrasive jet machining process so we have seen that the this dust particles are generated because this abrasive particles get crushed and when it is mixed with air so this dust particles actually come outside.

So that is why you have to a dust collection system in case of abrasive jet machining but in abrasive water jet machining process there is no dust because machining environment is done in water okay. So there is no dust and high cutting speed because here media media used base media is used as a water okay so abrasive particles here comes with a very high velocity around 900 meter per second. So that is why high cutting speed is there in case of abrasive water jet machining unlike abrasive jet machining process.

So no thermal stresses because the abrasive particles are hit by abrasive particle is the workpiece surface okay so there is heat generation is very less. So tool like in conventional machining process here tool does not touch the workpiece surface okay. So heat generation is less. Also whatever heat is generated it is taken away by the abrasive water jet okay. So so it is taken away by the abrasive water jet whatever heat is generated.

No delamination like in composite material while cutting this composite material there is a delamination phenomenon occurs okay so all layer actually means while cutting these layers actually separates out that is called delamination of composite material but in case of abrasive water jet machining process this kind of phenomenon of delamination does not observe.

So no fire hazards because temperature generation is very less so that is why there is no fire hazards in case of abrasive water jet machining. Low level of power requirement. So this is another advantage of the abrasive water jet machining and high edge quality also observed in case of abrasive water jet machining process. Okay so now what is the working principle of abrasive water jet machining.

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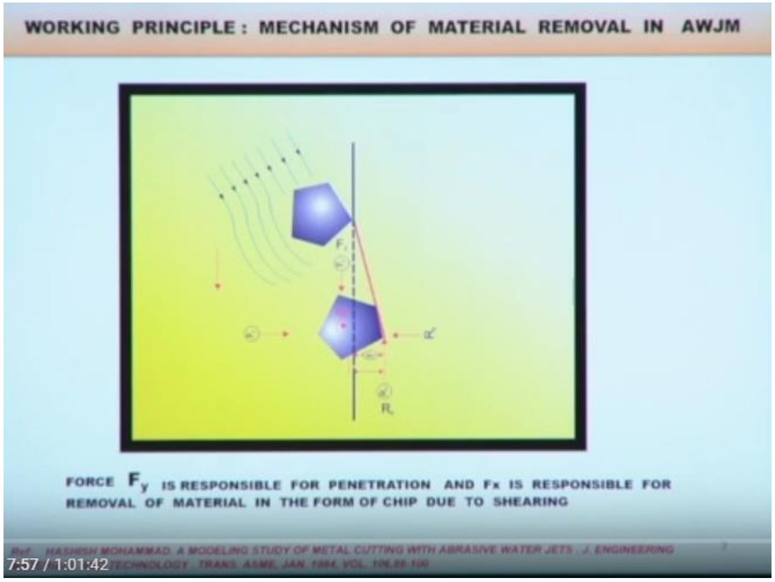

So here we can see that these abrasive particles it is coming with an angle and it is attacking so here abrasive particles are coming abrasive particles these abrasive particles are coming with an angle okay so it is hitting to the workpiece surface. So there are 2 forces you can see here this Fy this force actually it is this force is actually responsible for penetrating this abrasive particles into the workpiece surface. So it helps in penetrating the abrasive particles into the workpiece surface okay. So there is another force this Ry.

This R force is the resistance force by the workpiece okay. So this Fy is balanced by this resistance force okay. So this Fy is is helps in penetrating this abrasive particle into the workpiece surface which is (08:50) by the (08:53) force Ry and there is another force. This force Fx okay. So this force Fx actually it helps in cutting the surface and cutting the cutting from the workpiece surface okay. So this Fx actually helps in cutting operation and Fy it helps in penetrating into the workpiece surface.

So here Fy is responsible for penetration and Fx is responsible for removal of material in the form of chip due to the shearing action on the workpiece surface. So this figure actually it is taken from published by Hashish Mohamed, A modeling study of metal cutting with abrasive water jet, Journal of Engineering Materials and Technology, transaction of ASME, January 1985, volume 106 page number 88 to 100.

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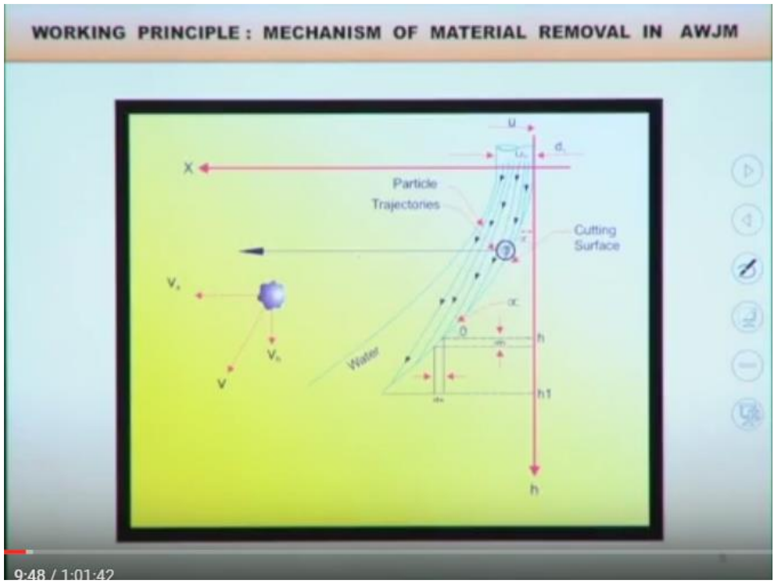

So another figure is there. Here we can see that this abrasive jets it is coming from this nozzle okay. So there is a traverse velocity of heat means this jet is moving with a velocity u with respect to the workpiece surface and this abrasive water jet it is coming with a velocity u0 at the workpiece surface here. It is coming with a velocity u0 at the workpiece surface.

Initially this diameter of this jet was d1. So while impacting into the workpiece surface you can see that this diameter actually it is increasing okay. So so this this diameter of this abrasive jet abrasive water jet it is shown into the workpiece surface inside the workpiece surface. Initially it impacting with a diameter of d1. So after impacting actually it will do this these particles actually there is a means tilting of these particles okay. So these particles it is tilting here you can see. So here this diameter is more than whatever it is diameter it is coming inside the on the top surface of the workpiece okay.

So this each abrasive particle if we consider it has 2 velocities velocity component. One is velocity Vh which is perpendicular to the workpiece surface which helps in penetrating into the workpiece surface and this Vx it helps this Vx actually it helps in cutting the workpieces cutting the cutting on the top surface of the workpiece okay. So this figure also taken from Hashish from transaction of ASME.

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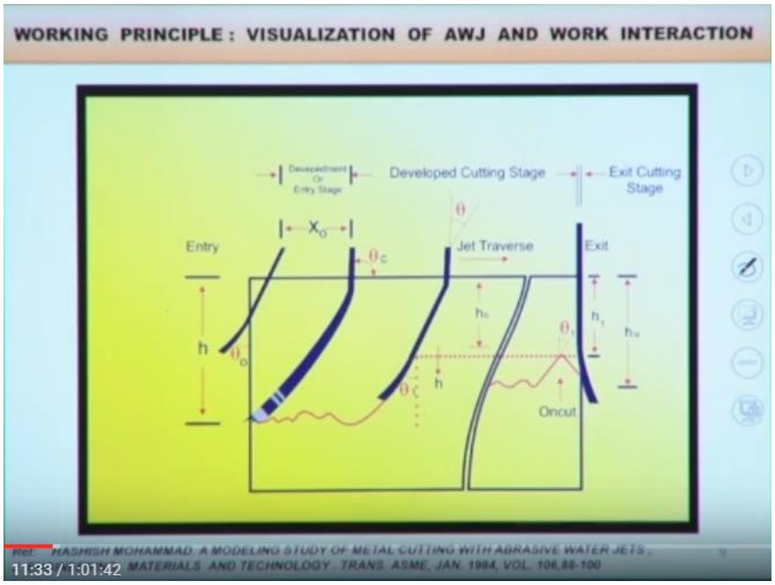

So another figure we can see here. So this is the entry to the workpiece surface and this is the exit on the workpiece surface. Here also you can see this this abrasive jet it is perpendicular it is hitting on the workpiece surface but there is a trajectory machine. So this velocity actually this direction of this of this abrasive water jet is actually changes after it hitting to the workpiece surface.

You can see just this is the depth means machine surface such below the workpiece you can see this kind of striations actually generated on the workpiece surface which is unwanted means whatever workpiece surface is generated on the workpiece surface if you are not making if you are making through holes by this abrasive water jet then it is okay but if are making a blind surface blind machine surface on the workpiece so you can see this kind of striations are generated on the workpiece surface okay. So at the end also you can see this kind of this workpiece surface here also this kind of striation generated okay so at the exit.

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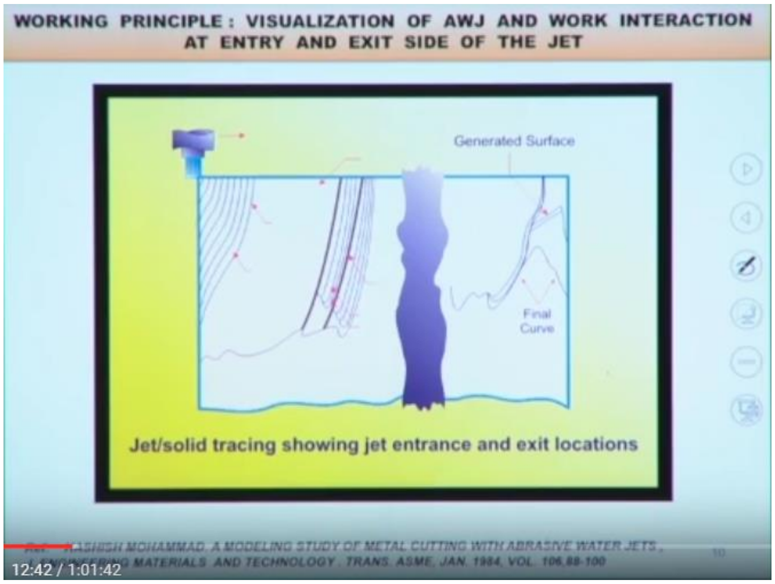

So you can see that this cross sectional so this figure is the cross sectional view of the machine surface means after machining we have taken cross section and on that cross section we have seen this kind of striation marks on the workpiece surface means whatever the particle trajectory is there so individual abrasive particle trajectory you can see on the workpiece on the cross section of this workpiece workpiece you can see this trajectory.

