Advanced Machining Processes
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Lecture 03
Abrasive Jet Machining

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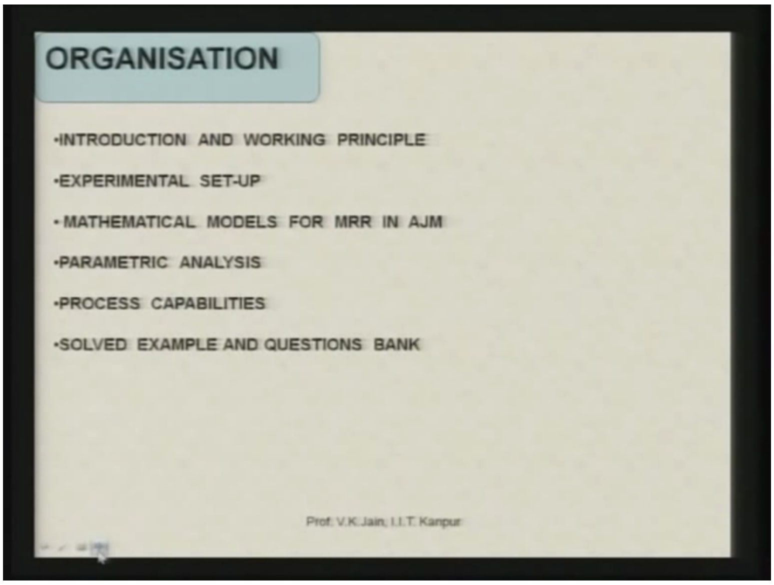

Welcome to the course on Advanced Machining Processes, today I am going to talk about abrasive jet machining. Organization of today's lecture is as follows, introduction and working principle of abrasive jet machining, experimental set-up used for abrasive jet machining, mathematical models for material removal rate in abrasive jet machining, parametric analysis of abrasive jet machining, process capabilities of abrasive jet machining process, some solved examples and question bank that is to be given.

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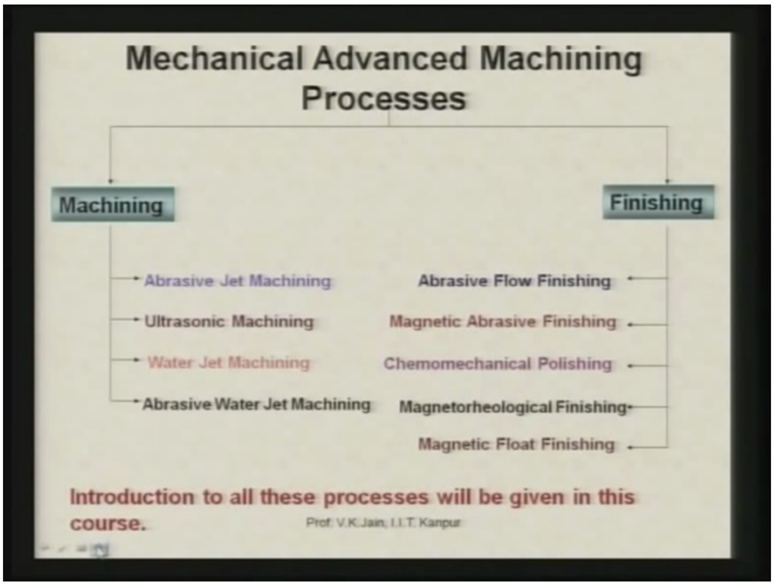

Let us start with the introduction and working principle of abrasive jet machining process, now mechanical type of advanced machining processes as we discussed in the classification in the last lecture, it is mechanical type where we have abrasive jet machining, ultrasonic machining, water jet machining and abrasive water jet machining. These are the various types of machining processes which come in the category of mechanical type of advanced machining processes.

Then there are the finishing processes with the help of which we can achieve micro or nano level surface roughness value that is the RA value in these processes. First one is abrasive flow finishing process or also known as abrasive flow machining process, second one magnetic abrasive finishing process, chemomechanical polishing CMP, next is magnetorheological finishing or also called as MRF process and magnetic float polishing. We will discuss most of these processes in this particular course. Introduction to all this processes will be given in this course.

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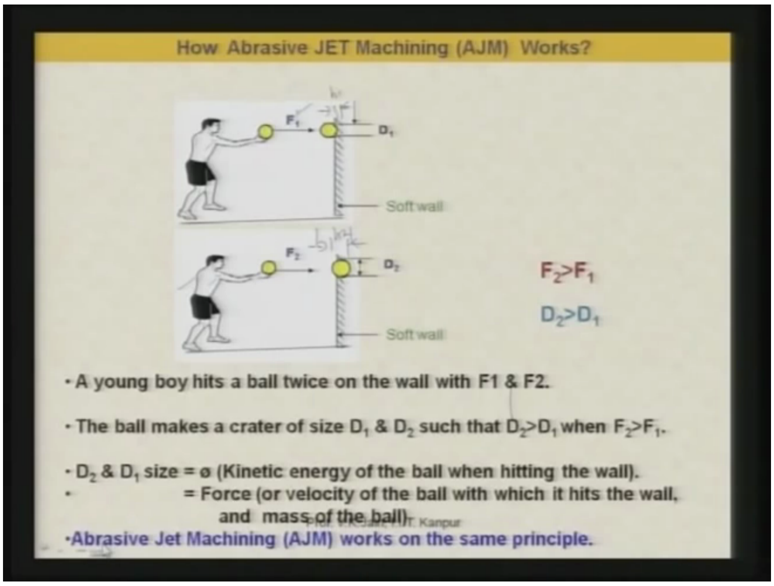

Now let us see this very interesting picture there are two persons throwing a ball on the wall and see first one is applying the force F1 and it is penetrating to a certain depth and the diameter is D1, second person is throwing with a force F2 and it is penetrating to a deeper depth and you can see here that force F2 is greater than the depth to which it is penetrating as you can see here H2 is larger than the depth for which it is penetrating in case of the force F1.

So this will depend upon how much with what velocity the person 1 is throwing the ball and the person 2 is throwing the ball. In second case the velocity or the force being applied on the ball is larger than the first one and that is why H2 is greater than the H1. Now in the second case the kinetic energy of the ball is larger than the first case that is why the depth of penetration H2 is larger than the case of H1.

Same way we will see that thousands of abrasive particles that are hitting the work piece, they are removing the material, smaller material or more amount of material, depending upon with what kinetic velocity, kinetic energy they hit the work piece surface.

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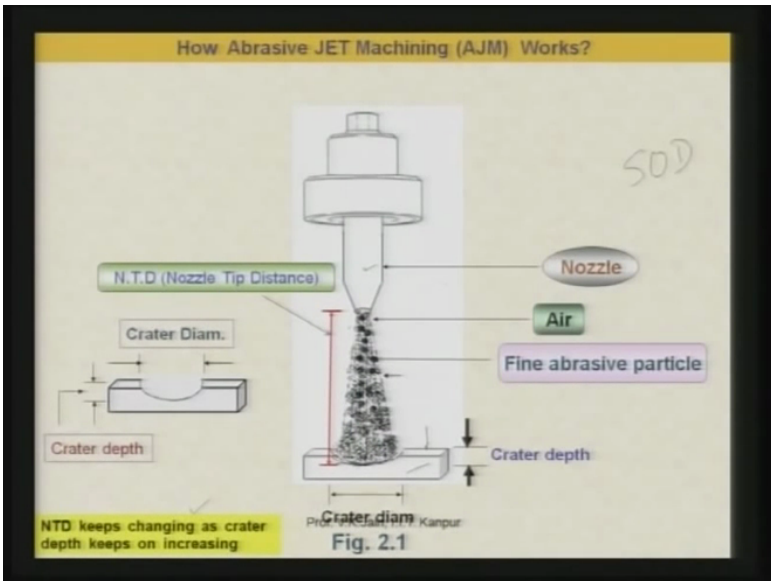

Now let us see how abrasive jet machining or AJM works which is the more or less the same as we discussed in the earlier slide, here you can see, here is a nozzle through which a mixture of air and abrasive particles is coming out in place of air you can have some other gas also now here you can see the distance between the tip of the nozzle and the work piece surface where it is hitting the work piece surface or abrasive particles are hitting the work piece surface, that distance is known as nozzle tip distance, NTD or it is also known as stand off distance SOD normally it is written as SOD.

Now this air and abrasive particles mixture consists very fine abrasive particles and you can see here this is the work piece from where the material is being removed in the form of the crater. Now as we see here on the left side, the depth upto which it has penetrated or the abrasive particles have penetrated the work piece that is known as cater depth and the width to which it is removing the material from the work piece that is called as crater diameter.

Normally depending upon the shape of the nozzle it can be a circular shape then you will call it as a diameter, it can be some other shape then accordingly you will have to call it as the width of the crater. Now nozzle tip distance keeps changing as crater depth keeps on increasing as you can see here if the jet is hitting the top surface of the work piece then you will have to measure this nozzle tip distance from the top surface, but in this particular case you can see it has penetrated to a certain depth so the nozzle tip distance is measured from that depth upto the bottom face of the nozzle, that is what is known as nozzle tip distance or stand off distance.

