Introduction to Abrasive Machining and Finishing processes

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Lecture - 14
Advanced Abrasive Machining Processes

Now, we move onto another part of this particular course that is called Advanced Abrasive Machining Process. We have completed already the conventional abrasive machining and finishing processes. Some of them are applicable for machining; some of them are applicable for finishing. Now, exclusively what we see is advanced abrasive machining processes, then once we complete this then we move on to advanced abrasive finishing processes ok.

So, that this is a particular segment where we come across some of the advanced abrasive machining process, as I said machining process will deal with how much material removal that you have taken out from the work piece ok. In a finishing processes normally you use what is the final surface roughness that you have achieved ok. From that point of you we will going to see here the machining processes using abrasives which are considered to be advanced.

Some of the people call it as nontraditional machining also ok. So, there is no much difference between nontraditional machining, unconventional machining and advanced machining ok. So, since this particular course deal with abrasive based processes that is why we are only talking about some of the advanced machining processes where abrasives are commonly used.

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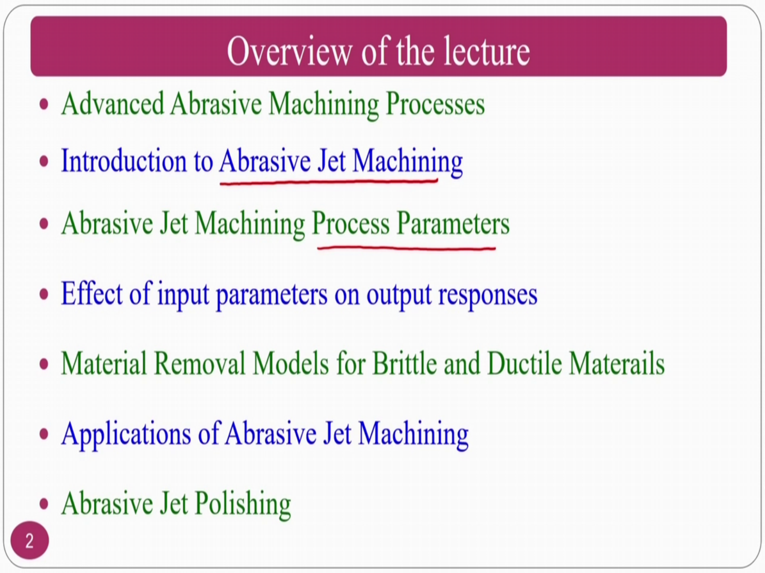

We will see the overview of the today's lecture. Normally we start up with what are the advanced abrasive machining processes that we are going to study in this particular segment. Introduction to abrasive jet machining so, we move on to one of the process called abrasive jet machining. And we will see jet machining process parameters and we move onto the input parameters on output responses, the effect how each input parameter plays a vital role on the output responses. And the material removal models for brittle and ductile materials.

Applications of abrasive jet machining and at last we just see a glimpse of abrasive jet polishing also. This particular process also can be used for polishing applications so, but the application wise for polishing very less. So, just we see a glimpse that is all.

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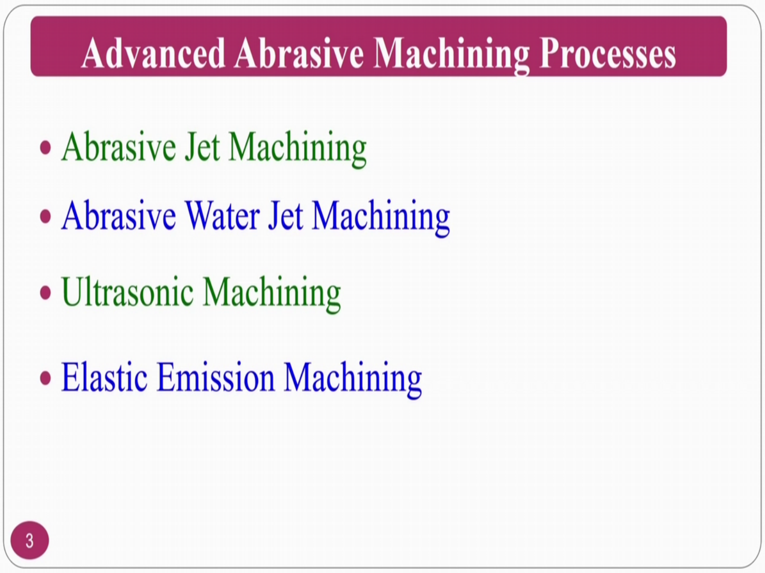

So, advanced abrasive machining processes, what are the processes that we are going to study in this particular section of this course is abrasive jet machining, abrasive water jet machining, ultrasonic machining and elastic emission machining. These are the mechanical processes where abrasives are used and there are few process, but these are predominantly used abrasive processes in the spectrum of advanced machining processes. We move onto the abrasive jet machining.

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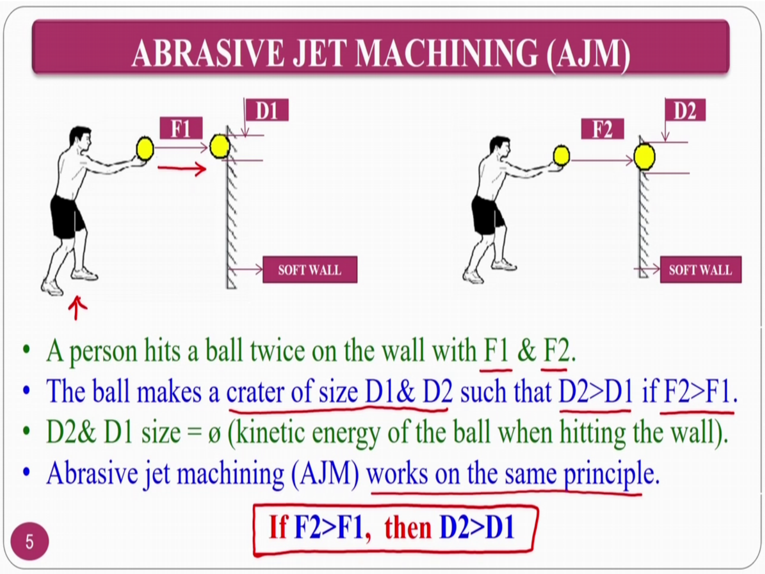

We will see if you see this particular slide most of the slides which we are borrowed from Professor Vijay Kumar Jain who is a professor emeritus in IIT Kanpur. So, some of the slides are courtesy to him because, he has shared the slides to with me and I am very thankful to Professor V K Jain for sharing his slides. So, when a person hits a ball twice on a wall with F1 and F2 ok; that means, that a person is there he is person, this person is hitting the wall with F1 and F2, whenever if you are force is F1 and F2 the crater size or cavity size that is formed is approximately assume to be D1 and D2.