So initially actually this erosion this machining is due to the erosion erosive action by this abrasive particles. After that there is a local machining chamber (()) (13:16). On that local machining chamber it is a mixing chamber, it acts as a mixing chamber of abrasives and water jet okay. So abrasive water jet there is a local mixing chamber. So at that local mixing chamber what happens this this machining is due to the deformation.

So initially at the workpiece surface this machining is due to the erosive action of this abrasive water jet and after that this machining action is due to the this deformation at the at below at the bottom surface of the machining zone. So here also you can see this kind of striations are generated which is unwanted. So this figure also it is taken from Mohamed Hashish from transaction of ASME 1984 where they have shown that this they have modeled actually this abrasive water jet, they have modeled there in their paper okay.

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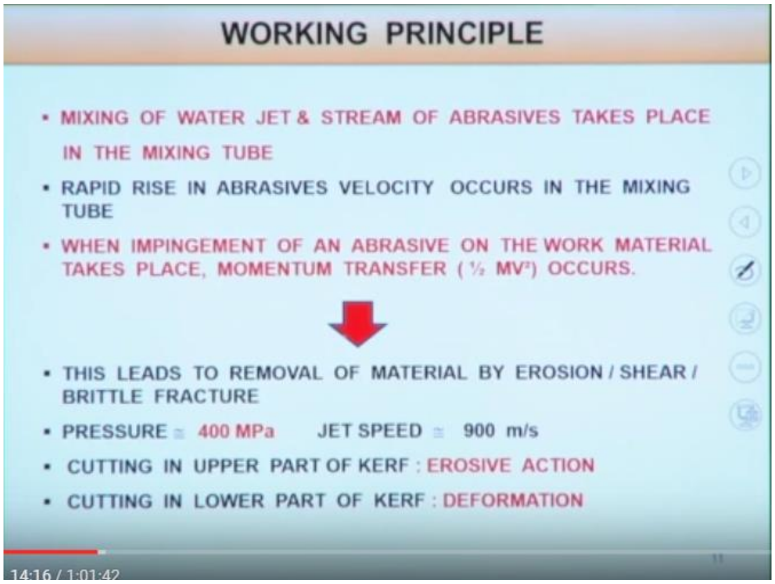

So what is the working principle here. So here in abrasive water jet machining process this abrasives along with means abrasives actually it is coming from the side of the nozzle and at the center of the nozzle actually water jet it is coming with a very high velocity. So maybe around 400 MPa pressure is generated from a pump okay so from an intensifier 415 MPa pressure is generated and because of this high pressurized highly pressurized water when it is coming through this nozzle it gains high velocity.

So this velocity is around 900 m/s and at this high velocity when this abrasive means water jet is coming through this nozzle at the side of the nozzle actually these abrasives are fed so these abrasives are actually sucked by this abrasive water jet or by this high velocity water jet and it inside this nozzle there is a mixing chamber is there. This abrasive and water jet actually mix there.

So after mixing this abrasive water jet it is coming through the nozzle okay so while coming through this nozzle their velocity is around 800-900 m/s so when this abrasive water jet, high velocity abrasive water jet while it is impinging or impacting on the workpiece surface with a very high velocity because of their high kinetic energy this kinetic energy so it hit on the workpiece surface and when this high velocity abrasive water jet hit on the workpiece surface it removes the material because of erosion from the workpiece surface okay.

So this kinetic energy is used high velocity kinetic energy of the high velocity jet is used for the machining purpose okay. So mixing of water jet and stream of abrasive takes place in the mixing tube so rapid rise in the abrasive velocity occur in the mixing tube in the nozzle and when this impingement of an abrasive on the work material takes place momentum transfer of 1/2 MV square occurs okay. So this leads to the removal of material by erosion, shear, brittle fracture on the workpiece surface.

So pressure, this water jet pressure is maintained at 400 MPa and jet velocity is maximum jet velocity is 900 m/s. So there are 2 modes of machining what I discussed in earlier figure. So cutting in the upper part of the kerf is due to the erosive action and cutting to the lower part of this kerf due to the deformation action okay. So because of this 2 different models are there, 2 different mechanisms are there this abrasive water jet actually it, this jet, velocity of this jet actually diverts in the deformation zone okay.

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So this is the setup for abrasive water jet machine okay. So this these are the links actually where you will get more information about this abrasive water jet machine okay. So this is the control panel here, you can write your program and this is the water tank here, this is the water tank and this is the xy table is there. You can move your table and you can make any kind of complex shape on the workpiece surface and this is the nozzle here okay and there is a this abrasive container is here okay. So you can see all these things clearly in the next figure okay.

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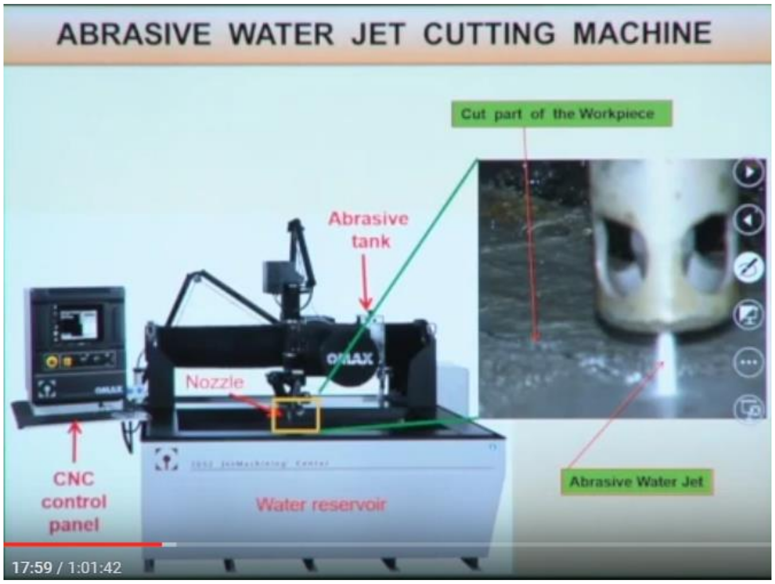

So you can see the same abrasive water jet machine here. So this is the water reservoir here. So this is the nozzle. You can see this nozzle in extracted view here. So this abrasive water jet is coming through this nozzle here. So you can see when this abrasive water jet coming and it is traversing with a velocity u okay. So with a traverse velocity u. You can see the cut marks on the workpiece surface. So this is the cut marks on the workpiece surface. So this is the abrasive water jet here okay.

Now here this is the abrasive tank. So from here usually these abrasives are mixed are coming and it is mixed into the mixing chamber. So this is the CNC control panel here. So here from here actually you can write your program and you can move your move your this workpiece okay so to cut any complex shape, complex shape of the workpiece.

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So this is the another view of this abrasive water jet machining machine. So this is the abrasive chamber here and this is the nozzle here. You can clearly see this nozzle and this is the workpiece here okay. This workpiece is kept over this over this over this table. It is properly fixed here this abrasives okay. So so this is the chamber water chamber is here and this abrasives through this pipe actually it is mixing through this mixing chamber and then this abrasive water jet is coming through this nozzle and it will come with a very high velocity okay so and it will remove it will do the machining action on the workpiece surface here okay.

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This is the another view of this abrasive water jet machine. Here you can see this chamber here, water chamber here okay.

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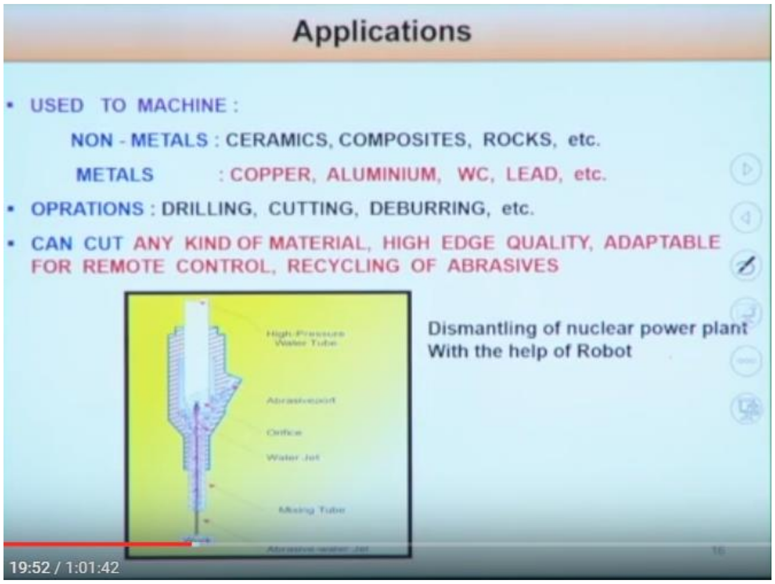

So this abrasive water jet machining basically it is used for cutting purpose. So that is why it is it is called abrasive water jet cutting or abrasive water jet machining okay. So people may, people also call it abrasive water jet cutting process also. So any kind of material either electrically conducting or electrically non-conducting material, hard or brittle material or soft material, any kind of material can be cut or machined by this abrasive water jet machining process.

So like nonmetals this ceramics, composites, rocks can be machined by this abrasive water jet machining okay. So like metals copper, aluminium, tungsten carbide, lead, etc., can be cut by abrasive water jet machining. So one thing we can remember here okay so here there is no fire hazard okay. So so it can be used, this abrasive water jet machining process can be used for making holes, making drills in mines in coal mines.

So because this water jet is coming so this water means with the jet actually it will inhibit with the formation of heat okay. So whatever heat is generated it is taken away so there is no fire hazard in case of abrasive water jet machining process. So what are the operations can be done? So these are the operations like drilling operation, cutting operation, deburring operation, okay. So these are the operations can be done by abrasive water jet machining process.

So it can cut any kind of material and whatever material is cut it has very high edge edge quality. So researchers have reported that this edge quality of this cut is very high okay. So adaptable for remote control. So this abrasive, either you can move this abrasive water jet, this nozzle you can move on a complex path or you can fix keep fixed this nozzle and you can move this workpiece okay. So you can move this workpiece using a CNC machine, CNC control using a CNC control okay. So so it can be used for remote control okay. So any kind of complex shape can be generated from this process and recycling of abrasives are done in case of this abrasive water jet machining because in abrasive water jet this abrasive particles actually this requirement of this abrasive particles are around 5 kg/min okay. So maximum point means maximum 5 kg/min. So because of this high requirement of this abrasives okay so this abrasive particles are actually recycled in case of abrasive water jet machining process okay.