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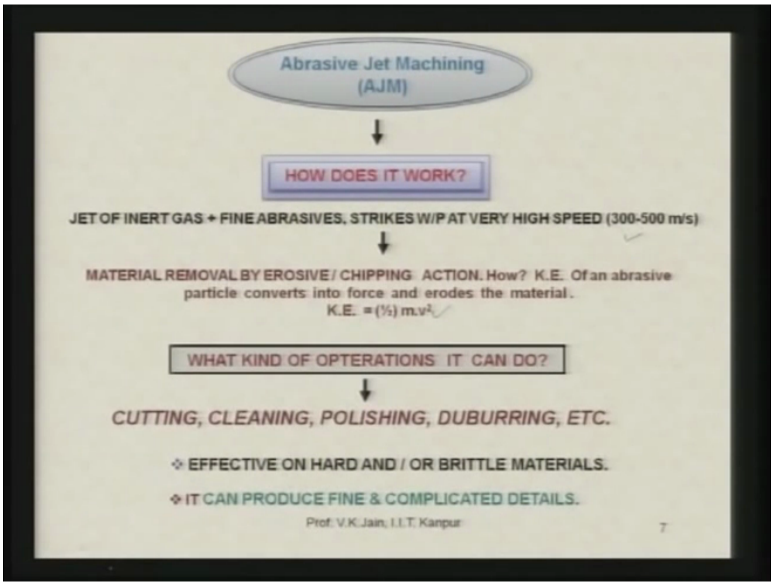

Abrasive jet machining, now we have just seen in brief how does it work, let us see this abrasive jet consists of inert gas in place of air you can have some inert gas and fine abrasive particles and these jet at a very high velocity hits the work piece surface and since abrasive particles have certain mass M and a velocity V so with half MV square they hit the work piece surface and the velocity with which normally this jet, air abrasive jet moves is somewhere between 300 to 500 meter per second, so it has huge kinetic energy.

So material removal by erosive or chipping action takes place, now the question arises how does this erosive action takes place? Kinetic energy of an abrasive particle converts into the force and erodes the material and the kinetic energy of the abrasive particle is given by half MV square, where M is the mass of individual particle and V is the velocity with which it is hitting the work piece surface.

Now the question arises what kind of operations the abrasive jet machining process can perform? So it can do various kind of operations like cutting of a piece in two pieces, cleaning, polishing, deburring, drilling the hole or cutting a different shapes of cavity, blind cavity or through cavity in the work piece, now this particular process is more effective on the hard and brittle material as compared to the ductile material in case of ductile material, the performance of the process is not that good as in case of brittle and hard materials. It can produce fine and complicated details also on the work piece.

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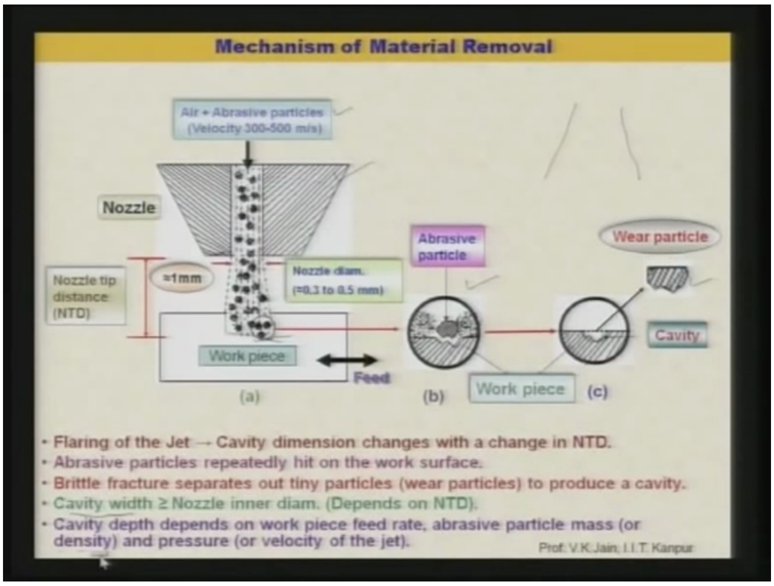

Now let us see mechanism of material removal in case of abrasive jet machining process here is the nozzle where you can find air plus fine abrasive particles are coming at a velocity ranging between 300 to 500 meter per second, now this abrasive particles at high velocity they come and hit the work piece surface as you can see here. The nozzle diameter normally is kept between 0.3 to 0.5 millimeter and the gap between the bottom of the nozzle and the top surface of the work piece is normally around 1 millimeter.

Now as you see here, when abrasive particles hits the work piece surface it fractures, brittle fractures the work piece material if it is a brittle and hard or if it is a ductile material then the deformation of the work piece material takes place and once this fracture has taken place and there are continuous hitting of the abrasive particles, thousands and thousands of times per second so that this fractured material that comes out of the work piece surface and you get a cavity created over there something like this.

Now there are thousands of such cavities formed on the work piece surface so according to the shape of the nozzle exit and the way in which this abrasive particles are hitting, you will get the shape of the cavity on the work piece surface and here is the worn out abrasive particle from the work piece that is creating the cavity.

Now you can see another thing that the jet is flaring as it is coming out of the nozzle that means the diameter of the jet is continuously increasing so it will depend upon the nozzle tip distance, what is the size of the cavity on the work piece so as you keep increasing the nozzle tip distance or stand off distance, the size of the cavity will keep increasing but depth keeps decreasing as I will show you in the next slide.

Abrasive particles repeatedly hit on the work piece surface to create the desired shape. Now the cavity width is greater than or equal to nozzle inner diameter what is the actual cavity width it will depend upon the stand off distance or nozzle tip distance. So cavity depth depends on work piece material feed rate, abrasive particle mass and pressure also.

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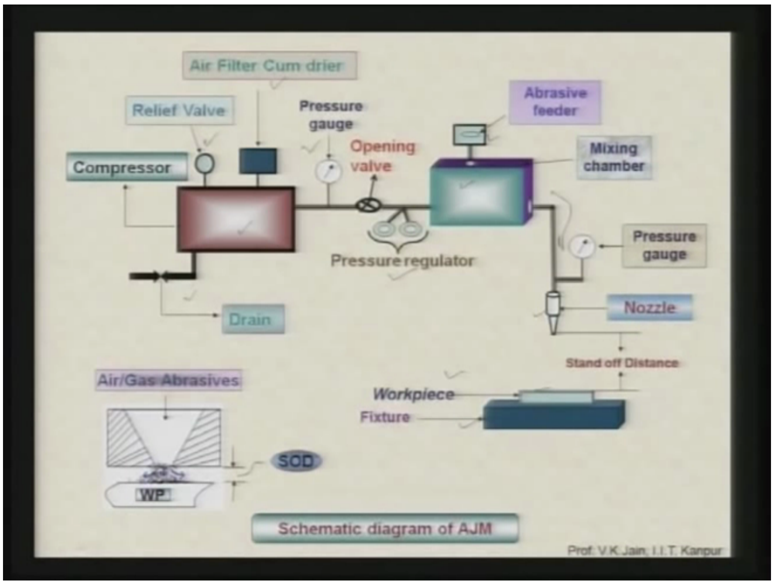

Let us see the experimental set-up for abrasive jet machining, there are various elements of abrasive jet machining set-up as you can see here, there is a compressor which compresses the air to the desired pressure as the reservoir or you can take out when there is a high pressure if you want to reduce the pressure of the air inside the reservoir then you can relieve the, you can either relieve valve to reduce the pressure then drainage is there connected to this reservoir and there is a another element which is very important, air filter cum drier.

The air which is going ahead is should be filtered and dried if it is not dried then you will not get a good performance in case of abrasive jet machining process and here is the pressure gauge with the help of which you can found out what is the pressure inside the reservoir and there is a opening valve and there is a pressure regulator and here in this case you can see here there is a abrasive feeder.

With the help of the abrasive feeder you supply the abrasive particles and inside this there is a mixing chamber itself, so where air and abrasive particles they mix up together and the mixture of the air and abrasive particles comes out and you can see here there is a pressure gauge with the help of which you can measure at what pressure air and abrasive particle jet is coming out and here is the nozzle.

From the nozzle as we have seen earlier the jet of air and abrasive particle comes out and it hits the work piece surface over here and this distance is known as stand off distance or nozzle tip distance and here is the work piece which is held by the fixture over there. Now you can see on this side, left side that as the mixture jet of the air and abrasive particles coming in, it goes let as well as right and then it separates out from the mainstream of the jet.

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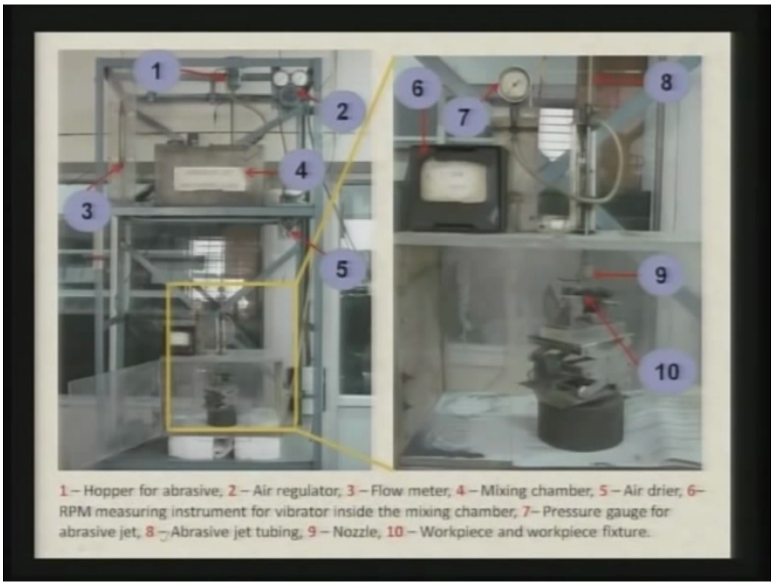

Now this is the picture of the AJM setup available in IIT Kanpur, you can see various parts or elements of the AJM setup shown over there. Here one is the hopper for abrasive particles and two is the air regulator over here and three is the flow meter with the help of which you can find out how much quantity of abrasive and air is flowing, four is the mixing chamber inside this as we have seen in the earlier case also and five is the air drier and six is the RPM measuring instrument for vibrator inside the machining chamber, how much quantity of the abrasive is mixing with the air it can be controlled with the vibratory motion and that vibratory motion is given with the help of CAM mechanism.