If the force F2 is greater than F1, then D2 will be; obviously, greater than D2, this is basic physics, abrasive jet machining follows like this. And D2 and D1 size is the thing is a function of kinetic energy of the ball when hitting the wall. That means, that the particularly this particular abrasive jet machining works on the various input parameters such as how velocity of the abrasive particle is travelling towards the work piece and how it is hitting, whether the material work piece material is a ductile material or a brittle material so, on many parameters are there. What one thing is that if you just hit with a stone to a particular material assume that you are hitting a stone to a dry mud. So, what will happen? There will be a crater there will be a cavity formation on the mud dry mud ok.

So, that is the basic concept of a abrasive jet machining. Now, we move on you can this basic concept we can pile up or compile towards using their abrasive jet machining. So, abrasive jet machining works on the, this particular principal whatever I explain where the stone is hit a dry soil or a mud which is soil I mean to say it is not a loose soil. It is a lump of a solid where you have a clay just hit with this particular stone which is slightly harder than this one and this clay which is a solid clay. So, it is less harder with respect to the stone.

So, and it is a brittle material so, there will be a crater formation that basic principle which we will see in particularly in abrasive jet machining. And if you are going to hit this particular clay with force F1 and F2, what will happen? The crater size or a cavity size that is formed on that particular solid clay will be more and more. If you are hitting with low force small crater, if you are hitting with high force crater will be very big.

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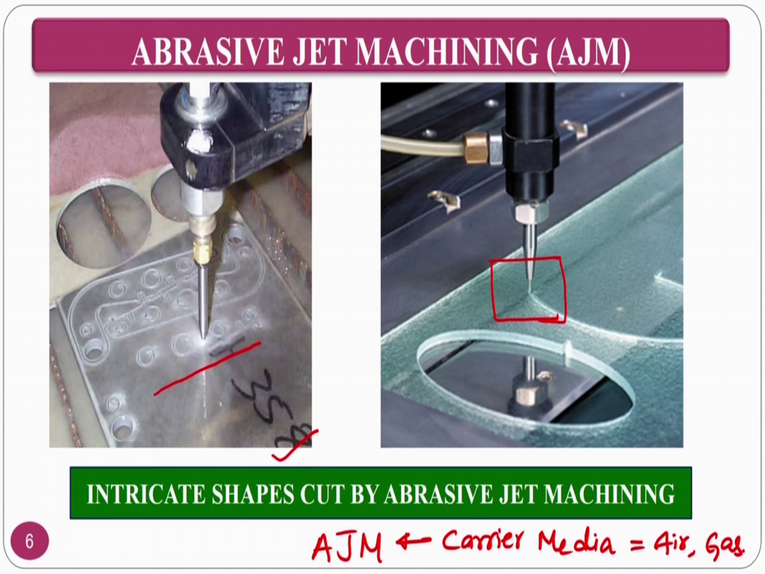

So, now based on this particular principle the people came up with a technology called abrasive jet machining. You can see the abrasive jet machining normally these are the highly compressed air along with the abrasive particles with impinge are which pass through a fine nozzle. And you can achieve or you can cut the intricate shapes like completes surfaces you can do and you can do a glass cutting or another cutting processes.

If you can clearly see here how a particular shape of a glass is cutting using the air and at the same time abrasive particles; the air is considered to be the carrier medium. As you have seen in the previous slide there is abrasive jet machining, abrasive water jet machining. So, in the abrasive jet machining you are going to use air or some gas as the carrier medium. In abrasive water jet you are going to use water which is a liquid as a carrier. In this particular AJM what you have to note here is carrier medium is air. Media or medium is one of the things is air, then gas, you can use inert gases or some other gases also you can use to carry the abrasive particles along the direction of the velocity of the air.

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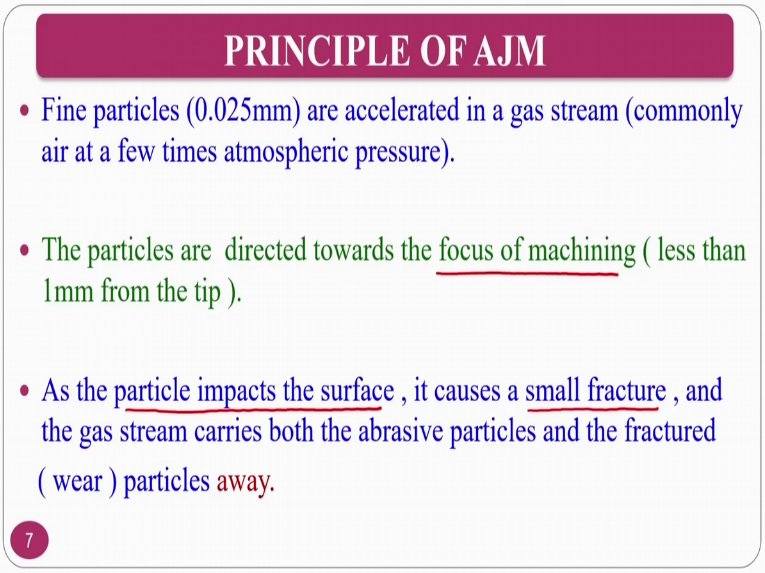

The principle, the fine particles normally 0.025mm are accelerated in a gas stream commonly used is air at a few times at possible pressure; that means, that you can use 10 bar, 20 bar, 30 bar, 50 bar like that if we can use in terms of bar, people will understand that is why I am saying a bar. But, internationally if somebody is watching assume that if I am going to use 10 bar; that means that 1 mega Pascal ok.

So, you can use 1 mega Pascal, 2 mega Pascal, 3 mega Pascal of the pressure of the air which is a carrier medium and you just mix the abrasive particles and you just inject on a surface to be impinged ok. So, that you can cut the intricate shapes or you can generate the craters as per your requirement. The particles are directed towards the focus of the machining less than 1mm or the tip that mean. Normally, it is called the nozzle tip distance normally you will come across all these words in the upcoming slides. Just you just focus on the work piece so that you can cut the work piece.

As the particle impacts on the surface, if the particle impacts on the surface with high velocity, this causes a small fracture and the gas stream carries both abrasive particle and the fractured particles away. So, this what it will do is this gas stream which is considered to be the air will carry both abrasive particle and the fractured wear surface away from the is; that means, that whenever you impinge if it is a through cut. So, it will carry the debris as well as abrasive particles also.