So this abrasive water jet machining another example good example is that dismantling dismantling of nuclear power plant. Suppose you want to dismantle a nuclear power plant so you can send this abrasive water jet machining nozzle through a robotic arm and you can do the dismantling operation because of this fire means radiation hazard people cannot go there for the machining operation so you can send this nozzle through a robot okay so and robot will do the cutting operation by using this abrasive water jet nozzle.

So here you can see this high pressure jet is coming here okay. So it is coming through this workpiece here, this high pressure jet it is coming through this workpiece and at the site actually you can see this abrasive port. So this abrasive particles are coming because of this sucking action by this high velocity water jet, so it will it will come and there is a mixing chamber so this is the mixing chamber here.

So in this mixing chamber this abrasive water jet this abrasive particles this dry dehumidified abrasive particles actually it will mix with the water jet here with the dry abrasive particles will mix with this water jet in the mixing chamber. After that it will come through this nozzle okay and it will hit the workpiece surface here. So here actually centrally this high pressurized water jet is pushed delivered and from the side actually abrasive particles are delivered.

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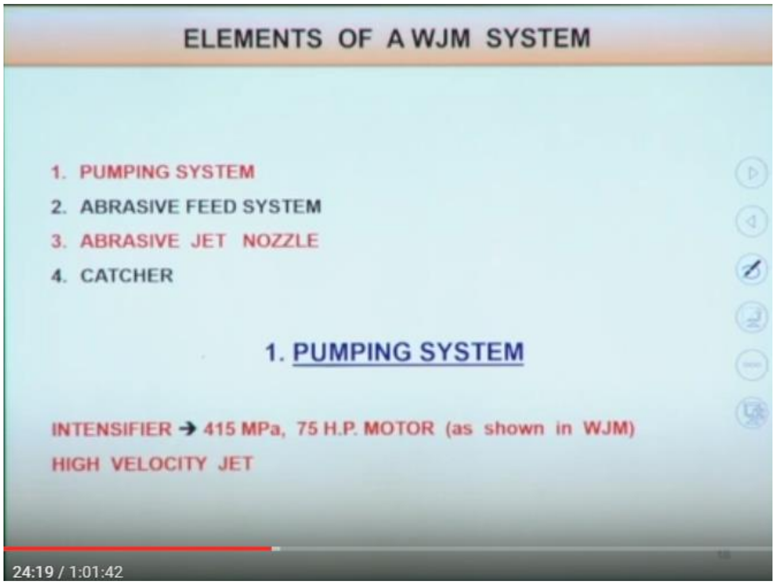

So what are the different elements of abrasive water jet machining process okay. So first element is the pumping system okay. So this first element is the pumping system. Second element is the abrasive feeding system and third element is the nozzle okay so abrasive water jet nozzle and mixing chamber okay and fourth element is the catcher in abrasive water jet machining process. So these are the 4 elements, 4 most important elements of abrasive water jet machining process okay. So now we shall discuss one by one all these elements.

Now pumping system already I have told. So this pumping system you need an intensifier to generate around 415 MPa pressure. So 415 MPa water pressure you have to generate and for that actually we need a high high kilowatt motor. So generally 75 H.P. motors 75 H.P. motor is used for generating this much of 415 mega pascal pressure okay. So this high pressurized water jet is converted into high velocity jet inside the nozzle okay.

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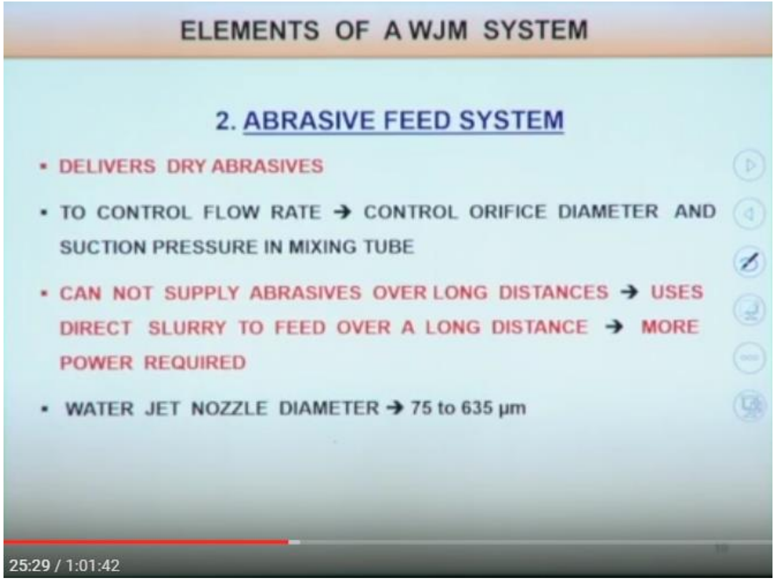

So abrasive feed system. So this abrasive feeding system this workpiece to deliver the dry abrasives okay so to control the flow rate control the orifice diameter and suction pressure in mixing tube should be changed okay.

So by changing the control orifice diameter okay and by changing the suction pressure in the mixing tube we can change the flow rate of this abrasive particles. So cannot supply abrasives over a long distance. So by this process while you are using a dry abrasive particles your supply which is dry abrasive particles through this from the side of this nozzle and from the center you are delivering the water jet high high pressurized high velocity water jet.

So by this process actually you cannot supply abrasive over a very long distance okay. So nowadays new system has come where instead of mixing this abrasive and water inside the mixing chamber you can mix with this slurry, you can mix this abrasive and water jet somewhere else and you can flow the slurry and you can feed this over a long distance okay.

So but in this case actually means when you are delivering the slurry over a long distance in that case you need a high velocity, means you need a high power pump or intensifier okay. So water jet nozzle diameter is so it is 75 to 635 micron. So this is the very small diameter is there 0.65 means 0.6 mm. So 0.075 mm to 0.635 mm. So this is the very small diameter of water jet means abrasive water jet nozzle is used to generate this high velocity.

So even a very even a big size abrasive particles comes into this passage way okay so it will clog the entire nozzle. So that is why you have to be very much careful about the abrasive particles. So these abrasive particles should be dry enough okay so that it should not make any agglomeration among themselves. Also it should this this size of this abrasive particles should be maintained so that it should not clog the this nozzle. Also what about the chips formed from the workpiece surface it may also clog the nozzle okay.

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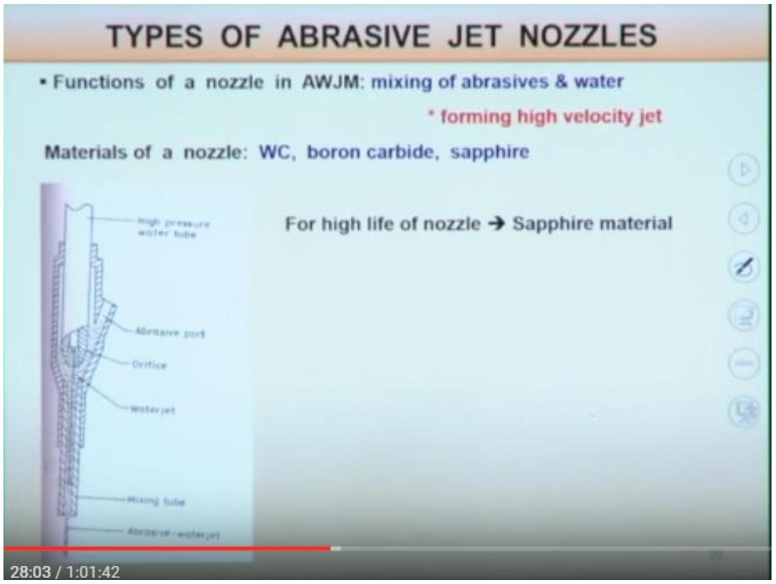

So types of abrasive jet nozzles. So depending on the time of work okay and applications there are different types of nozzles, nozzle materials are used. So these nozzle materials abrasive water jet nozzles because high velocity abrasives in abrasives actually it is coming towards the outer periphery of the nozzle okay so and jet water jet is coming at the center so this abrasive this nozzle material this inner surface of this nozzle it is directly in contact with this abrasive particles okay.

So directly in contact with this abrasive particles that is why so there is huge wear out of this nozzle is there means because of this abrasive particles which is coming towards the surrounding or surrounding this nozzle surrounding this nozzle okay. So this abrasive actually it will wear out the inner surface of this nozzle. To reduce that thing there are different combinations of the nozzles are there.

So we shall discuss all this different kinds of nozzle one by one. So there are different kind of different types of materials are used for this nozzle okay like tungsten carbide then boron carbide and sapphire. So among this these 3, tungsten carbide, boron carbide, and sapphire, sapphire is actually mostly is most generally mostly used so because it has a high wear it has a high tool life okay. So this nozzle life of this nozzle is high in case of sapphire okay.

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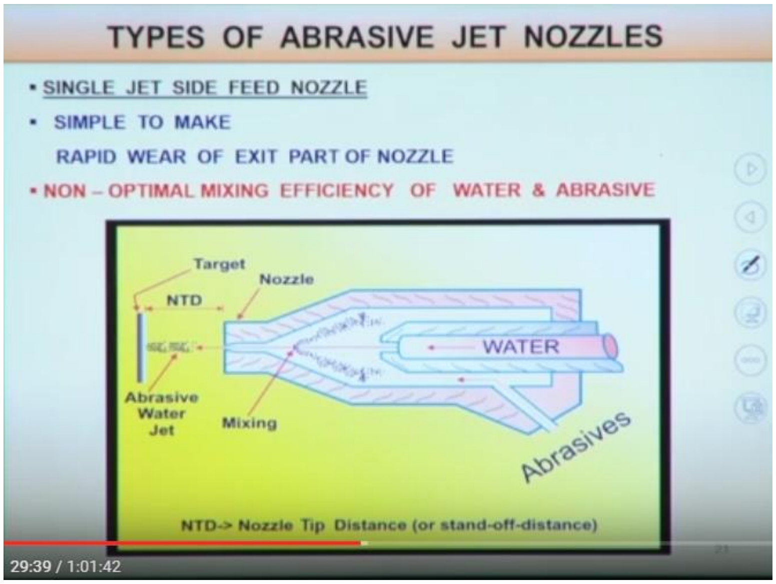

So different kinds of abrasive water jet nozzles are generally used. So here you can see that single jet side feed nozzle okay. So single jet means water is water jet at this single at the same time it is coming water jet but this abrasive particles are side feeded okay. So this abrasive particles are side feeded here. Here you can see these this abrasive water this water high pressurized water is coming through this orifice and it is coming here and from this side actually you can see these abrasives it is sucked in the machining chamber so this is the machining chamber or mixing chamber here.