So that the desired quantity of the abrasive particle can be mixed along with jet of the air then you have abrasive jet tubing indicated by eight over here you can see now this is the enlarge view of this particular part is shown over here and nine is the nozzle as you can see here not very clearly see nozzle is there and ten is the work piece and work piece fixture so the jet actually comes from here and hits the work piece surface.

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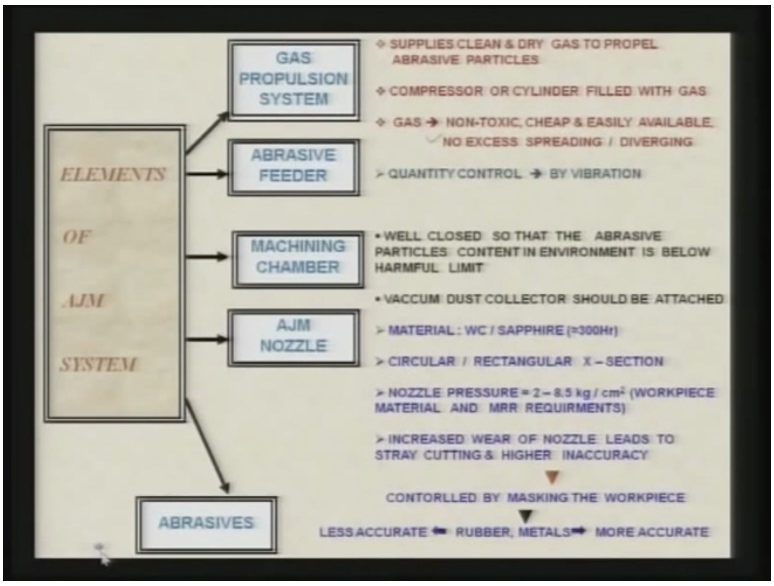

Now elements, what are the various elements of the abrasive jet machining system? We can see first is the gas propulsion system. Gas propulsion system supplies clean and dry gas to propel abrasive particles this gas maybe air or some gas which should be inert gas. Then you have the compressor or cylinder filled gas because compressed air has to be filled somewhere in the reservoir for that purpose you can use the cylinder also.

If you are using other than air you can use some other gases also as but those gases should be non toxic in nature, cheap and easily available and it should not have access spreading or divergence otherwise the size of the cavities that you are forming on the work piece will be difficult to control.

Second element is abrasive feeder now abrasive feeder with the help of the vibratory mechanism as I just mentioned you can control the quantity with the help of the vibration then third is the machining chamber it is close so that the abrasive particles contain in environment is below harmful limit this is very important we should always keep the machining chamber closed so that the fine abrasive particles do not spread in the environment otherwise they will be very harmful to the operator and the people standing nearby to the AJM setup.

And there should be vacuum dust collector attached to the machining chamber so that you know dust particles etc. they are collected and they are put out of the machining chamber. AJM nozzle, the material or the AJM nozzle normally used is tungsten carbide or sapphire and if sapphire is used in general you can get reasonably good life of the sapphire nozzle that is around 300 hours.

The shape of the nozzle can be circular, it can be rectangle or other cross-section it depends upon the designer of the nozzle and the requirements of the work piece. Nozzle pressure normally ranges between 2 kg per centimeter square to 8.5 kg per centimeter square but actual value to be used depends upon the work piece material that you are machining and the required material removal rate.

Now increased wear of nozzle leads to stray cutting and higher inaccuracy, we should use the material of the nozzle such that the wear of the nozzle is minimum if there is a access wear of the nozzle then definitely you are not going to get accurate work piece over there and I can just show you over here.

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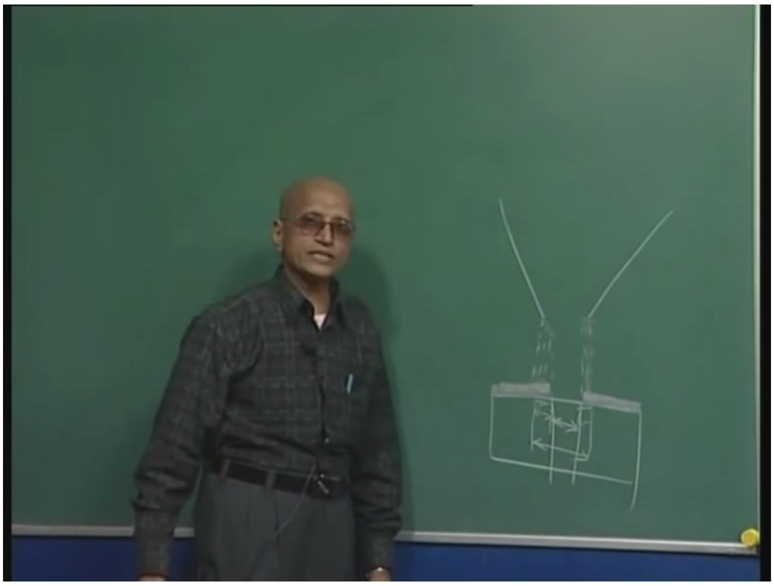

Here if you see the cavity it is forming like this now if there is an axis wear of the nozzle like this then the cavity it is going to form is like this although the what you have design machining parameters for this particular cavity but since the nozzle has worn out so you will get this cavity which will not be good as long as your requirement of the component are concerned.

So this is known as stray cutting this portion you can call as stray cutting. Now there are various parts of the abrasive particles which are used in AJM process. Now the question arises how to control this stray cutting so one of the ways is you can control it with the help of the masking the work piece.

I will just show you here what you can do I you want them cutting only in this region, you can use the masking in this region and this masking can be obtained with the help of light material so that when this abrasive particles they are hitting the mask they will be removing the material from the mask but they will not be removing the material from the work piece over here.

So the masking can be used for accurate machining in case of AJM and specially then the nozzle has worn out more than the limit that you designed for. Now you can use rubber as the mask but it gives you less accurate machine component you can use the sot metals and that will give you more accurate machine component.

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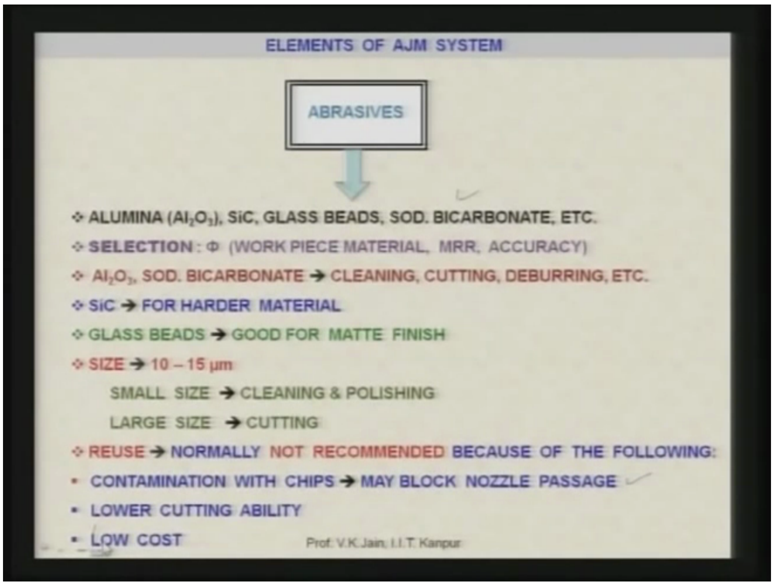

Now there are various types of the abrasive which are used in abrasive jet machining just like alumina AL2O3, silicon carbide SIC, glass beads, sodium bicarbonate, etc. Now selection of right kind of abrasive particles for AJM process depends upon work piece material properties, material removal rate that you require and the accuracy that you want. Alumina AL2O3, sodium bicarbonate, they are normally preferred for cleaning the work pieces for cutting, for deburring, etc.

Silicon carbide is normally used or harder material as compared to alumina, glass beads are good for matt finish. Size of the abrasive particles normally used is 10 to 15 micron size the small size abrasive particles are good for cleaning purposes and finishing purposes. Large size abrasive particles are good for cutting because they can give you higher material removal rate as compared to the small size abrasive particles.

Reuse of the abrasive particles is normally not recommended for the simple reason that contamination with the chips, these abrasive particles they get contaminated with the material that has been removed from the work piece and you cannot easily remove the work piece material so what will happen this contamination may block the nozzle passage and if it is able to block the nozzle passage then nozzle will break, will get damaged and it is very expensive.