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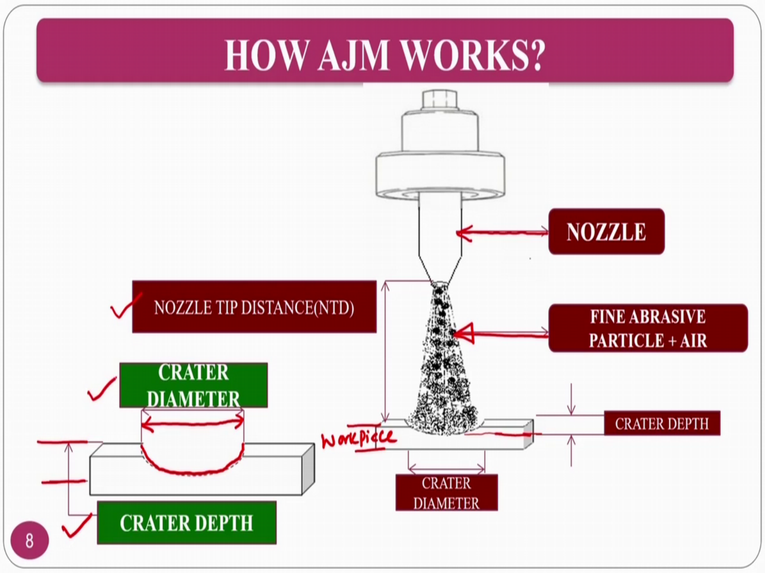

If you see here how the abrasive jet machining works, this is the nozzle ok. So, this is the nozzle tip distance, this is my work piece which is nothing, but the distance between work piece top surface to the nozzle exit is nothing, but nozzle tip distance. And fine abrasive particles plus air is coming here and this is the crater depth that normally this is a crater depth that is formed on a surface.

So, how you can measure the crater diameter as well as a crater depth, if you see this is my crater, crater have it is own crater depth at the same time crater diameter also you can measure. So, depend on your input parameters like air pressure, abrasive particle size, type of abrasive, type of work piece material these are all will decide the crater depth as well as crater diameter this it will decide.

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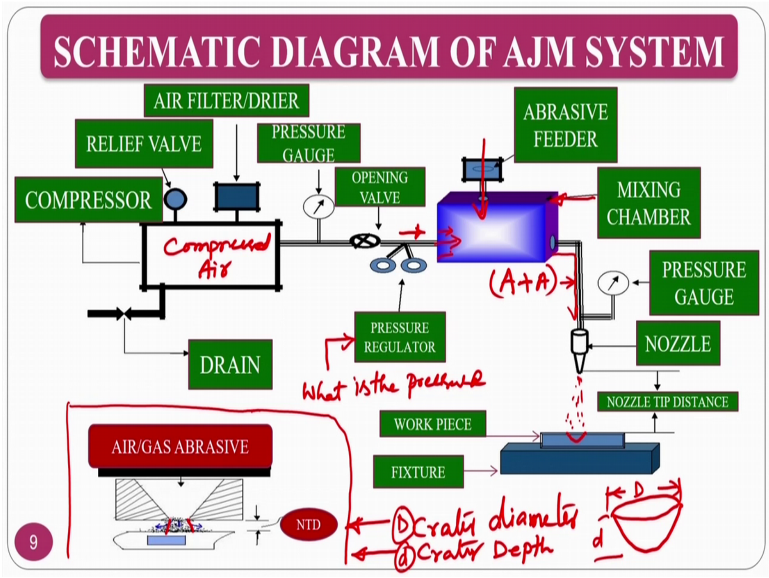

If you see the schematic diagram of AJM system, I mean to say previously whatever you have seen is a machining region where nozzle is there and work piece is in back, but how to generate this much pressure? How to generate the velocity of into abrasive particle and other things? Will come under the complete system, ok. So, first what you have to required what first what you need is air compressor, so compressor with a relief valve, air filter, drier and other things. Drier is required because you do not want any wet condition in the air force with pressure.

So, the compressed air now will be generated, will be opened and the opening wall will be there, pressure regulator. This pressure regulator will tell what is the pressure, what is the pressure? That means, that output pressure what at what pressure it is the air that is passing here is 1 mega Pascal or 10 mega Pascal or 20 mega Pascal or something whatever the Pascal that will show.

Now, it will go into a mixing chamber, this is a mixing chamber where you are feeding the abrasive particles and your gas is compressed gas is coming ok, both will mix and it will come like this. In this area what is compressed air is there plus abrasives are there ok. So, this abrasives and compressed air plus abrasive particles will be there and this will come and hit on the surface. So, that you can generate a crater which have a crated depth as well as crater diameter. Now, once you the crater is generated or a cavity is generated you can measure the crater and the other things crater diameter as well as. If you see this particular diagram just whatever you have seen in the previous one is just shown in a schematic way.

So, the abrasives are falling on this one and it will generate the crater which is having 2 parameters, one is crater diameter and crater depth ok. The crater will be generated like this which will have assume that if it is like this, this is the diameter D and this is the depth small d, this will be a crater diameter and this will be crater depth. So, like that you can generate the cavity or crater on a particular material.

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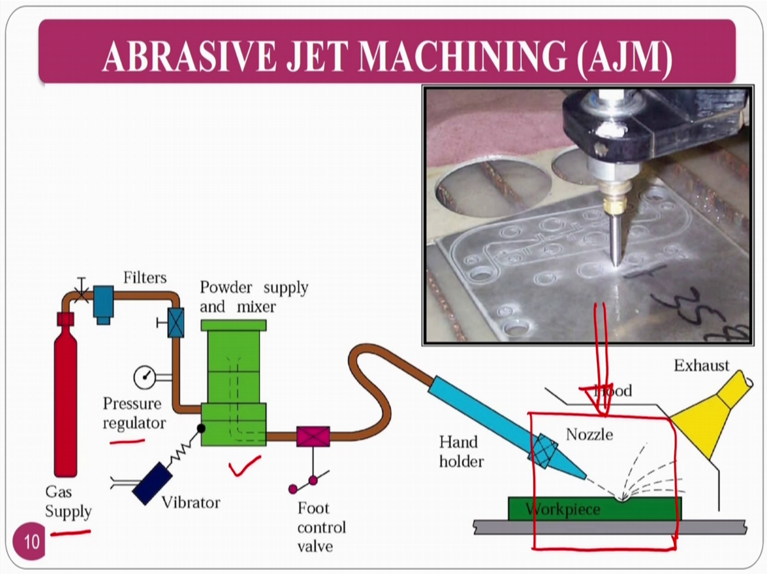

If you see the schematic diagram and the picture normally you can compress the gas supply normally air will be supplied. At the main motto to show you is how the system look like and you can also see the practical setups that are developed by some of the IIT's also. So, the gas supply filters are required to filter out the moisture or filter out the other things and which is unwanted and the pressure regulator just you mix the powders here and you can even give the vibrations to it.