So in this machining chamber this high velocity high water jet along with this abrasive particles is mixed here in this zone and then after that it will come outside through this nozzle okay. So from here to here this is called nozzle tip distance or stand of distance okay. So this is called stand of distance and nozzle tip distance.

So it has a used importance of this nozzle tip distance, by changing this nozzle tip distance you can change your material removal rate also you can change your this kerf with an accuracy of this machine surface. So different other things also you can change by changing this nozzle tip distance and this is the target or workpiece here.

So here abrasive water jet whatever mixed abrasive water jet it is coming through this nozzle here. So this is the mixing chamber here. So in this case you can see this abrasive particles it is coming from this outside, outside periphery of this nozzle and water jet is coming through this inner side, inner periphery inner periphery.

So as this abrasive particles are coming through this outer periphery while it is going coming from this nozzle while it is coming from this nozzle it will it will do the when it is coming through this nozzle it will do the wear out. So it will wear out the inner surface of this nozzle because this abrasive particles are coming from the outside periphery okay.

So it is this abrasive particles are at the outer periphery. So when it is coming through this nozzle it will wear out this nozzle. So so by this method so this side single jet side feed nozzle this wear means this wearing action is very high okay. So it is simple to make rapid wear of exit part of this nozzle and non-optimal mixing efficiency of water and abrasive. So here mixing efficiency is not good for this kind of single jet side feed nozzle.

After that there are another model which is called annular jet okay annular jet and center feed nozzle. So here it is opposite. Earlier this abrasive particles are side feeded. Here this abrasive particles are at centrally feeded centrally feeded and this water jet water jet is coming from this annulus region. So high pressurized water jet is coming per this annulus region.

So here better mixing of water and abrasives, so you can you can see here that this water this water jet is coming from this outer periphery and abrasive particles are coming from the inner surface of this nozzle and this is the mixing chamber, so here in this zone only, outside when it is coming outside this nozzle so there only actually this mixing occurs at the outside of the nozzle okay. So better mixing of water and abrasives can be observed for this kind of model of nozzle okay. So mixing is outside this nozzle and less accurate machining cuts are avoided.

So here you can see this there is a used divergence of this abrasive water jet okay. So this kerfs generated is less and kerfs generated is high here in this case and this accuracy of this water is generated here is accuracy is less accurate means workpiece is less accurate okay.

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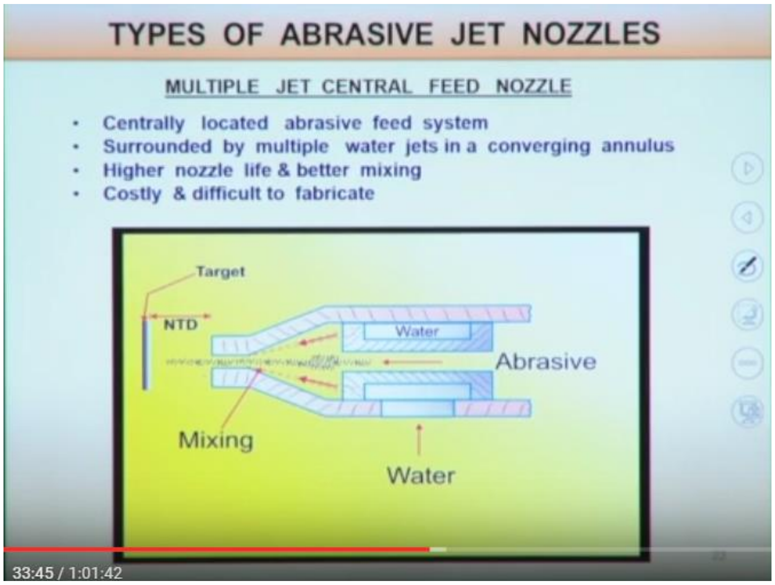

So third one is the multiple jet central feed nozzle. So this multiple jet nozzle okay so this water water is coming from this at the outer periphery of this nozzle from the outer periphery of the nozzle with multiple jet here so you can see here 2 jets. There are other jets are there and abrasive particle is fed towards the center from the center.

So this abrasive particles are fed to from the center so surrounded by multiple water jets in a converging annulus. So this abrasive jets are surrounded by multiple water jet okay. So it is surrounded by multiple water jets in a converging annulus here in this converging annulus it is multiple water jets are coming and abrasive particles are coming from the center here.

So here in this case higher nozzle life and better mixing is there but these kinds of nozzles are costly because it is very difficult to fabricate this kind of nozzle because whatever this water jet is coming from the inner periphery of this nozzle it has to be concentrated into one point. So this concentration and also abrasive particle has to be concentrated at this nozzle entry okay so so that there is a proper mixing can be done here okay. So it is very costly because it is very difficult to concentrate all this annulus from this all this water jet supply system to a certain point.

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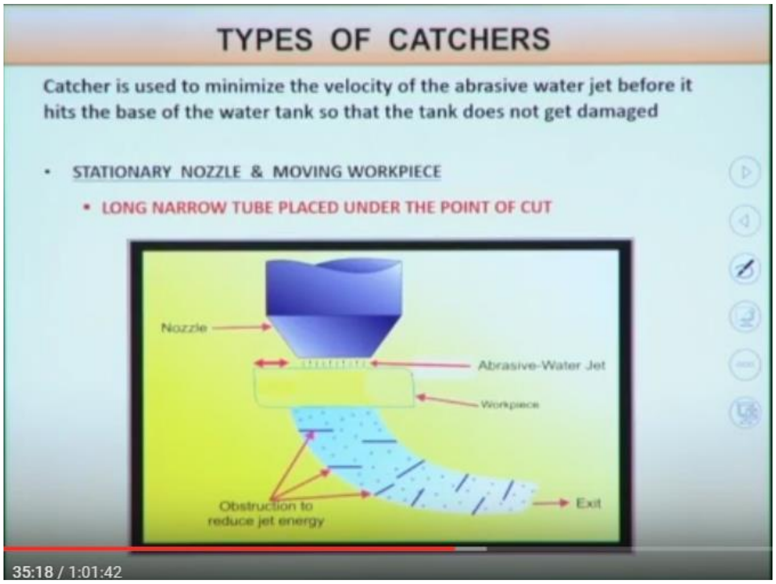

So now we shall discuss different kinds of catchers. First we shall discuss why this catchers are needed actually. So when this high velocity jet is moving and it is impacting into the workpiece surface and after machining operation after machining after machining what happens whatever this or just below the workpiece whatever material is available with the workpiece or fixed available below the workpiece okay so it will hit that portion okay.

So means after machining the workpiece it will hit the bottom surface of the of the machine okay. So when this high velocity jet is impacting into the just below the workpiece surface after machining okay it will do the cutting operation there itself on the machine okay. So to reduce this unwanted machining okay so you have to reduce the velocity of this abrasive water jet. So how to reduce this velocity of this abrasive water jet?

So in this case your workpiece is moving here but your tool is actually constant, tool is actually constant so here stationary nozzle and moving workpiece. So here workpiece is moving and here tool or nozzle is constant and just below the nozzle there is a long pipe is there so you can see there is long pipe flexible pipe is there.

On this flexible pipe these kind of construction okay so these kind of hard materials construction using very hard materials are kept okay. So (36:48) this abrasive water jet after cutting this workpiece okay so it is hitting back to the workpiece surface okay so it will hit the individual this individual this plates it will hit the individual plates which is (()) (37:02) okay.

So automatically its velocity because it is hit by this individual blades or individual material okay so it will its velocity will be reduced okay because because of this impact motion by this nozzle okay on this blade okay.

So after that this high velocity jet its velocity will reduce and it will exit this pipe okay. So catcher is used to minimize the velocity of this abrasive water jet before it hits the base of this water tank so that the tank does not get damaged okay. So this is the stationary nozzle and moving workpiece. So long narrow tube placed under the point of cut okay.

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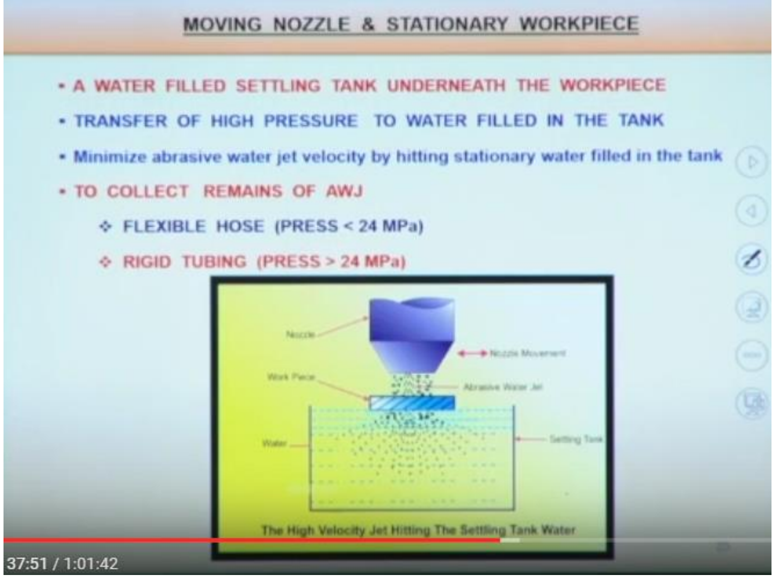

So now second one is the moving nozzle and stationary workpiece. So here in this case workpiece is stationary but your nozzle is moving okay. So in earlier case we kept one water water tube okay but in this case actually we are using a water tank. So on this just above that water tank we have kept the workpiece using a friction okay. So water filled settling tank underneath the workpiece is kept. Transfer of the high pressure to water filled in the tank so high pressure water jet okay so after machining okay so it will fall on the water tank and its automatically its velocity will be reduced.

So minimize abrasive water jet velocity by hitting the stationary wall filled in the tank and to collect the remains of this abrasive water jet flexible hose pipes okay. So flexible hose pipe is used when from this intensifier you have to connect this nozzle. So you have to flow the fluid from the intensifier to the nozzle okay.

So when your pressure is more than 24 MPa in that case flexible hose you can use and when your pressure okay so your pressure is greater than 24 MPa so in that case rigid tubing tubings are used to connect the rigid tubing is used to connect the nozzle with the high velocity pressure jet okay.