Secondly if the abrasive particles gets contaminated with the chips removed from the work piece material then the cutting ability of abrasive particles reduces and thirdly the abrasive particles are not very expensive so when one can easily afford to not to reuse the abrasive particles in the AJM process.

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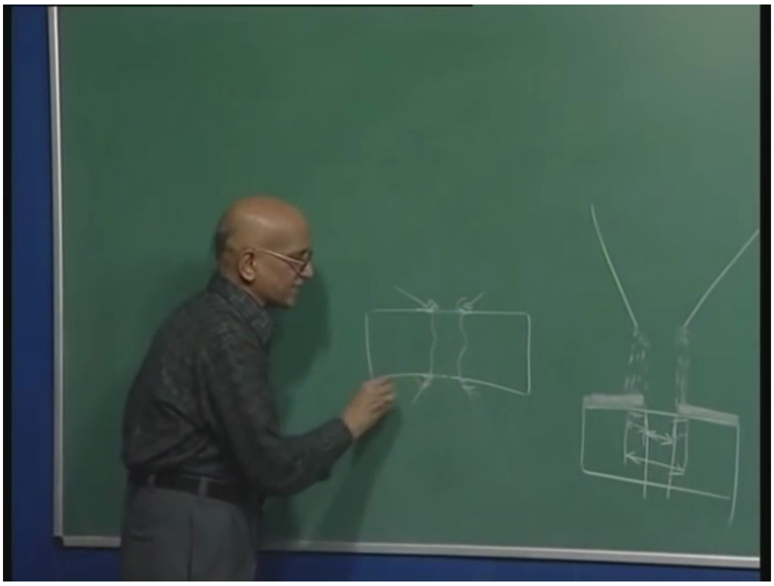

Now the question arises I have just told you deburring. What is deburring? I hope you know it that when you are drilling a hole inside the component then you find that some of the material is left over there at the top as well as the bottom when you are able to drill the hole now removal of these burrs is very important otherwise you put this component into sub assembly or assembly without removing the burr then this burr will be dangerous fatal for the failure of the component and this removal of the burrs is known as deburring and this process is very good for deburring purposes.

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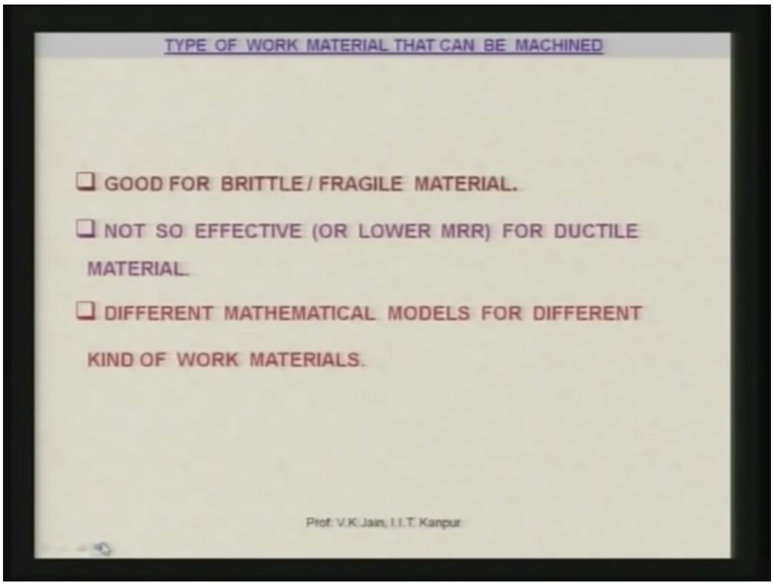

This particular process, AJM process is good for brittle or fragile materials it is not so effective or not so good for ductile materials although it can be used but it will give you lower material removal rate. Now theoretically calculation of material removal rate in case of AJM is also important and different researchers have proposed different models separately for ductile materials and brittle materials.

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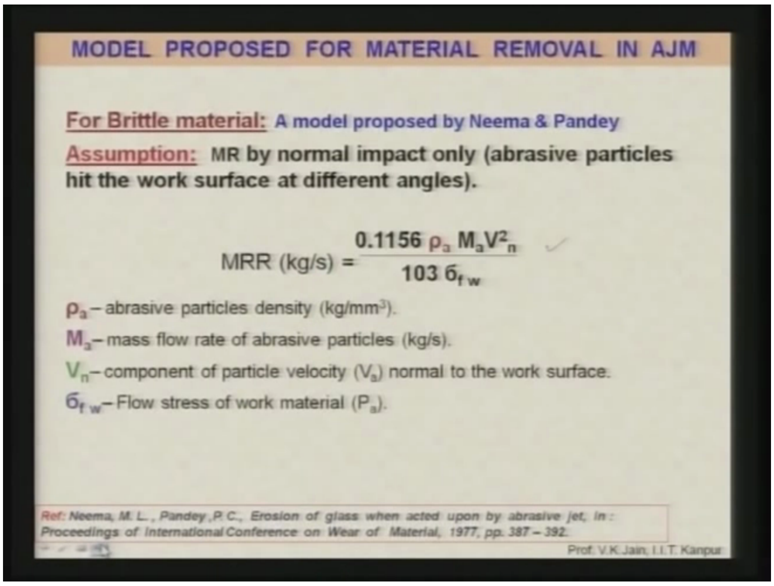

I will just tell you in very brief two models proposed by two different researchers one for ductile material another for brittle material. Model proposed for material removal in AJM for brittle material, a model was proposed sometimes back by Neema and Pandey, assumptions they have made is material removal by normal impact only that means the abrasive particles is hitting the work piece surface at an angle of 90 degree they are not considering that the abrasive particle hitting the certain angle other than 90 degree.

Abrasive particle hit the work piece surface at different angle in general not only at 90 degree. Now material removal rate in terms of kilogram per second they are proposed it can be calculated with the help of the formula 0.1156 rho A MA VN square divided by 103 sigma FW where rho A is the abrasive particle density in kilogram per millimeter cube, MA is the mass flow rate of particles in kilogram per second, VN is the component of particle velocity normal to the work piece surface and sigma FW is the flow stress of the work piece material in pascals.

Now this is the paper which I have referred by Neema and Pandey, erosion of glass when acted upon by abrasive jet in proceedings of international conference on wear of material, 1977.

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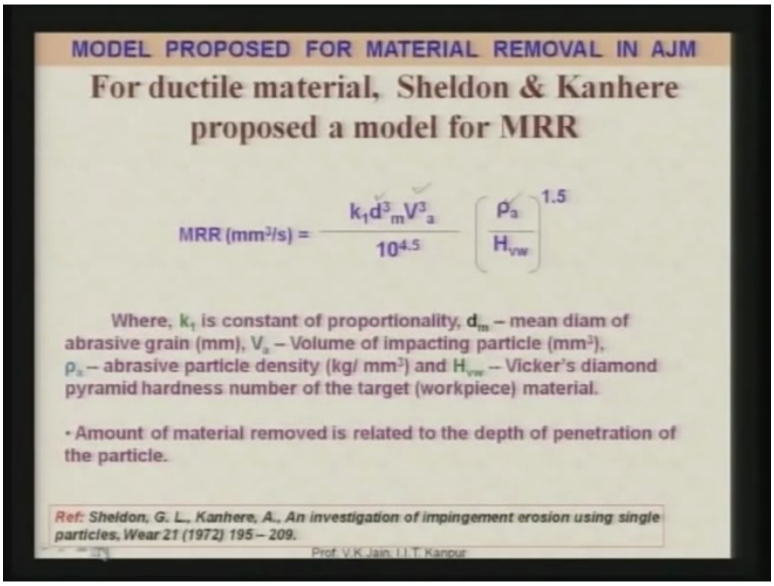

There was the another model for ductile material proposed by Sheldon and Kanhere for calculation or evaluation of material removal rate. You can see here material removal rate in terms of millimeter cube per second now K1 DM raise to power 3 VA raise to power 3 upon 10 raise to power 4.5 multiplied by rho A over HVW whole raise to power 1.5, where you can see K1 is a constant of proportionality, DM is the mean diameter of abrasive grain that is given over here and VA is the volume of impacting particle in terms of cubic millimeter. Rho A is the abrasive particle density and HVW is the Vicker's diamond pyramid hardness number of the target that is the work piece material.

With the help of this you can find out the material removal rate in terms of cubic millimeter per second removed from the work piece, amount of material removed is related to the depth of the penetration of the particle definitely you have to find out the depth of the penetration and then if you know the size of the crater formed you can calculate the amount of material removed and the time taken if you divide by then you will get the material removal rate in terms of cubic millimeter per second. Now this paper appeared in the international journal of wear in the year 1972.