So, that you can get more and more mixing at the same time once you done then you just impinge. Now, if you can impinge what will happen? The machining will takes place properly and you can orient your nozzle as per your requirement ok. So, practically you can see how the cutting action is taking place by the abrasive jet machining. So, the same thing you can see here ok. So, this is a nozzle and this is a machining ok. The box which is shown in a schematic is clearly shown in the experimental way.

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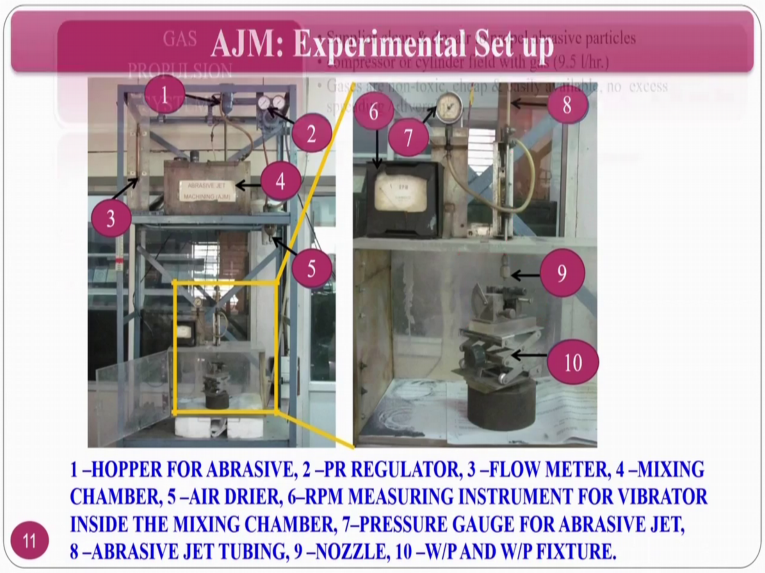

So, this is the one of the experimental setup practically that is developed at IIT Kanpur. So, again I am very thankful for the professor who developed at IIT Kanpur this. The normally 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 it shows hopper for the abrasive pressure regulator flow meter mixing and other things whatever if you see here. So, this is a work piece and abrasive jet machining region where the high pressure abrasive mixing is coming and impinging on your work piece surface; so, that the machining takes place, the crater takes place and the material removal takes place.

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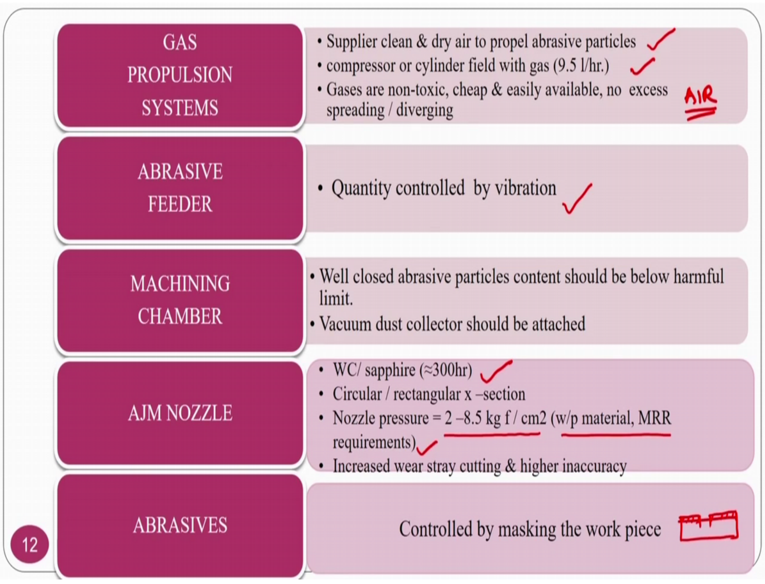

So, what are all the systems that you require? What are the components that are that play? What are the component that play a major role in abrasive jet machining is one is the gas propulsion system. That is nothing, but the supplying of clean and dry air which propels abrasive particles. Compressor are normally required now when if you want to compress the air for higher and higher you require a compressor. And the gases which are non toxic cheap available, easily available the one of the best example is air.

Air is considered to be the cheapest and economic one which is easily available in the atmosphere. Then the abrasive feeder, normally the abrasive feeder will have the quantity controlled by the vibration you can control the vibration and you can control the amount of the abrasive particles that are falling and you can control this particles how much particles you require. You come up across one word called mixing ratio in the upcoming slides.

So, there you will see how much abrasive particles that are coming with respect to the carrier medium that is nothing, but the air. Machining chamber well closed abrasive particles content should be below harmful limit and the vacuum dust collector should be attached; that means, that as I said this particular things should be carried out at the closed environment.

So, that the dust particles are because a ceramic assume that you are going to machine a ceramic material or a brittle material and your abrasive particles is a brittle. What will happen? There will be a brittle fracture fragments will come up because, the fragments will be a nano particles and the surface area is so, high that this may come out and causes lot of problems to the operator. So, it should be done in a closed environment. The abrasive jet nozzle so, normally sapphire nozzle will be used whose life will be approximately 300 hours and circular or rectangular cross section depends on your requirement.

Assume that if I want to make a whole, I can go for circular. If I want to go for a pocket some of the applications required pockets and in a ceramics or something; in that circumstances you can go for rectangular cross section or a square cross section and this type of cross sections. Nozzle pressure, normally normal pressure which varies from 2 to 8.5 kg f per centimeter square when the work piece material and MRR requirements are very high, then you have to go for very high pressures.

Increased wear stray cutting and high inaccuracy, if you are going for very high pressures and high standoff distance or something then what will happen? Stray cutting, normally stray cutting does mean that assume that my assume that this is the work piece and my requirement is cutting in this section.

Assume that I want in this particular section only, as if my nozzle is here the diversions goes like this. Stray cutting means the extra portions this is which is unwanted which is called as a stray. So, here also you can see here, see unwanted is nothing, but the stray. So, it is going beyond what I require as a customer or as a manufacturer if I want 5 centimeters a hole if I am generating 5.2 or 5.3 that extra portion is nothing, but the stray.

So, the abrasives controlled by masking the work piece you can control the whole size and other things by masking the work piece. Assume that this stray cutting if I want to control in the circumstances what you can mask it assume that I want in this portion. So, you can mask the other portions with other material, sacrificial material so, that what will happen? The required portion is exposed and abrasives will take away the material in the form of craters or cavities.