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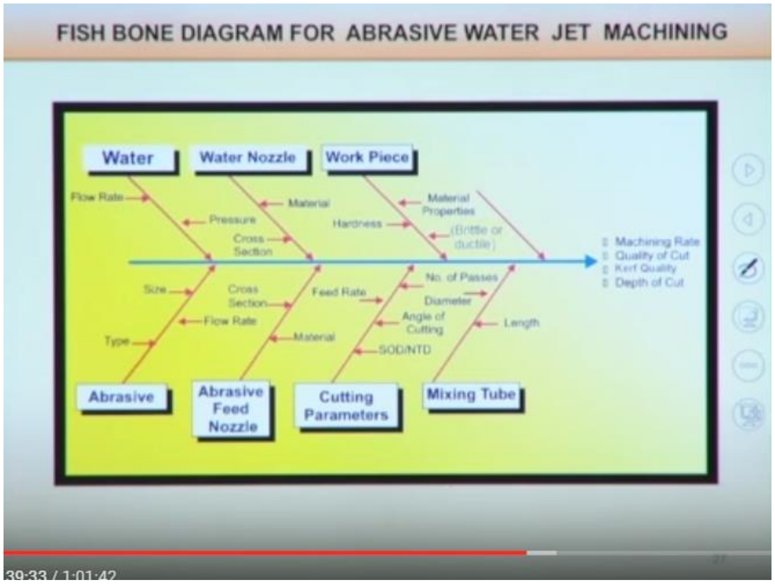

So these are the different parameters these are the different parameters which are used okay like water what are the parameters. So water in case of water this water jet flow rate of this water jet is an important parameter. Then pressure of this water is the important parameter okay. Like water these nozzles nozzle material is important because based on this material actually its wear life actually depends on the depends on this this nozzle material and cross section of this nozzle material also important like you can use circular cross section you can use the square cross section whatever you want, so you can use different kinds of nozzle cross section.

And then third one is the workpiece workpiece hardness, workpiece material properties brittle or ductile material okay so these are the parameters for workpiece. Now abrasive, abrasive type, what kind of abrasive type you are using, what is the size of this abrasive, and what is the flow rate of this abrasives both are important.

Abrasive feed nozzle, so this cross section of this nozzle, what is the different cross sections, what is the different materials used for this, so what are the different materials used what are the different materials are used for this abrasive feed nozzle okay. Then cutting parameters, among the cutting parameters is the transverse speed. So transverse speed was is one of the parameter, stand of distance is the one of the parameter, cutting velocity is one of the parameter, and number of passes is also one of the parameter, angle of the cutting is the and one of the parameters. So these these are the different parameters for cutting parameters or machine parameters and mixing tube length of this mixing tube is very important thing.

So number of passes or sorry mixing tube diameter also an important parameter. So by changing all these parameters you can change the efficiency of this abrasive water jet machine. So what are the output expenses are there. Output expense is this penetration width, then material removal rate, depth of cut, kerf quality, and then quality of cut so these are the actually machining means output expenses are there.

So kerf quality we have discussed earlier. Kerf is actually when this jet is with a diameter d actually cutting okay so what is the width of suppose there is a diameter of d abrasive water jet but after cutting you can see this is the width of cut is there. So this is called actually this one this one is called actually kerf. So what is the kerf generated is called what is the width of kerf on the workpiece surface.

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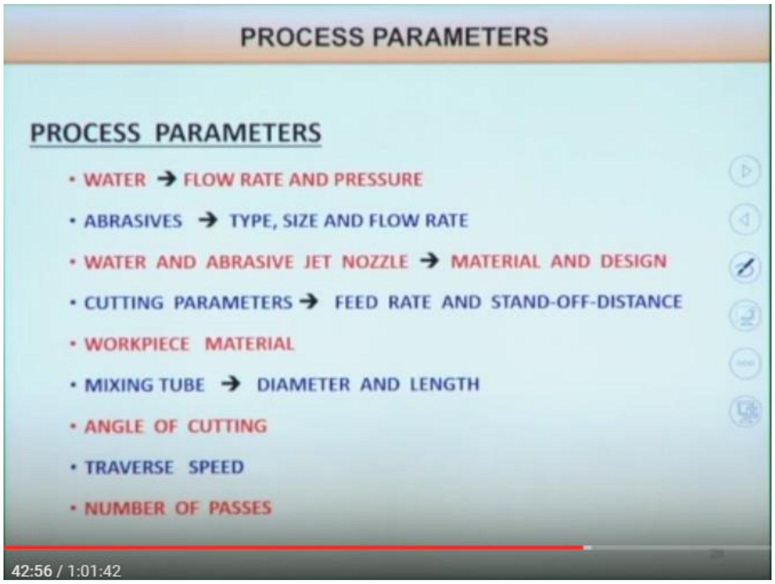

Then process parameters already we have discussed water. Water process parameters are flow rate and pressure abrasive type, size, and flow rate, water and abrasive water jet nozzle material design material and design. Cutting parameters are feed rate or traverse speed, stand of distance, workpiece material. These are the cutting parameters.

Mixing tube diameter and mixing tube length is also an important parameter. So angle of cutting is also an important parameter. Traverse speed is another important parameter and number of passes also an important parameter okay. So one by one all these parameters we shall discuss here.

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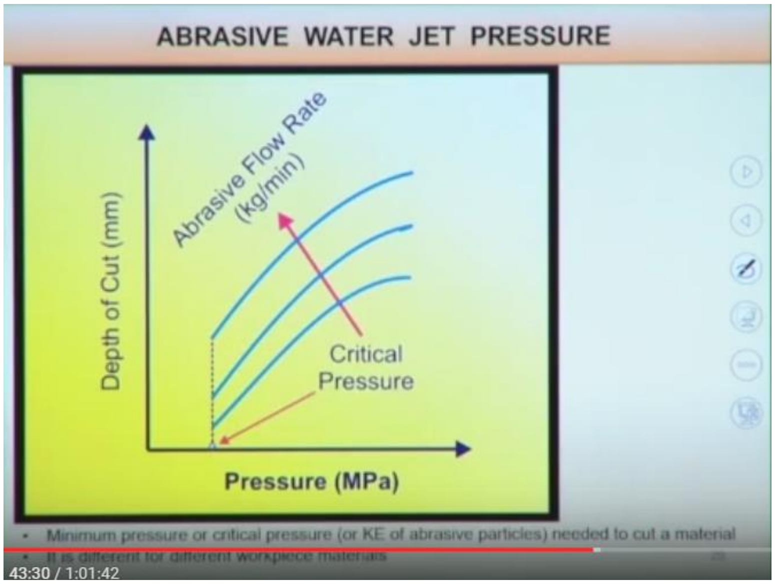

So here you can see with the increasing pressure, depth of cut actually increases. So this all this depth of cut increases with increasing the pressure okay. So if we increase the pressure, in that case your cutting velocity or also increases. This water jet velocity increases. So if your velocity increases it hit the workpiece surface with a higher kinetic energy so that is why you will get higher depth of cut.

So now here also you can see if you increase the abrasive flow rate so in that case also your depth of cut increases. Now here there is a critical pressure, minimum pressure or critical pressure is required to generate. So here beyond this means below this critical pressure there is no machining rate okay so there is no machining below this critical pressure because a certain pressure is required to generate the to gain the abrasive particle, certain kinetic energy. When this kinetic energy is strong enough then only it will do the machining okay.

So this minimum pressure or critical pressure or kinetic energy of abrasive particles are needed to cut the material okay so it is different for different workpiece materials. So this critical pressure is different for different workpiece material.

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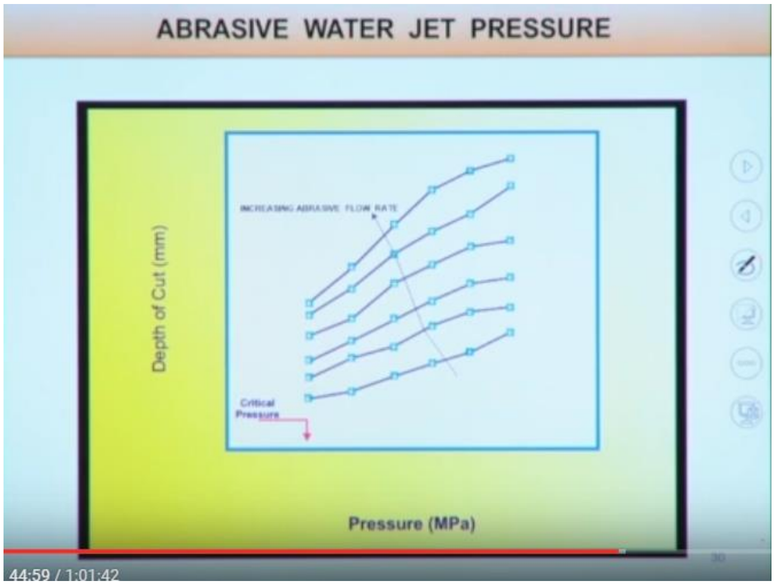

So again you can see here with increasing pressure depth of cut also increases okay so increasing abrasive flow rate also you can see if you increase the abrasive flow rate so in that case also this your depth of cut increases.

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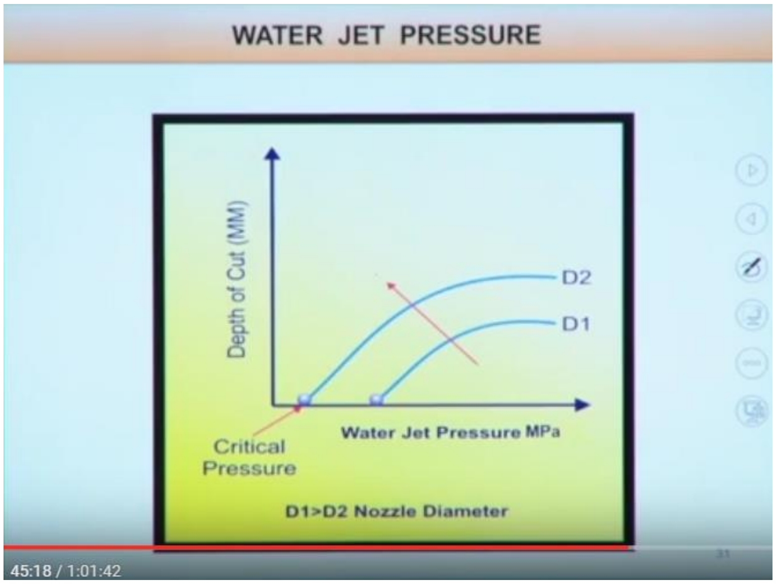

So here another another graph is there okay. So here D1 is more than D2 okay. So when this diameter of this abrasive jet nozzle is increased okay so diameter of this abrasive jet nozzle is increased so in that case there is a decrease in depth of cut okay. So means for lower depth lower diameter of lower diameter of this abrasive jet nozzle your depth of cut will be more okay.