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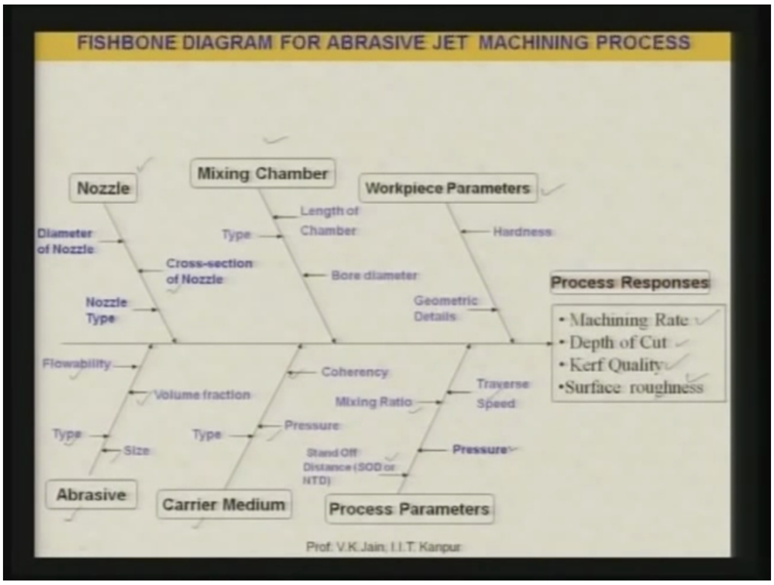

It is important to understand the effect of various process parameters on the performance of the AJM process that is why I will give you a brief of parametric analysis of AJM process. Now this is the fishbone diagram for abrasive jet machining process where you can find what are the different parameters which really affect the response in case of the process performance. So let us start from here if you see nozzle the diameter of the nozzle is one of the parameters, what type of nozzle you are using or what type of material you are using for the nozzle another point is cross section of the nozzle whether it is circular, rectangular etc.

Then mixing chamber, length of the chamber, type of the mixing chamber and bore diameter over there, work piece parameters like hardness of the work piece and geometric details that you want to create on the work piece. Abrasive if you see flowability of the abrasive, type of the abrasive I have shown you various types of the abrasive, size of the abrasive again very important parameter and volume fraction of the abrasive which is flowing along the air abrasive jet that is again a controlling parameter as long as material removal rate is concerned, also it controls the accuracy of the machine cavity.

Carrier Medium is another very important parameter, which type of carrier medium you are using whether it is air or some gas both affect the performance of the process then what is the coherency of the carrier medium and what is the pressure at which you are using it, both of them will affect the performance of the process.

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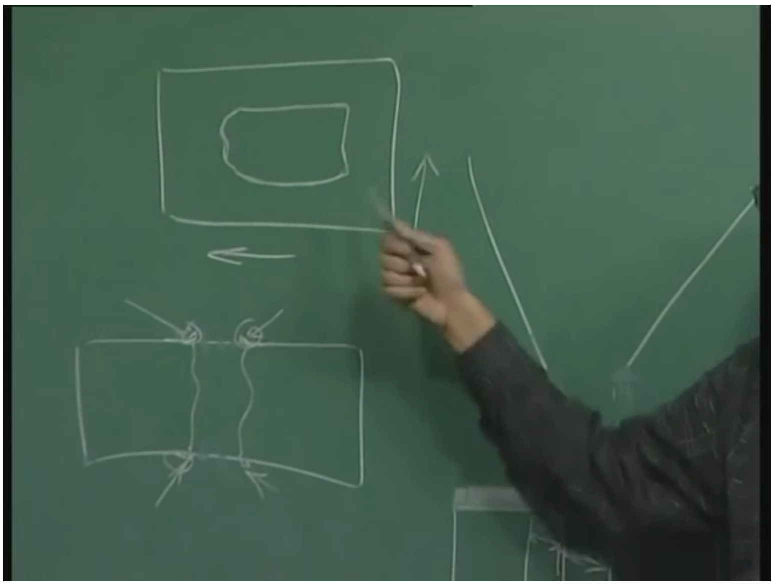

Then as a machining parameters of process parameters includes traverse speed, this is the speed with which you are moving the work piece to get different shape and size of the cavity just like this you want to create this kind of cavity on the work piece then you have to move the work piece in the X direction as well as in the Y direction with reference to the jet so that jet keeps cutting along this periphery that is why the traverse speed is important and how much deep it is penetrating it will depend upon the speed of the work piece in X direction and Y direction with reference to the air abrasive jet.

Then the pressure with which the jet is coming out this pressure will decide also the velocity of the jet that means it will decide the kinetic energy half MV square. Then mixing ratio this will give you the how much volume of abrasive is there in the abrasive air jet and what is the stand off distance we have already seen it is an important parameter which will decide the shape and size of the cavity as will see in the following slides.

The performance of the process specially AJM process can be evaluated in terms of machining rate that is volumetric machining rate or mass machining rate you can also call as the penetration rate which will be in terms of the millimeter per second.

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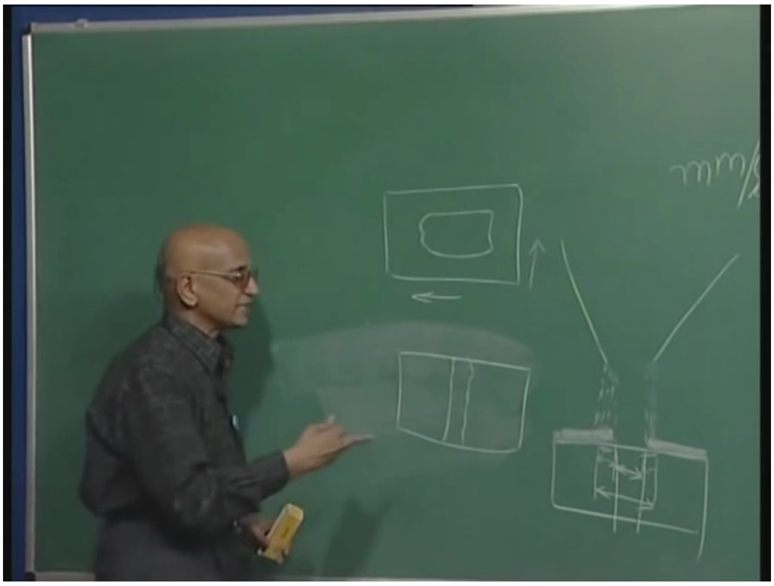

Then what is the depth of cavity, kerf quality and surface roughness. What is this kerf quality, when you are cutting this work piece over here say this work piece you want to cut. You are cutting it like this, then what is the quality of the surface is after cutting this piece perpendicular to the board if you see there is a certain surface generated one on this side, one on this side, so what is the quality of that surface generated over there that is known as kerf quality.

And surface roughness, this can be evaluated either in terms of CLA values that is the center line average value or peak to valley value or there are various ways of evaluating the surface roughness.

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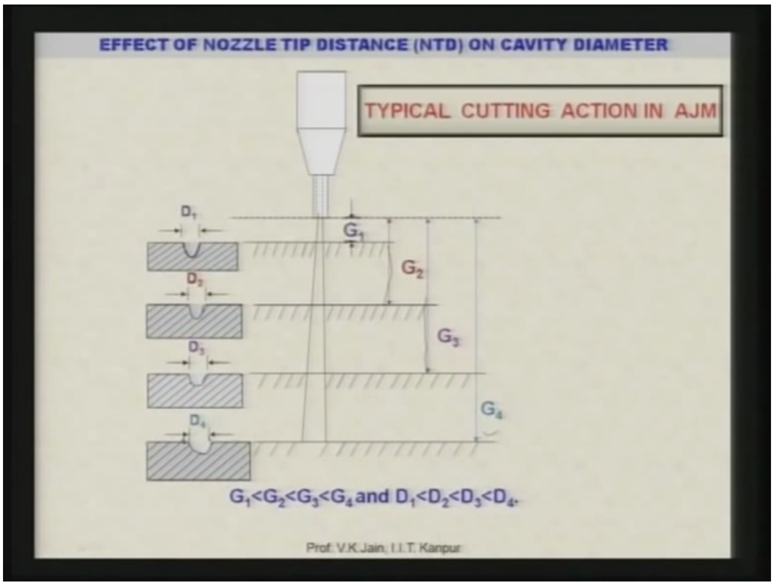

Now how the stand off distance or nozzle tip distance is affecting the shape and size of the cavity it is well illustrated in this particular figure, let us take this is the nozzle and jet is coming over here and this distance is the nozzle tip distance G1, now you can see here the size of the or width of the cavity or the diameter of the cavity depending upon the cross section of the nozzle is D1.

Now if you increase the nozzle tip distance from G1 to G2, you can see this D2 is bigger than the D1. However the depth beyond a certain limit will decrease now if you further increase this then you make it G3 then you can see D3 is bigger than D2 and if you further increase to G4 you can see this width has increased further however beyond a certain limit if you further keep in increasing the stand off distance or nozzle distance the depth to which the penetration is taking place will keep decreasing because as you as the abrasive particles keep moving further their kinetic energy keeps decreasing because of so many factors that is why the depth keeps decreasing but width or diameter keeps increasing as the stand off distance keep increasing.