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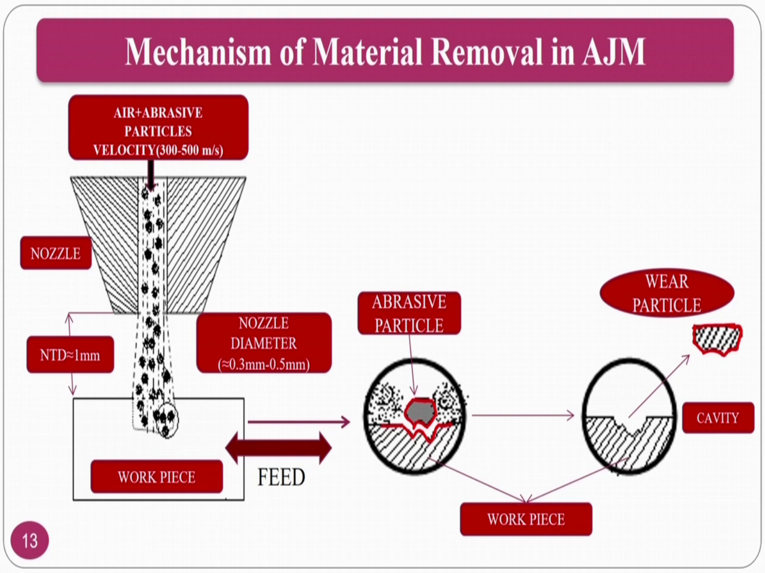

Mechanism of material removal if you seen the abrasives and nozzle tip distance and other things when the abrasive particle heat what will happen? It will fracture the material and the fracture mechanism and other things you will see in the upcoming slides.

Whenever this particular abrasive comes and hit so, it will generate the similar convert shape of particular portion of hitting. And it if it is a brittle material it goes out as a brittle chip like this. If it is a ductile material the material mechanism will be goes by deformation, continuous deformation, then the shearing, chipping and other things will takes place in ductile work.

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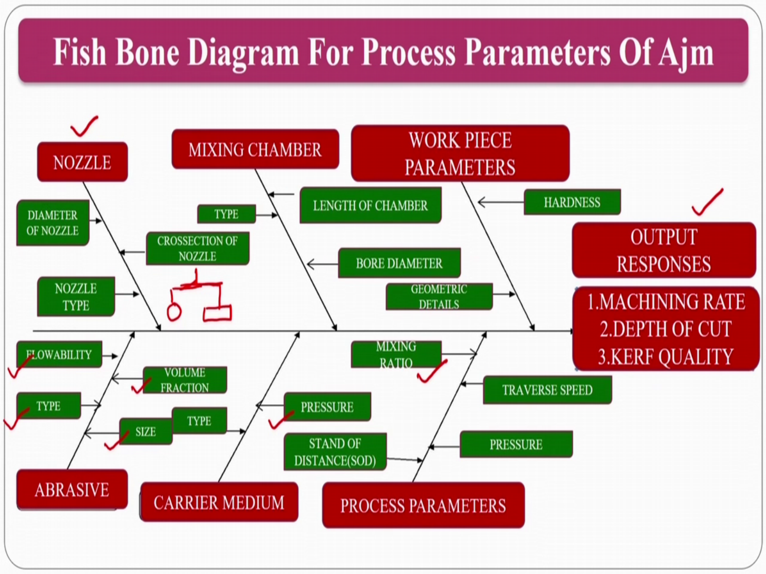

The fishbone diagram shows what are all the parameters that are affected by abrasive flow, what are the parameter that will affect the output responses in abrasive jet machining. So, one first one is a nozzle, nozzle will play a major role. So, nozzle diameter, nozzle type and cross section of nozzle as a we have seen 2 cross sections will be there. One is circular cross section one, another one is rectangular cross section. The mixing chamber the length of the chamber length of the chamber is increases what will happen? What the mixing will be better at the same time it may decrease the velocity.

So, the bore diameter, type of chamber and other things, work piece parameters normally, hardness of the work piece, geometry details and the other things will play a major role. And the abrasives flow ability of abrasives, type of abrasives like SiC that is silicon carbide or alumina or boron carbide or cerium oxide. And what is the volume fraction that you are going to mix; that means, whether you are going to mix 1 is to 1 or 1 is to 10 or something. At the same time abrasive particle size whether, it is fine size or a core size or a medium size like that and the carrier medium.

Career medium also play a major role which type of carrier medium whether you are going to use the air or whether you are going to use argon or which is inert gas you are going to use and pressure how much pressure, if your pressure is very high what will happen? The indentation will be very high.

So, the process parameters such as mixing ratio, how much abrasive particles to the carrier medium that you are going to mix and the standoff distance, how far yours nozzle is from the work piece surface and the traverse speed and the pressure. So, these are the input conditions which determines the output responses such as machining rate, how fast you can do the machining, depth of cut and the kerf quality; that means, that whether you have achieved a good quality or a bad quality which is a qualitative one.

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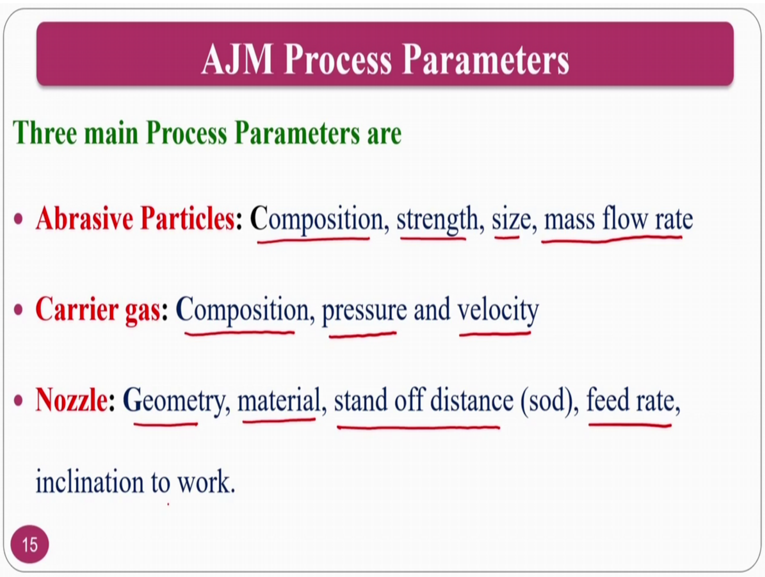

So, the abrasive jet machining process parameters the main 3 parameters among all the spectrum we have 3 or few more some people will follow. So, the mostly important one is abrasive particle which is nothing, but a composition, strength, size and mass flow rate of abrasive particles. At the same time carrier gas composition like air whether you are going to use or argon you are going to use or any other inert gas. At what pressure and at what velocity it is helping the abrasive particles to hit the work piece and the nozzle, nozzle geometry, nozzle material.