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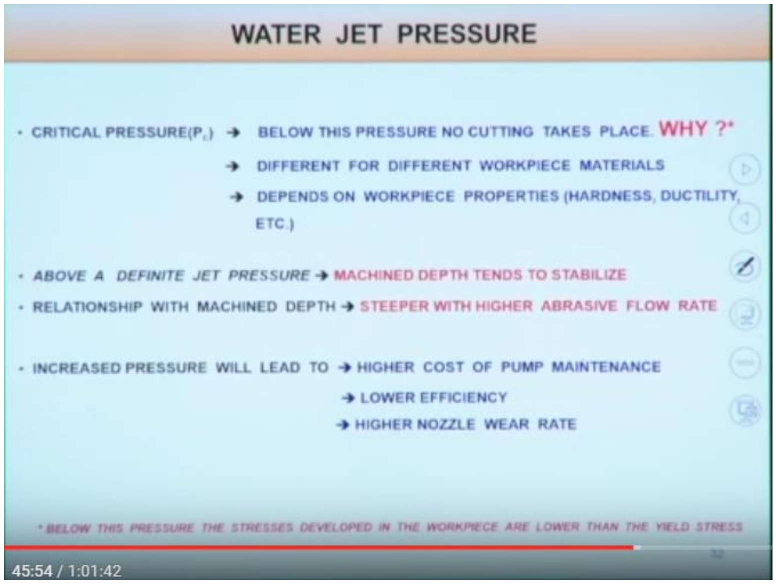

So this critical pressure is below this pressure. No cutting action takes place. So this critical pressure is different for different workpiece material. So it depends on the workpiece properties like hardness, ductility etc. So above a definite jet pressure machine depth tends to stabilize and their relationship between with the machine depth okay so steeper with the higher abrasive flow rate.

So with the abrasive flow rate with higher abrasive flow rate your this machine depth also increases. So increase in pressure also means we have seen that with the increase in the pressure here material removal rate or depth of cut increases but after means under certain limit or it will it will increase with up to some optimum level of this pressure okay.

So beyond this critical pressure what happens? There is a decrease in material removal rate. So what happens? This increased pressure leads to the lower efficiency because with the increase in pressure your velocity increases and with this high velocity abrasive particles it is coming outside this nozzle and it will wear out because here velocity is high and it will wear out the inner surface of this nozzle. So you have to change the nozzle okay.

So increased pressure will lead to the lower efficiency, higher nozzle wear rate, also higher cost of pump maintenance okay. So if we increase the pressure so pump maintenance is pump will be more. So now water flow rate.

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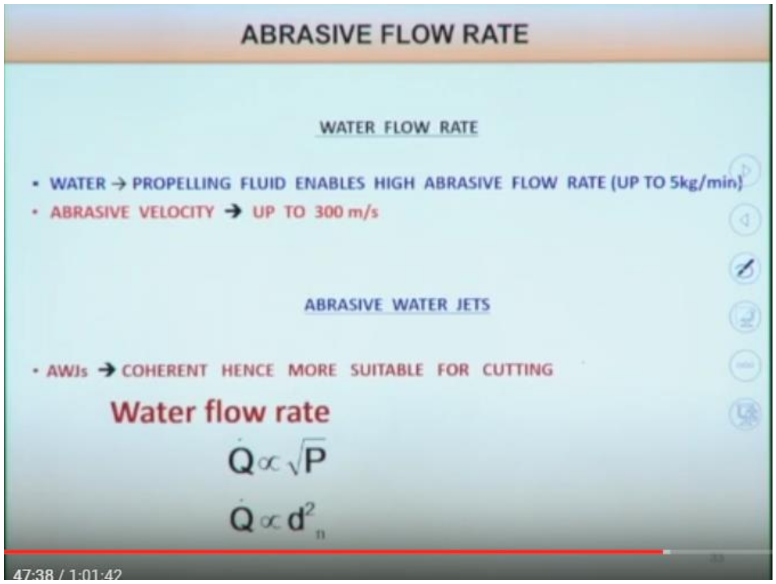

So water flow rate also increases the material removal rate in case of abrasive water jet machining process. So propelling fluid enables high abrasive flow rate okay up to this 5 kg/min and abrasive velocity is 0 to so abrasive velocity also increases up to 300 m/s okay.

So this water flow rate, flow rate of water is proportional to this root over of this P pressure, fluid pressure. Also this flow rate of this abrasive is proportional to the diameter of this nozzle. So it also it is proportional to the diameter of this nozzle. So one reason is that abrasive water jet why it is better than abrasive jet machining because in case of this abrasive water jet machining whatever diameter of this abrasive water jet is generated okay so this diameter this it is coherent.

So this abrasive water jet it is coherent in nature. So its it impinges or impacting into the workpiece surface into a small diameter. So it is a coherent jet is generated in case of abrasive water jet so that is why it is more suitable for cutting operation okay. So machine depth also depends on the kinetic energy of the abrasive particles, kinetic energy of the abrasive particles. So here this kinetic energy 1/2 MV square so you can see that machine depth is proportional to this velocity of this particle square and then mass flow rate of this abrasive particles.

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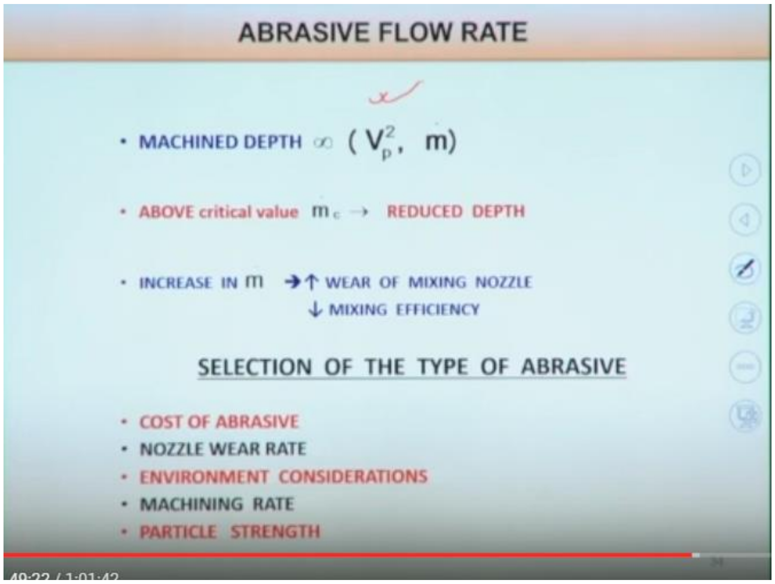

So above the critical value of this mass flow rate or abrasive flow rate reduce there is a reduced depth of this machine surface okay. So increase in material removal rate sorry increase in increase in material removal rate so wear of mixing nozzle will be there so and then mixing efficiency will reduce. So selection of this abrasive particles will depend on the cost of abrasives, nozzle wear rate, environmental consideration, machining rate, and particle strength.

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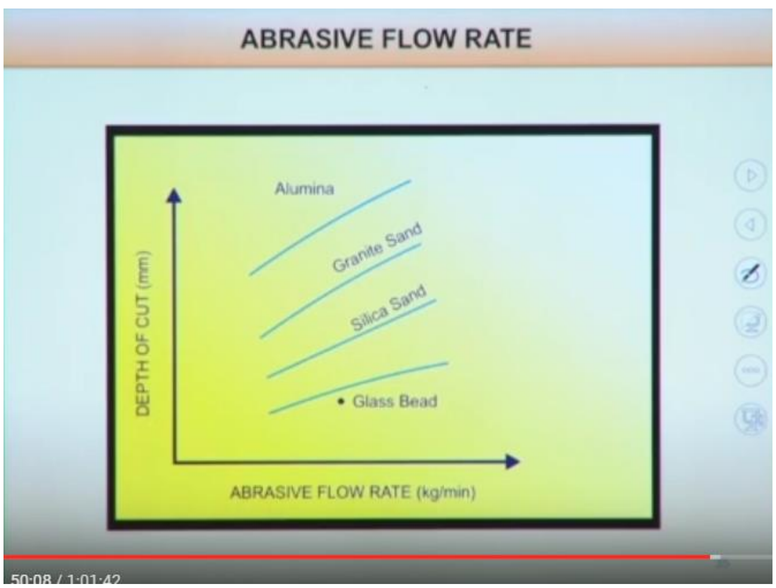

So now you can see this abrasive flow rate if you increase the abrasive flow rate you can see this depth of cut also increases okay so if we take different kinds of abrasive particles for different abrasive particle different depth of cut will be observed. So among this glass bead, silica sand, granite sand, and alumina as the hardness of this alumina is higher than all this abrasive particle all this kind of abrasive particle so depth of cut will be maximum for this alumina.

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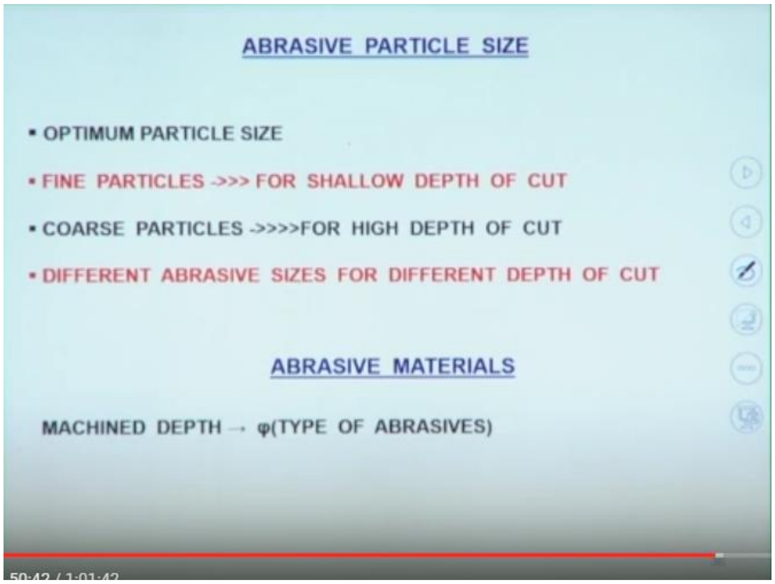

So abrasive particle size there is a optimal particle size is required because when abrasive particle size is more means more than this optimal particle size it will clog the inner surface of this nozzle okay. So because this nozzle diameter it is in the submicron range if we increase the diameter of this abrasive particles okay it will clog the internal surface of this nozzle.

So fine particles actually is used for shallow depth of cut and coarse particles are used for high depth of cut. So different abrasives sizes for different depth of cuts are actually used. So these are actually optimized from preliminary experiments.