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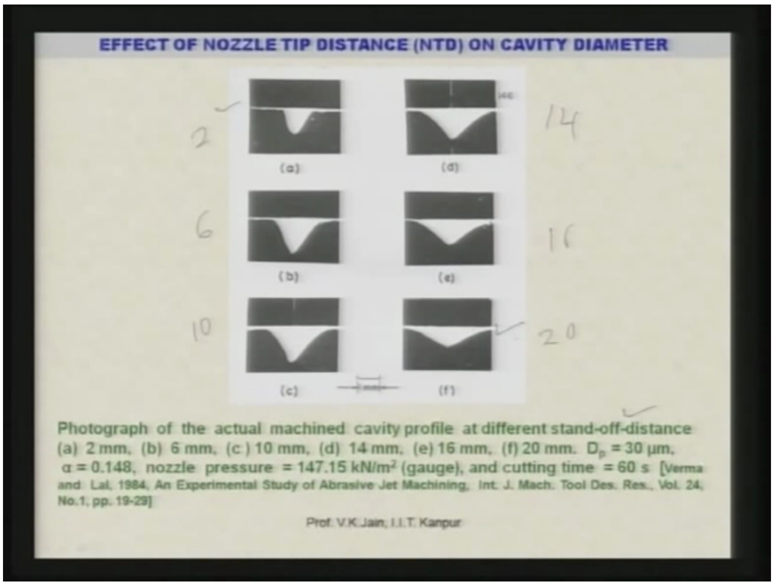

Now these are the actual photographs taken from the paper by Verma and Lal published in the year 1984 you can see here A B C D E F all these are the cross-section of the surface or the work piece machined at different nozzle tip distance or stand off distance as you can see A is at 2 millimeter B is at 6 millimeter and C is at 10 millimeter, D 14 millimeter, E for 16 millimeter and F for 20 millimeter. You can see compare the width of the cavity in case of A and in case of F, there is a substantial difference in the shape and size cavity so as the stand off distance or the nozzle tip distance keep increasing the shape and size of cavity also keeps changing.

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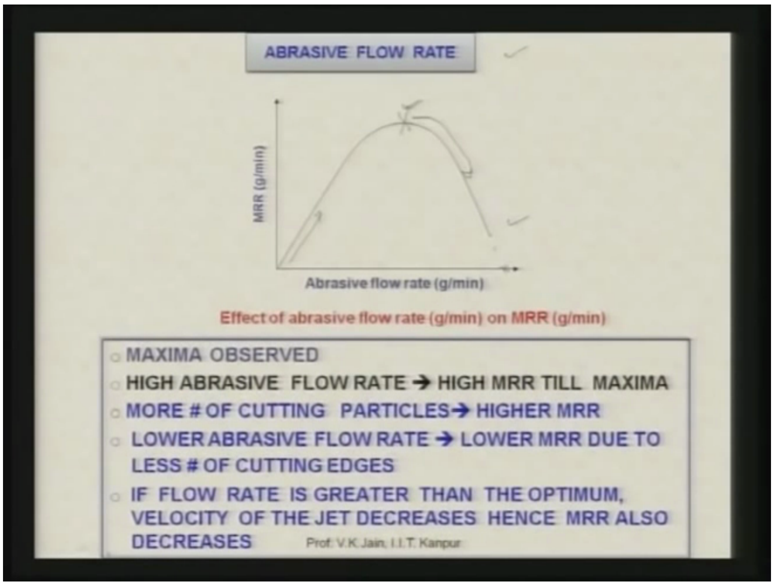

Now let us see the effect of certain process parameters on the performance of the abrasive jet machining okay let us now see the effect of different process parameters on the performance of abrasive jet machining process. First let us consider abrasive flow rate now you can see here as abrasive flow rate is increasing the material removal rate in terms of gram per minute is continuously increasing upto a certain point and there is an optimum or maximum value of material removal rate beyond which it starts decreasing now let us see what are the regions for this. Once there is a flow rate you will get high material removal rate till the maxima that you obtained over there.

Once more number of cutting particles are there as you keep increasing the flow rate, the number of abrasive particles that has removed the material or cutting the work piece material keeps increasing as a result of that you can see material removal rate is increasing upto the maxima. Now lower abrasive flow rate you will get lower material removal rate due to less number of cutting edges.

Now if flow rate is greater than the optimum value that is beyond this value then velocity of the jet decreases hence MRR also decreases because the pressure that you are having of the jet is distributed amongst the more number of abrasive particles as a result of that their velocity decreases and once the velocity decreases then material removal rate also start decreasing that is what you can see beyond this line that material removal rate start decreasing and you can see it may join even here beyond at a certain point.

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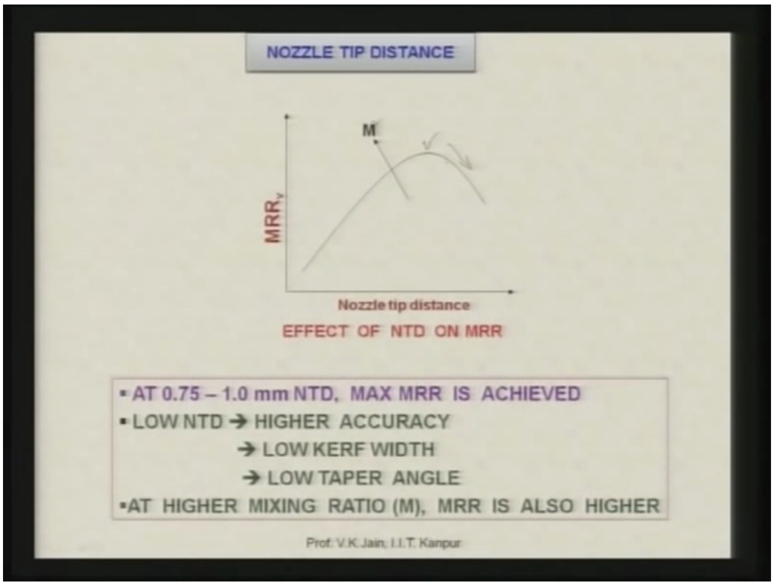

Another important parameter is the nozzle tip distance. We have already seen two slides with reference to the effect of nozzle tip distance on the cavity shape and size. Now here we can say effect of nozzle tip distance on the volumetric material removal rate. Now it is also having the more or less the same trend or same nature as in the previous slide that volumetric material removal rate is increasing and then you have the maxima over there and then it starts decreasing.

At 0.75 to 1 millimeter as the nozzle tip distance, maximum material removal rate is achieved. Now if nozzle tip distance is low you will get the higher accuracy that means the gap between the bottom of the nozzle and the top surface of the work piece is small then you get more or less the reproduction of the shape of the nozzle cross-section on the work piece surface, you get low kerf width, kerf width reduces, low taper angle at higher mixing ratio M is the mixing ratio at higher mixing ratio material removal rate is also higher.

And when the nozzle tip distance is very high material removal rate start decreasing because at very high nozzle tip distance the velocity as I mentioned earlier of the abrasive particles keep decreasing because of the losses in the air and that is why material removal rate start decreasing beyond the optimum value.

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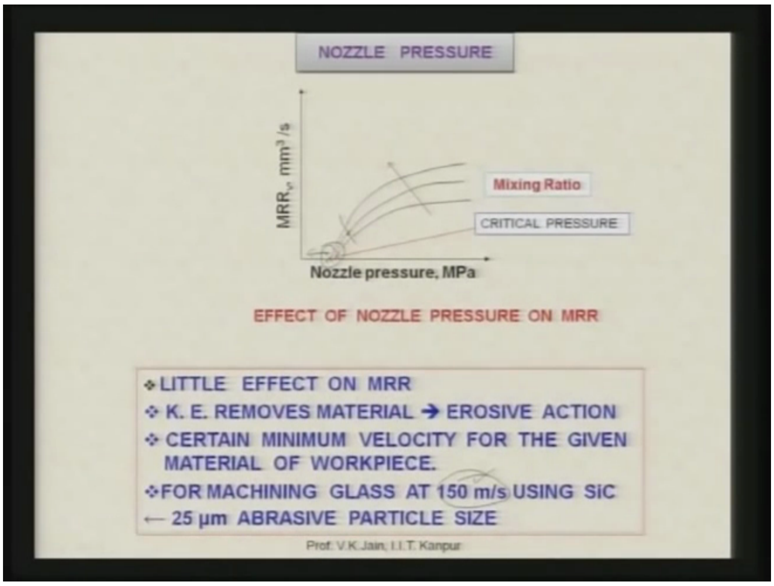

Now nozzle pressure, nozzle pressure is another parameter which affects to some extent the volumetric material removal rate. Now an important point to note over here is the critical pressure, now this is the minimum pressure which is needed for start of removal of material because see unless an abrasive particles has certain minimum kinetic energy it cannot penetrate inside the work piece surface only above that particular kinetic energy it will start penetrating inside the work piece surface and removal of the material.

So in all work piece materials you need a certain critical pressure and that critical pressure will be different for different work piece materials it will to some extent may depend on the size of the abrasive particles also. Now another is the mixing ratio now I will show you some formula also for mixing ratio.

Here you can see as the mixing ratio increases the material removal rate is also increasing and you can see here the material removal in this particular case starts from here only and in this shown it is a very small nozzle pressure so actual data are not available and the data are available beyond this limit only.

But there will be no material removal if the pressure is less than critical pressure, so the effect is not very high of the nozzle pressure on the volumetric material removal rate. Kinetic energy removes the materials and this is responsible for erosive action that we have already discussed certain minimum velocity for the given material of work piece is needed that I have already explained that is the critical pressure.

And for machining glass at 150 meter per second using silicon carbide you need for using the 25 micron size abrasive particle, this is the minimum velocity that you require of the abrasive particle for machining glass this silicon carbide abrasive particles of 25 micron size.

If the velocity of the abrasive particles is less than 150 meters per second it will not be able to remove the material from the glass so this will decide whatever is the critical pressure that pressure should be able to give velocity equal to 150 meter per second or beyond the critical pressure it will give the velocity more than 150 meter per second.