Because, nozzle material as we have seen in the previous slide that the sapphire is one of the best material; so, that the life will be approximately 300 hours for one nozzle. So, if you are going to use very low quality materials for the nozzle what will happen? Your nozzle goes out your nozzle on out and you have to go for a new nozzle.

So, the non productive time increases. So, the product cost will go off because, your production time will increase for a particular component. The standoff distance is one of the thing that is nothing, but nozzle tip distance. Some people, some of the books follow nozzle tip distance, some of the books follow the standoff distance. Standoff distance and nozzle tip distance is both are same which is nothing; but the starting of the nozzle to the surface of the work piece. This is nothing, but the standoff distance or nozzle tip distance.

And the feed rate at the same time inclination to the work. So, whether you want to go for certain inclination to the work piece or whether you want to put it perpendicular or that is all the parameters that play a major role among the fishbone diagram. You have a set a complete set, but some of them have huge influence or the major influence, some of them have less influence. So, these are all whatever you are seeing in this particular slide are having a major influence on the material removal rate, crater depth and crater diameter.

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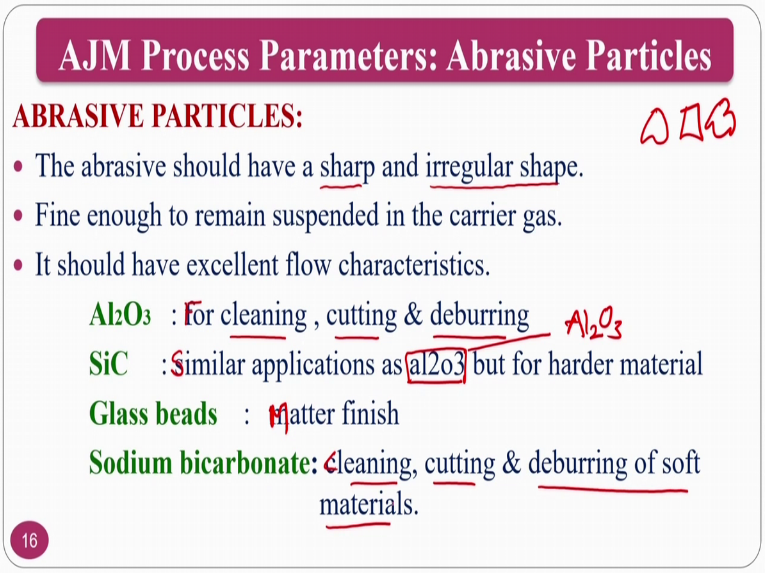

So, the first one is abrasive particles that play a major role. The abrasive should have the sharp and irregular shape. Normally, all the abrasive particles are randomly oriented at the same shape is random. One abrasive particle may like this; one abrasive particle may like this, one abrasive like this. So, shape normally will not be a constant in this one. The fine enough to remain the suspended in the carrier gas, if we you can go for particle size, lower particle size, the suspension or the suspending in the gas is very good because of the high surface area. It should have excellent flow characteristics because it should follow the path of carrier gas. So, that it will do the required purpose.

Al 2 O 3 normally uses for the cleaning purpose, cutting purpose and deburring purpose. The silicon carbide normally uses for similar applications of Al 2 O 3. But for harder material; that means, that if you are going to use Al 2 O 3 for a softer materials slightly harder material if you were customer comes with a slightly harder material then you can go for silicon carbide. And glass beads, you can go for Matter finish or mat finish. Sodium bicarbonate, normally you can use for the cleaning applications, cutting, deburring of soft materials and other things you can use.

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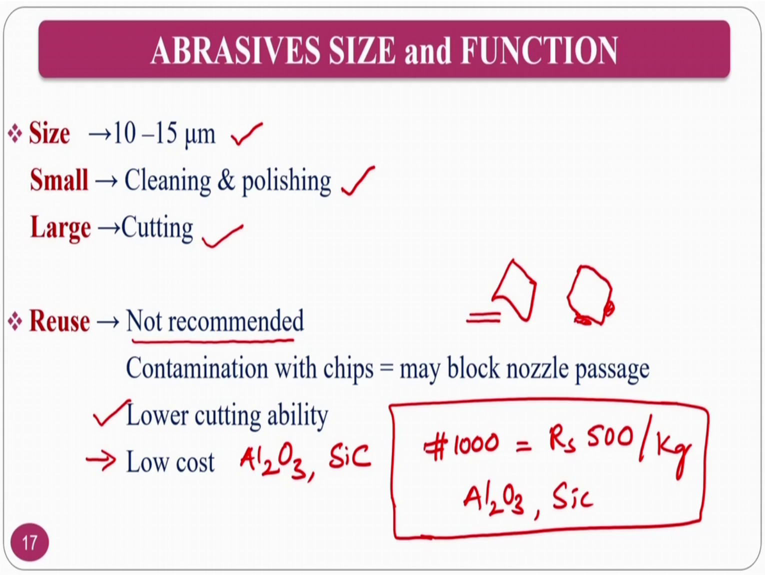

So, abrasive sizes and functions, if the size is small, large and other things, normally if you see here the size the abrasive particle size is 10 to 15 microns is a commonly used. Because, if you are going to use very very small then there will be a problem of agglomeration; that means, that multiple particles will come as agglomerate. But, normally in this particular gas assisted process you may not get, but in the water, jet machining or some all people will use some of the other liquids also there the agglomerations will be a problem.

So, you should go for a specified particle sizes. Normally, small sizes you will use for cleaning and polishing and larger size will be used for the cutting process. As I said we see abrasive jet polishing at the last of this particular class where you will use the fine abrasive particles; so, that you can get the polishing operation.

Reuse basically it is not recommended because, it will be contaminated with the chips and may block the nozzle passage and lower ability and low cost; that means, that whenever assume that I have a abrasive particle like this, this is very sharp edge is there ok. So, whenever you are using a first time the sharp edge may remove the material, but whenever you use the second time what will happen, this will become blunt and its efficiency goes down.

At the same time whenever you are going to use it, what will happen? This may accompanied by the chip material also this chip material accompanying. So, the performance of this particular abrasive particle goes down and the performance goes down by lowering the cutting ability, at the same time abrasive particles are not that much costly.

So, it is economical to go for Al 2 O 3 or SiC normally these particles now a days or the previously which we used in the 2015 and 16. So, you can get in Indian market like a 1000 mess size or something approximately like below 500 rupees. So, the 1000 mess size up to thousand mess size you can get approximately 500 rupees per kg Al 2 O 3 or SiC, both proximately you can get this particular mess size for within India.

So, some of the companies placed in Agra and this companies provides this type of abrasive particles. If you are going for better abrasives which placed in a abroad nations like Germany and other countries. So, import and export charges maybe come into picture and the cost of the abrasives may goes up. For the applications of abrasive jet machining I guess you can go ahead with this particular thing, I guess you can go ahead with these available abrasive particles in India.