So abrasive materials what so what kind of materials are what kind of materials of abrasive machining used okay so machine depth actually it depends on the type of abrasive, so what kind of abrasives we are using. Suppose if we use diamond abrasives in that case obviously your machine depth will be more because of this hardness of this abrasive particles is more.

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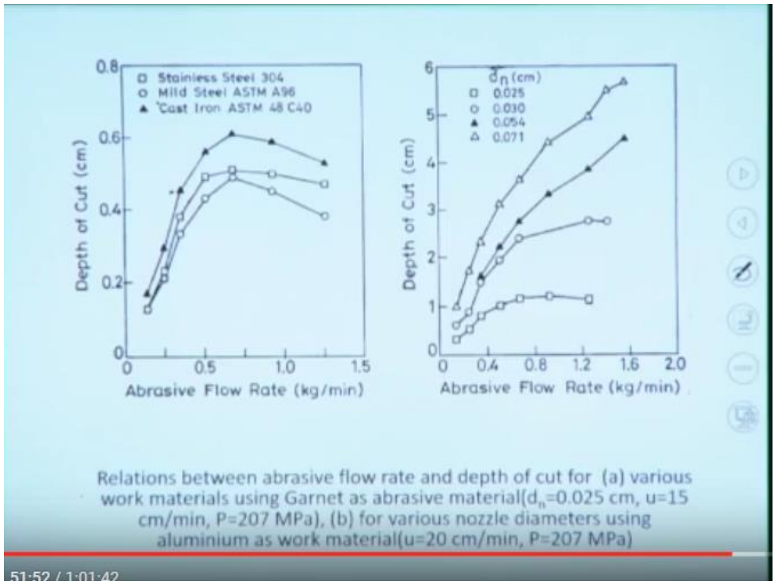

So here you can see this with the increasing the abrasive flow rate this depth of cut so this rate you can see it is very high here. So after that it touches the optimum abrasive optimum abrasive flow rate okay so where your depth of cut is maximum. After that this depth of cut actually decreases. When we increase the abrasive flow rate okay so in that case beyond the optimum value in that case actually your depth of cut after the optimum value is achieved this depth of cut again it is decreases.

Because more abrasive particles (()) (52:32) more abrasive particles this abrasive particles actually will collide with each other okay so it may make agglomeration also okay. So these abrasive particles are not good for machining okay. So then beyond the optimum value of abrasive flow rate your depth of cut will reduce okay.

So here also you can see abrasive flow rate if you increase your depth of cut also increases but here one interesting thing is that when your means your this depth of cut increases with the increasing the nozzle diameter okay. So here nozzle diameter is 0.25 cm but here in this case nozzle diameter is 107 1 mm sorry 0.71 cm okay. So with the increase in the nozzle diameter your depth of cut also increases.

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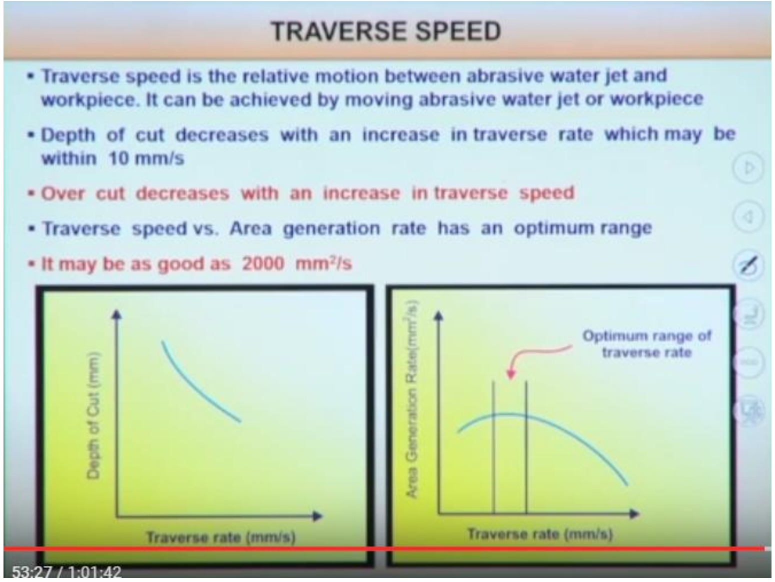

Okay traverse rate. So traverse rate means this nozzle actually we are moving with a certain velocity. So these nozzles we are moving with a certain velocity. So based on this traverse rate of this nozzle keeping your workpiece fixed, based on this traverse rate of this nozzle your machining rate also increases machining rate also machining efficiency also depends on the traverse rate of this nozzle okay.

So traverse speed is the (()) (53:53) between the abrasive water jet with the workpiece surface okay. So it can be achieved by moving the abrasive water jet or either moving the abrasive water jet or moving the workpiece. So depth of cut decreases. So this depth of cut decreases with the increase in the traverse speed. So if we increase the traverse speed your depth of cut actually it will reduce.

So overcut decreases with the increasing the traverse speed. Suppose you want to decrease the overcut so in that case we have to move the abrasive water jet nozzle with a very higher velocity or you have to increase the higher traverse rate to reduce the overcut on the workpiece surface and traverse speed has this area generation rate as an optimum value okay.

So this area generation which are discussed this area generation means it is the kerf area generation. Kerf area generation means it can be calculated by this traverse rate then this multiplied by the depth of cut. So this depth of cut multiplied by this traverse rate will give the your this kerf area generation okay.

So now we can see that there is a optimum kerf area generation with a certain traverse speed. After that actually this kerf area generated is reducing okay. After it achieves the optimum value then this kerf area generated it also then reduces.

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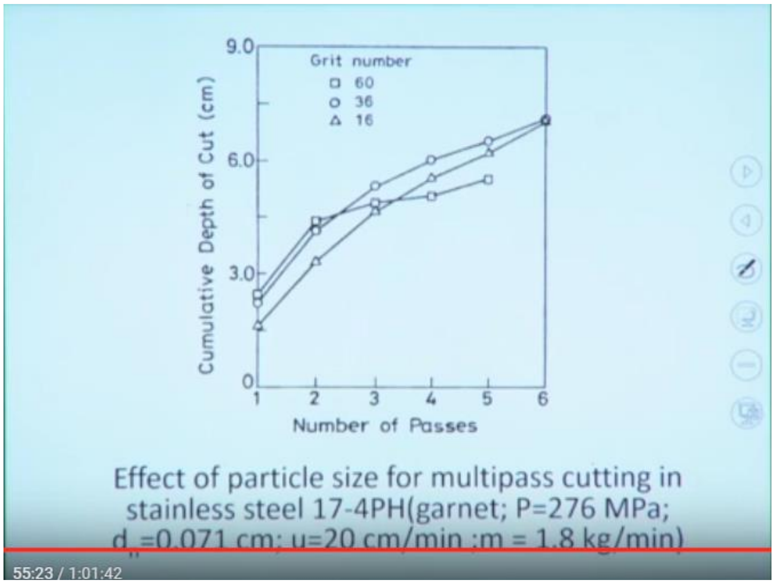

So number of passes means we can use means single nozzle or different pass different passes you can use for this certain for generating for getting certain depth of cut into the workpiece surface certain depth of machining into the workpiece surface or you can use multiple tandem of jet and you can move together all this jet nozzle you can move together okay.

So if we increase the number of passes okay you can see this cumulative depth of cut increases because at the second pass this whatever this machining cavity generated it behaves as a means local mixing chamber okay. So then third time when you are using this third pass this whatever machining cavity generated in the second pass it acts as a mixing chamber okay.

So that is why this number of with the increase in the number of pass your this cumulative depth of cut also increases with the increasing the number of passes okay.

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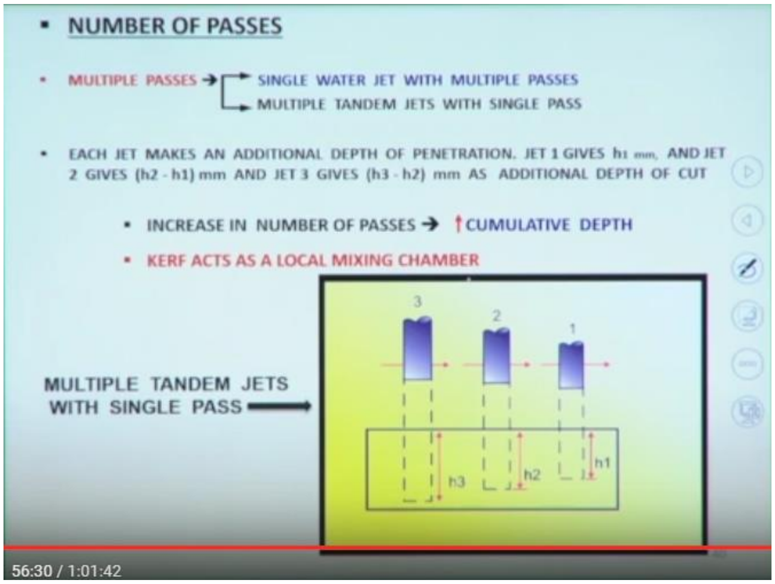

So here you can see that okay single water jet with multiple passes so here same single water jet we are using multiple pass a multiple tandem of jets with single pass is there okay. So each jet makes an additional depth of penetration jet 1 so here you can see this jet 1 it is penetrated up to this h1 and then h1 max and then jet 2 gives the h2 - h1 as the local mixing chamber and jet 3 gives the h3 - h2 mm as the additional depth of cut okay.

So with the increase in the depth of number of passes you can see that with the increase in the number of passes so we can see that we can see that your depth of indentation increases okay. So increase in the number of passes cumulative depth of depth of cut increases. Kerf acts as a local mixing chamber for this case okay. So multiple this is the multiple tandem jet with single pass okay.

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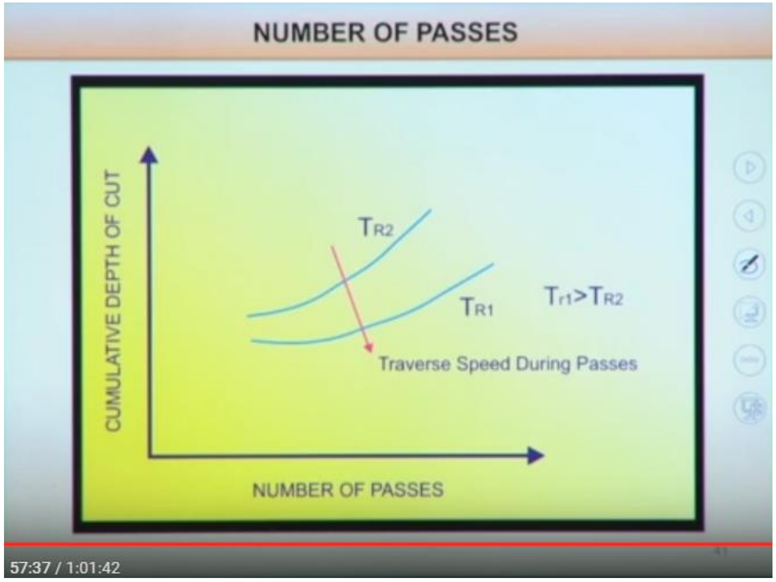

So with the number of passes you can see cumulative depth of cut also increases with the number of passes.