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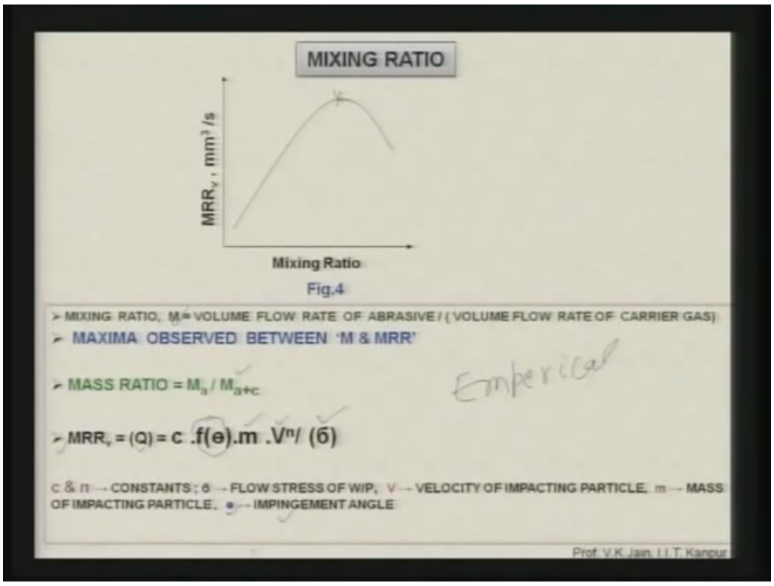

Then there is another parameter that is the mixing ratio. Mixing ratio is given by M, is given by volume flow rate for abrasive particles divided by volume flow rate of carrier gas. Now this decides the mixing ratio and you can see as the mixing ratio increases the volumetric material removal rate in terms of cubic millimeter per second also increasing and there is an optimum value beyond which it starts decreasing this we have discussed earlier also in some sense.

Maxima is observed between M and MRR, there is another term which is known as mass ratio and it is given by MA divided by M A plus C where MA is the mass of abrasive particles and M AC is the mass particles plus carrier gas. Now there is a emperical formula, this empirical formula is given over here for calculating the volumetric material removal rate that is Q then C and then theta, M, V raise to power N divided by sigma. Now theta, this parameters is a function of theta then you can have C and N are the constants, sigma is the flow stress of the work piece materials, V is the velocity of impacting particle or abrasive particles and M is the mass of the impacting particle and theta is the impingement angle and this is not exactly see the, there is some function of theta which will affect the volumetric material removal rate.

So if you know these constants and impingement angle then theoretically you can calculate the volumetric material removal rate in case of abrasive jet machining process, and this is the formula which has been proposed by some of the researchers which is simpler compared to other 2 formulae which we have seen.

But in this formula they have not categorically mentioned rather it is applicable only for brittle or only for ductile material. So it is applicable for both materials as you can see it is taking into consideration the impingement angle which need not be 90 degree.

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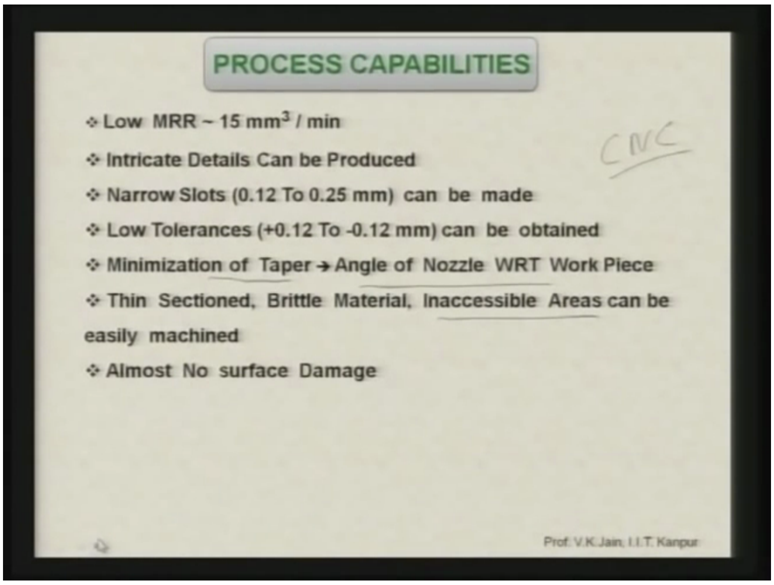

Now the question arises what are the capabilities of AJM process, in case of AJM process the material removal rate is comparatively low as compared to many other advanced machining processes. It is somewhere 15 cubic millimeter per minute does not mean exactly 15 cubic millimeter per minute every time it will depend upon or vary with the machining parameters, type of the work piece materials and type of the AJM set up you have got.

But the advantage is you can machine intricate details or you can produce intricate details on the component or the work piece. You can have the CNC or AJM process where the movement of the work piece and the jet you can numerically control with the help of the CNC features of that machine.

Narrow slots can be cut, the size of the slots can be 0.1 to 0.25 millimeter, a low tolerance can be achieved plus minus 0.12 millimeter, minimization of taper angle of nozzle with respect to the work piece. This taper can be minimized by properly setting the angle of the nozzle with respect to the work piece.

Thin sectioned can be machined, brittle materials, it is very good for brittle materials also the inaccessible areas can be machined, those areas which cannot be machined by conventional methods, tool cannot approach there if jet can go inside that particular location it can drill the hole, it can machine the cavity over there through cavity specially.

Almost no surface damage because there is not a much amount of heat generation and the work piece is always in contact with the air so the rise in the temperature is very low comparatively and there is no thermal damage to the work piece and not large forces are also not acting so there is no mechanical deformation of the work piece.

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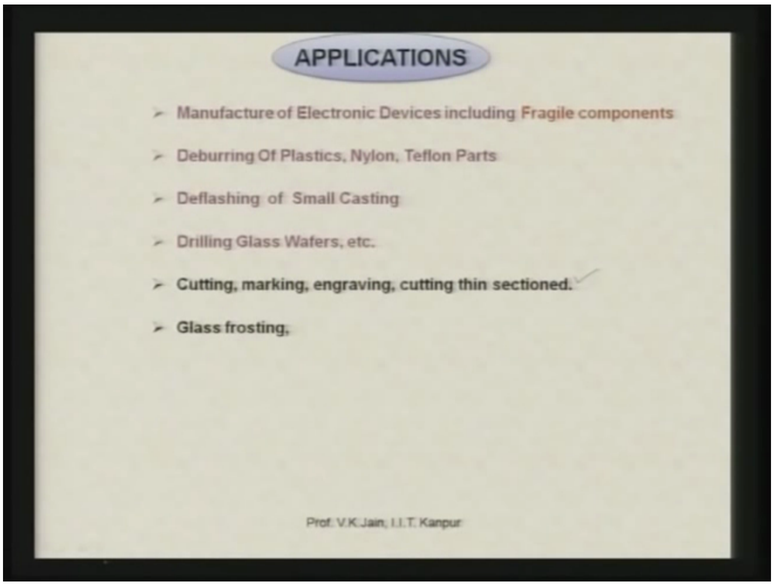

Applications, it is very much applicable in the manufacture of electronic devices including devices made of fragile components, it is very good in deburring of plastics, nylon, teflon parts in other similar parts maybe made up of very hard materials or even the soft materials. Deflashing of a small casting, the excess material which is not useful after you obtain the casting those can be deflashed or cut with the help of the AJM process.

Drilling of glass wafers, etc. can be done. Cutting, markings, engravings, cutting thin section this is the application where AJM is widely used. Glass frosting is another very important application of AJM process for frosting a glass so that glasses become opaque normally the glasses are transparent but if you do the frosting with AJM process they become opaque or if you want to write anything, any letter, any name on the glasses then AJM process is commonly used for writing purposes very fine letters can be written on the glasses with the help of the AJM process.

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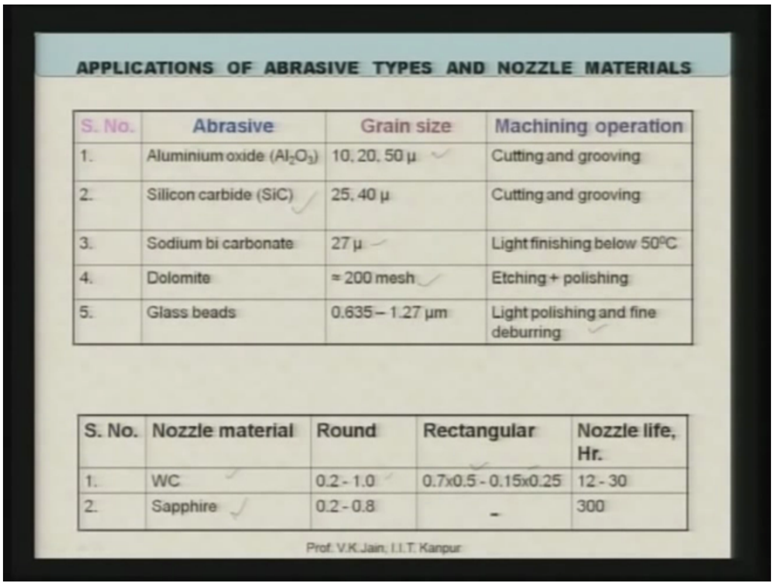

APPLICATIONS OF ABRASIVE TYPES AND NOZZLE MATERIALS

S. No.	Abrasive	Grain size	Machining operation
1.	Aluminium oxide (Al_2O_3)	10, 20, 50 μ	Cutting and grooving
2.	Silicon carbide (SiC)	25, 40 μ	Cutting and grooving
3.	Sodium bi carbonate	27 μ	Light finishing below 50°C
4.	Dolomite	≈ 200 mesh	Etching + polishing
5.	Glass beads	0.635 – 1.27 μm	Light polishing and fine deburring

S. No.	Nozzle material	Round	Rectangular	Nozzle life, Hr.
1.	WC	0.2 - 1.0	0.7x0.5 - 0.15x0.25	12 - 30
2.	Sapphire	0.2 - 0.8	-	300

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So you can see here application of various types of abrasive and nozzle materials. Alumina grain size normally used is 10, 20, 50 micron size and this is good for cutting and grooving purposes. Silicon carbide normally used grain size is 25 micron and 40 micron and it is good again for cutting and grooving. Sodium bicarbonate it is good for light finishing below 50 degree centigrade temperature. Dolomite again for etching and polishing purposes and glass beads light polishing and fine deburring purposes.