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AJM Process Parameters: Abrasive Particles

S. NO.	ABRASIVE	GRAIN SIZE	MACHINING OPERATION
1	ALUMINIUM OXIDE (AL_2O_3)	10, 20, 50 μm	CUTTING AND GROOVING
2	SILICON CARBIDE (SIC)	25, 40 μm	CUTTING AND GROOVING
3	SODIUM BI-CARBONATE	27 μm	LIGHT FINISHING
4	DOLOMITE	≈ 200 mesh	ETCHING + POLISHING
5	GLASS BEADS	0.635 –1.27 μm	LIGHT POLISHING AND FINE DEBURRING

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So, the second thing which you have to note down is normally the aluminium oxide that Al 2 O 3, silicon carbide, sodium bicarbonate, dolomite and glass bead these are the commonly used the particles different particle sizes are also mentioned in this one. And this aluminium oxide and silicon carbide are mostly used in abrasive jet machining for the cutting operation, grooving operation.

At the same time light finishing if at all I want to go normally I go for sodium bicarbonate and which can use for the finishing applications. At the same time dolomite you can use for etching and polishing applications and the light polishing and fine deburing if at all you want to go you can go for the glass beads ok. So; that means, that in the abrasive jet machining process if you can control the pressure, if you can vary the abrasive particles, if you can vary the pressure you can convert this particular process into abrasive jet polishing process also.

So, some of the people who are do doing masters and wish to do PhD and other things. So, you can work with this particular thing that how to convert or how to change the setup or change the parameters to change from abrasive jet machining to abrasive jet polishing. So, there may be a very less papers on abrasive jet polishing. So, you can choose this particular thing or abrasive polishing, abrasive jet polishing as one of the topics by choosing dolomite or a sodium bicarbonate as your abrasive particles. You use appropriate pressures and you can do all those work piece materials, you just do some literature and you can get some information and you can move on to a good topic.

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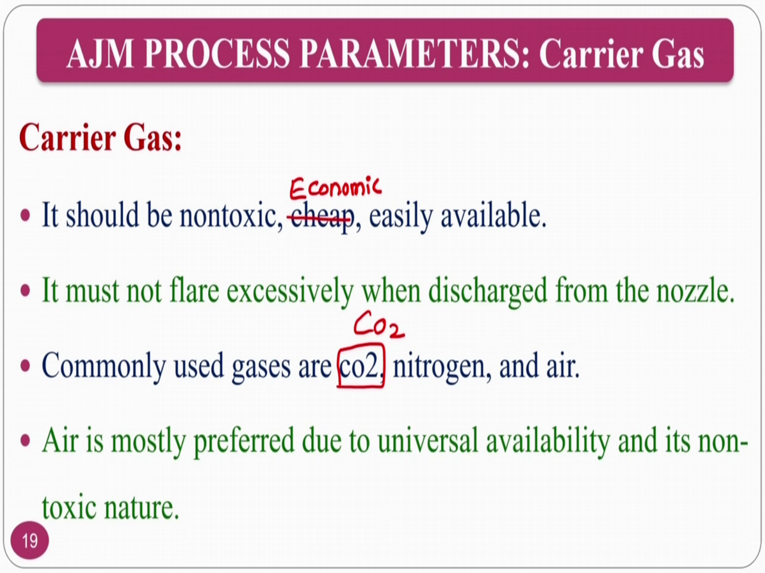

So, the second one is a carrier gas, normally carrier gas it should be non toxic, cheap, easily available. I can say instead of cheap you can say economic is a good word to use rather than cheap. It must not flare excessively when the discharge from the nozzle; that means, that it should not diverge much. If it is diverge then what is my requirement will be gone.

And commonly used gases are CO2, nitrogen air and other things, air is commonly available one. So, the air is mostly preferred due to universal availability and it is non toxic nature because really we are breathing it. So, air is non toxic at the same time it is economic.

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So, these are the nozzles, the third one is a nozzles you can go for this type of nozzles of various dimensions, you can see all here multiple nozzles also available and single big nozzles also here available. You can go this type of nozzles to fit into the abrasive jet machining and you can achieve your goals ok.

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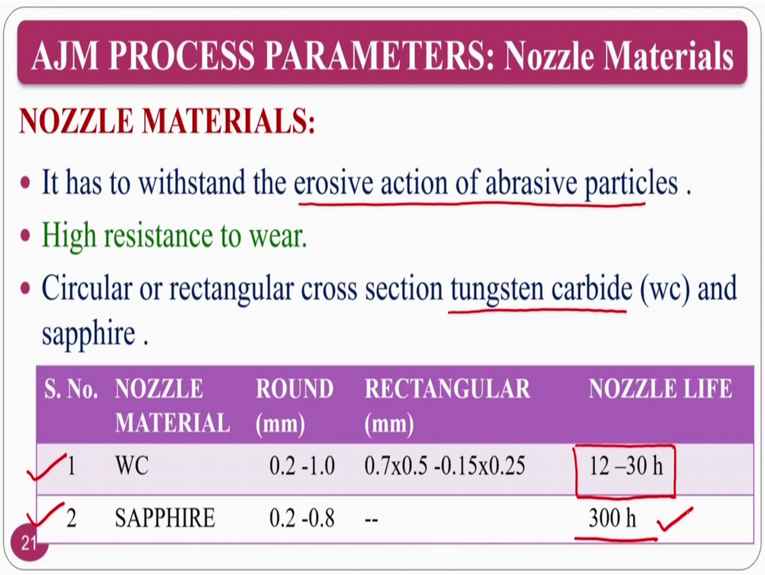

The nozzle material is most important one. So, it has to be it has to withstand the erosive action of abrasive particles that are passing by the nozzle. Because, the abrasive particles are mixed with the highly pressurized gas in the mixing chamber, then it is pushed; that means, that this abrasive particles also attack the walls of or the inner walls of the nozzle.

So, the erosive wear of this particular nozzle should be less. High resistance to wear; that means, that it should be wear resistant material that the nozzle is fabricated. And the circular or rectangular cross section normally you can use a tungsten carbide and sapphire is basically used material; so, tungsten carbide if you see and sapphire if you see normally the nozzle life.

If you see here tungsten carbide is approximately 20 to 30 hours. But, here the problem is that you have to replace the nozzle again and again. Assume that average if it is like 20 hours or something. So, every 20 hours you have to replace the nozzle, because of this the non productive work or the non productive cost of your manufacturing will increase.