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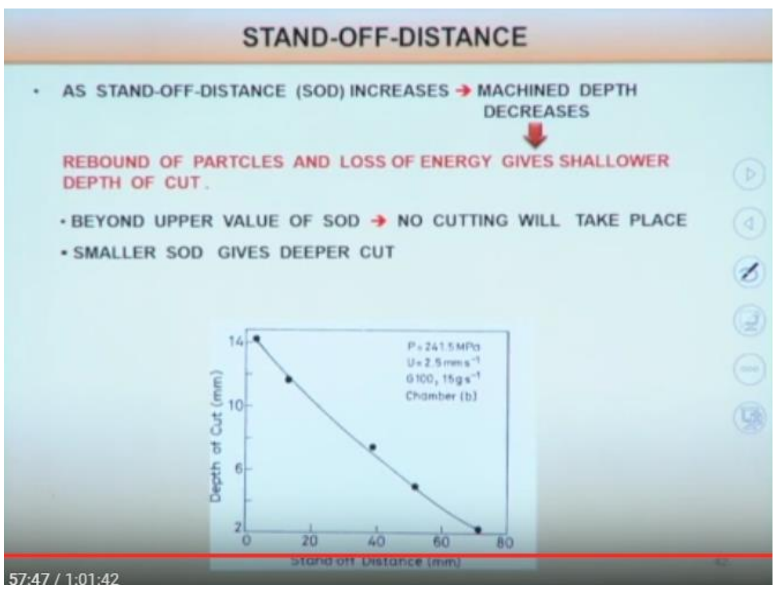

Okay stand of distance also an important parameter. So with the increase in the stand of distance you can see your depth of cut also decreases okay. So higher material removal rate higher depth of cut can be observed with a lower stand of distance okay. So as the stand of distance increases machine depth machine depth decreases because of rebounding of the particles, rebounding of the particles or loss of energy give shallower depth of cut okay.

So beyond the optimum value of this stand of stand of distance or nozzle tip distance no cutting will take place as small stand of distance give deeper depth of cut okay.

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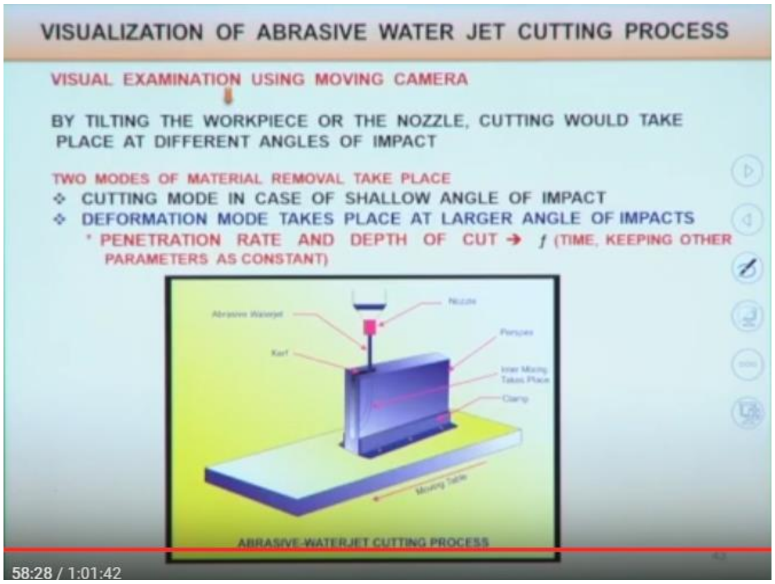

So this is the visualization of this abrasive water jet cutting operation using a moving camera. So you can see here so whatever this jet whatever whatever this jet is actually generating in case of abrasive water jet machining inside means inside the workpiece surface. Now if you take a moving camera along with this water abrasive water jet you can see this kind of projector is actually united in case of abrasive water jet machining process.

So by tilting the workpiece or nozzle a cutting mode take place at different angles of impact okay. So 2 modes of material removal is there one is the (()) (59:10) mode at the top surface of the workpiece and another one is the deformation mode at the bottom surface of the workpiece where local mixing chamber is already there. So penetration rate and depth of cut is a function of time keeping other parameters as the constant okay.

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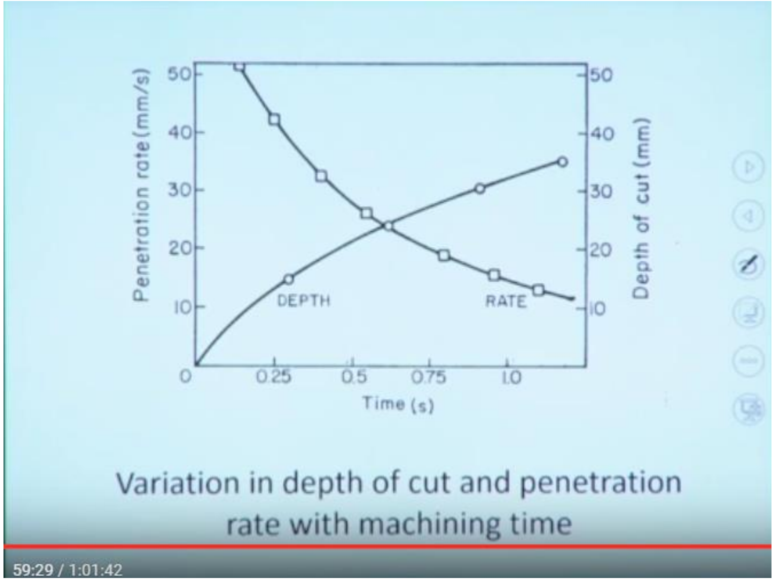

So now from here from this graph you can see with the machining time you can see depth of cut also increase with the machining time but this penetration rate but this penetration rate actually reduces with the with the depth of cut sorry with the with machining time so penetration rate reduces but this depth of cut increases with the machining time.

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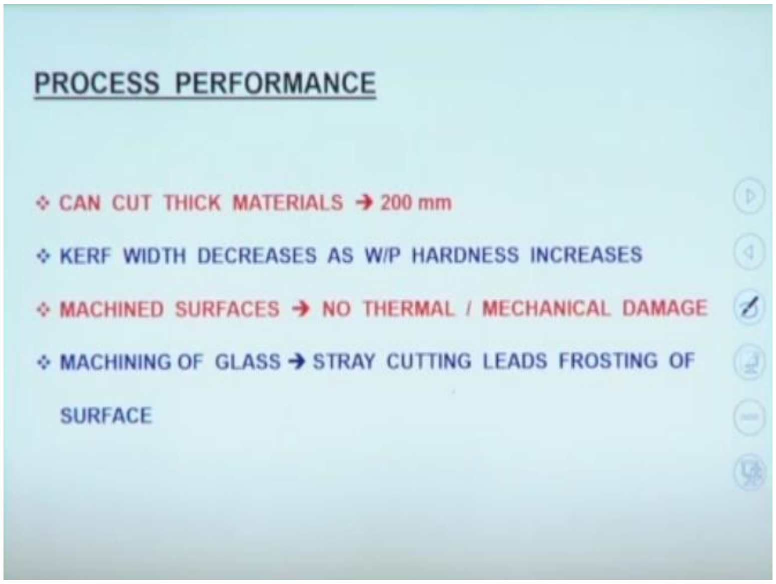

So process performance. So these abrasive water jet machining process mostly used for cutting purpose can cut thick material as much as 200 mm, this much of thick material can be cut okay. So kerf width decreases as the workpiece hardness increases. Machine surfaces, no thermal damage, no mechanical damages are there. Machining of glass so while doing this machining of glass by using abrasive water jet machining process because of this divergence of this jet instead of cutting actually there will be a frosting operation.

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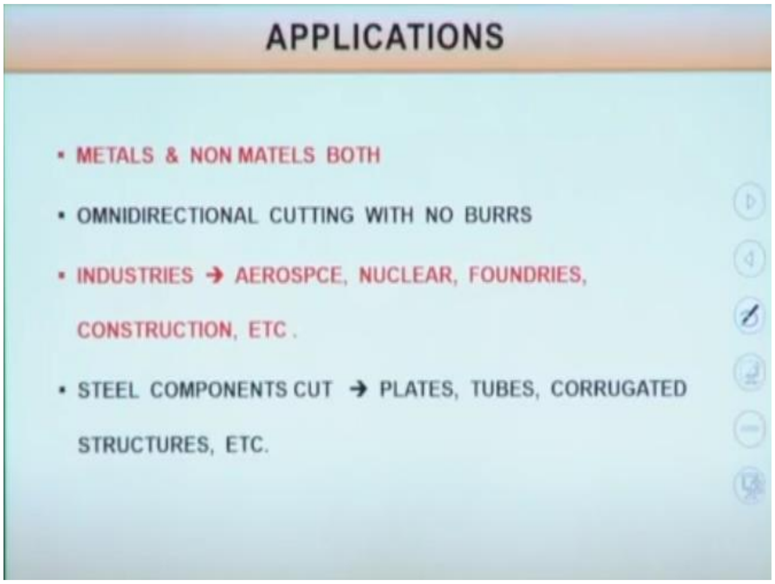

Applications, so any kind of material can be cut nonmetals, metals okay. So omnidirectional cutting so like in wire EDM process we have to do the hole okay so after that you can do the machining operation but in abrasive water jet machining process from (()) (1:00:52) from the workpiece surface you can start doing the experiment. So that is why it is it is called omnidirectional cutting okay. So industries like aerospace industry, nuclear industry, foundries, construction so they are using this abrasive water jet machining. Steel components cut plates, tubes, corrugated structures okay so this kind of structures can be cut.

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So here this is the cutting or pressing on a granite sheet okay so by using abrasive water jet machining process. So this butterfly also it is made up from granite sheet. This deer also it is made from granite sheet, it is made by a CNC abrasive water jet machining process okay.

Thank you.