Two commonly known are the materials for making the nozzles and they are tungsten carbide and sapphire, if they are round then their size is somewhere 0.2 to 1 millimeter, in case of tungsten carbide 0.2 and 0.8 millimeter, in case of sapphire they can be rectangular also in which case you can have these sizes varying from 0.7 to 0.5 to 0.15 to 0.25 as the cross-section or one can be the length another can be width of the nozzle cross-section.

Nozzle life in case of tungsten carbide it is quite low as you can see it is 12 to 30 hours and in case of sapphire it is 300 hours but actual nozzle life will depend upon how severely or how lightly you are performing the AJM process that will also decide the actual life of the nozzle.

With this brief introduction to the abrasive jet machining process, its working principles, setup, parametric analyses and three models for the calculation of the material removal rate either in terms of gram per second or millimeter cube per second let us see very simple examples, numerical examples related to AJM process.

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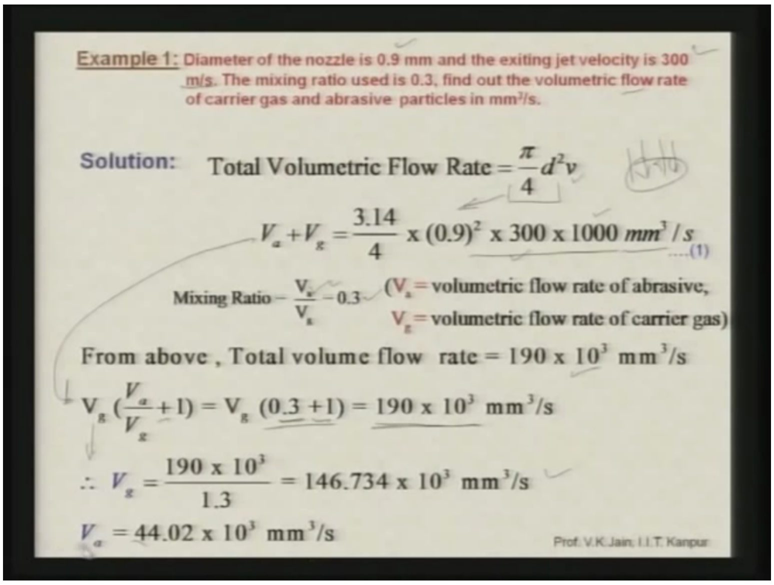

Let us see example 1, diameter of the nozzle is 0.9 millimeter and the exiting jet velocity is 300 meter per second, the mixing ratio used is 0.3, find out the volumetric flow rate of carrier gas and abrasive particles in cubic millimeter per second. Now here we have to find out the flow rate of carrier gas as well as the abrasive particles, total volumetric flow rate we can calculate because we know the jet diameter and whatever is the flow velocity and cross-sectional area if you multiply both of them then you will get the volumetric flow rate and so here is the cross-sectional area of the jet and this is the velocity with which widget is going out so you can calculate the volumetric flow rate.

Now when we say volumetric flow rate it includes the flow of the air or the gas as well as the abrasive particles so this can be written like this 3.14 divided by 4.

0.9 as you can see here is the nozzle diameter, 0.9 square and 300 is the flow velocity and you have to convert it, it is the velocity is given in terms of meter per second over here you can convert it in terms of cubic millimeter per second by multiplying by 1000. Mixing ratio we all know already, mixing ratio is given by VA over VG and that value is given as 0.3

VA is the volumetric flow rate of abrasive and VG is the volumetric flow rate of carrier gas. So from these we can total volume flow rate if you calculate the values over here you will get 190 multiplied by 10 raise to power 3 cubic millimeter per second as the volumetric flow rate.

Now we can write this equation like this, that is the VG multiplied by VA over VG plus 1 that is equal to VG and VA over VG is given as 0.3 so we substitute 0.3 and plus 1 from here, plus 1 so it becomes equal to 190 into 10 raise to power 3 cubic millimeter per second. So from here we get VG is equal to 190 into 10 raise to power 3, that is this divided by 1.3 so you get 146.734 into 10 raise to power 3 cubic millimeter per second as the gas flow rate or carrier gas flow rate.

Now if you know the carrier gas flow rate we can also calculate from this equation or from this equation as the abrasive flow rate and that comes out to be 44.02 into 10 raise to power 3 cubic millimeter per second. So in this way we can make the calculation for finding out volumetric flow rate of abrasive particles as well as career gas.

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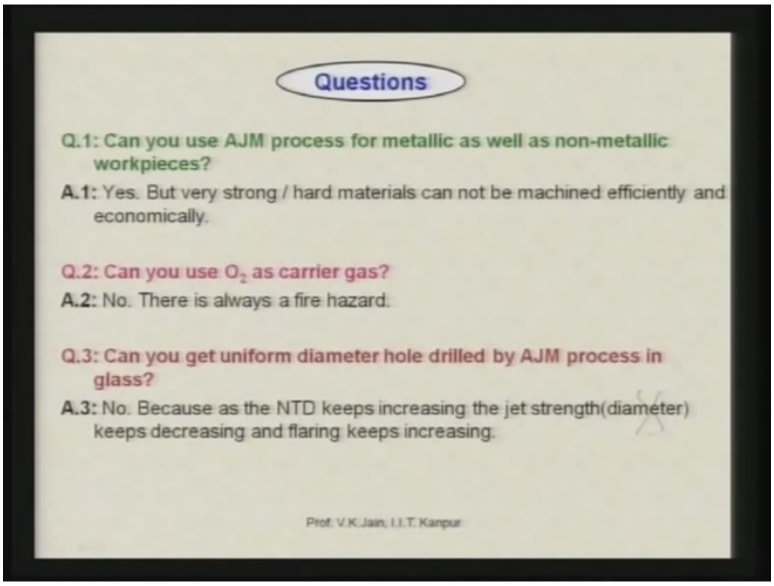

Now there can be various questions, some of the questions I am just showing you. Can you use AJM process for metallic as well as non-metallic work pieces? Answer is yes but very strong or hard materials cannot be machined efficiently and economically. Same way question arises can you use O2 as carrier gas? Answer is no, there is always a fire hazard as O2 is helping in fire or burning.

Can you get uniform diameter of the hole drilled by AJM process in glass? No because as the nozzle tip distance keeps increasing the jet strength or diameter keeps decreasing and flaring keeps increasing. Here actually not the diameter, jet strength keeps decreasing and flaring keeps increasing so the diameter or the cross-section of the cavity that is forming will keep increasing, diameter will definitely keep increasing as the nozzle tip distance keep increasing.

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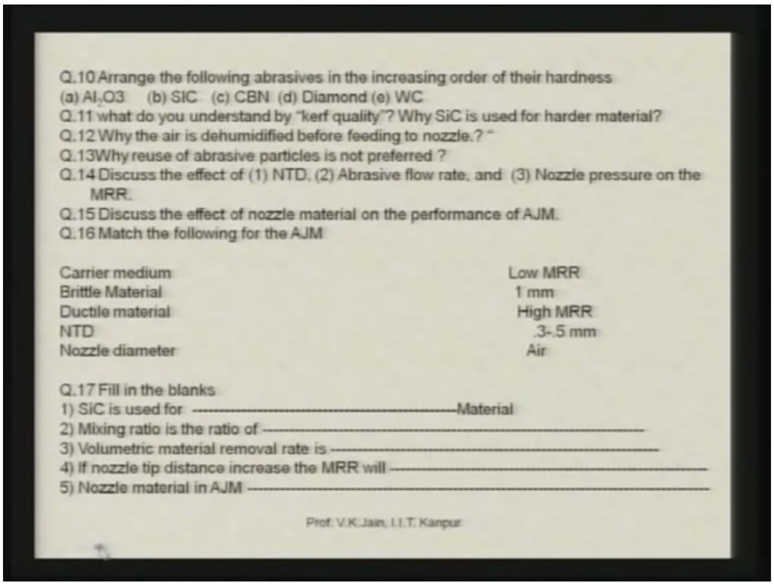

Now there is a question bank which you can solve yourself. These are the simple questions you can attempt at home and you can find solutions for them. Thank you very much. Is there any question? Okay, thank you.