So, to avoid that you can go for the sapphire whose life is 300 hours ok. So, the changing of this nozzle will be reduced, at the same time the time will be saved and the production rate will be increased. So, you can sell the product at the economic price subjected to the cost of tungsten carbide and sapphire. If the both cost are approximately same then you can recommend to your shop floor people that you can go for the sapphire.

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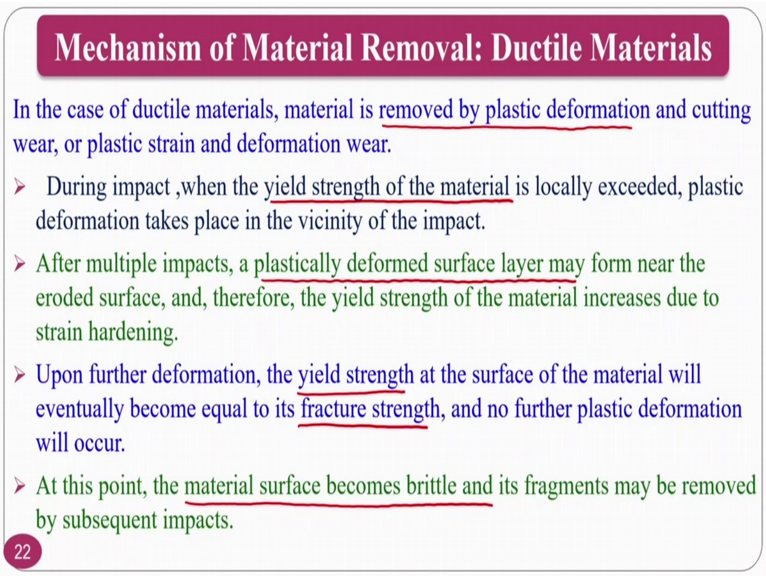

So, the material removal mechanism, the ductile materials, in case of ductile materials material is removed by the plastic deformation and cutting wear and plastic strain and the deformation wear. During the impact, when the yield strength of the material is locally exceeded, the plastic deformation takes in the vicinity of the impact. That means, that whenever the abrasive particle goes and hit a ductile material there will be a plastic deformation and nothing in this world is perfectly flat. So, you have a peeks on the surface. So, it also shear the peaks; that means, that it will remove the material by shearing action also.

So, after multiple impacts, plastically deformed surface layer may form a near eroded surface, and, therefore, the yield strength of the material increases due to strain hardening. And upon further deformation, the yield strength at the surface of the material will eventually become equal to the fracture strength. No further plastic deformation will takes place and the fracture will takes place. At this point the material surface become brittle and fragments may be removed in a subsequent impacts.

That mean that if you are going to impinge because the millions and millions of abrasive particles which are carried by the carrier gas impinges on the work piece. So, plastic deformation, plastic deformation, strain increase and the plastic deformation still goes on increase and fracture will takes place. At certain position what will happen becomes the eventually yield strength will become the fracture strength and the fracture will takes place in the material and it will goes out as a chip ok. This particular point you have to note that the yield strength increases and it will reaches to the fracture strength and the fractured material will goes off as by leaving a cavity there.

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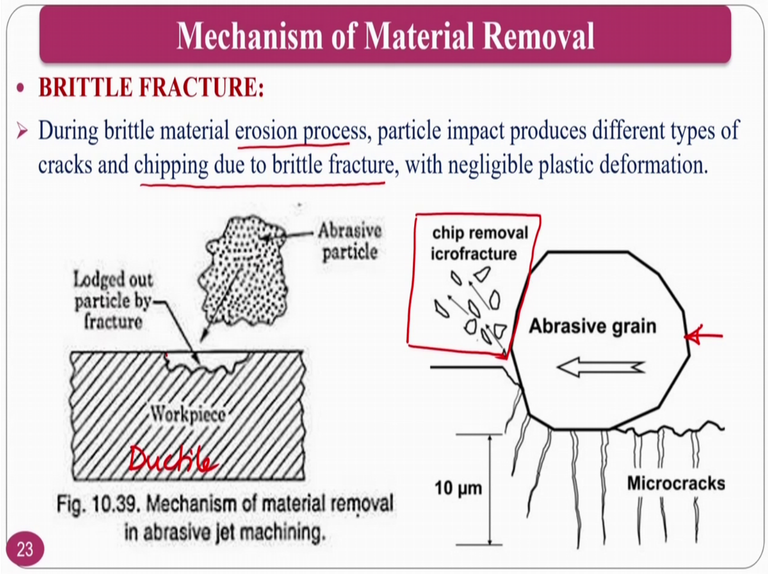

So, material removal mechanism, normally whatever you have seen in the previous slide that is for ductile material. If you are going for brittle material what will happen? During the brittle material erosion process, at the particle impact produces different types of cracks and the chipping is due to brittle fracture and negligible plastic deformation ok.

So, whatever you are seeing here there is a plastic deformation is taking place for the ductile material. And whatever you are going to see here is a for a brittle material. If there is a impact is coming and hit on the surface there will be a cracks and this will eroded material will remove the material in the form of a fine chips. So; that means, that for the abrasive jet machining the best suitable material to remove material is the brittle materials.

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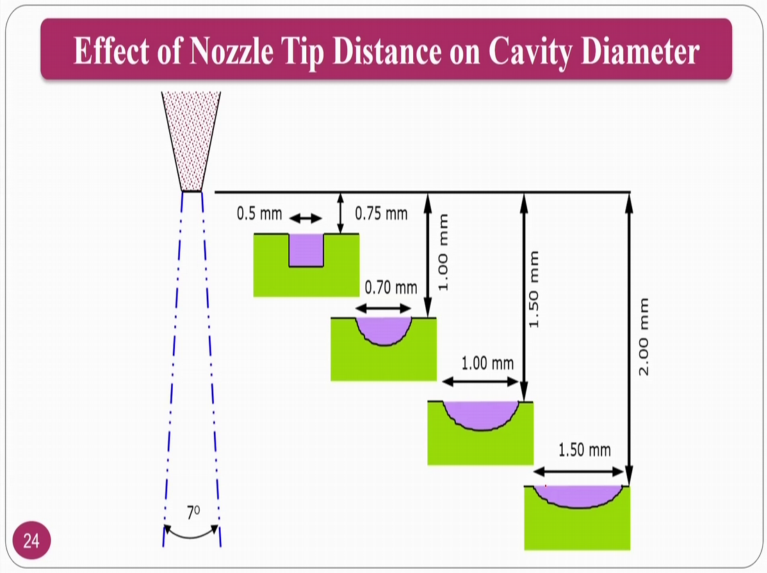

So, nozzle tip distance versus cavity, if the tip distance increases what will happen? The cavity diameter will increase and the depth will decrease. If you see here this is a schematic for your better understanding.

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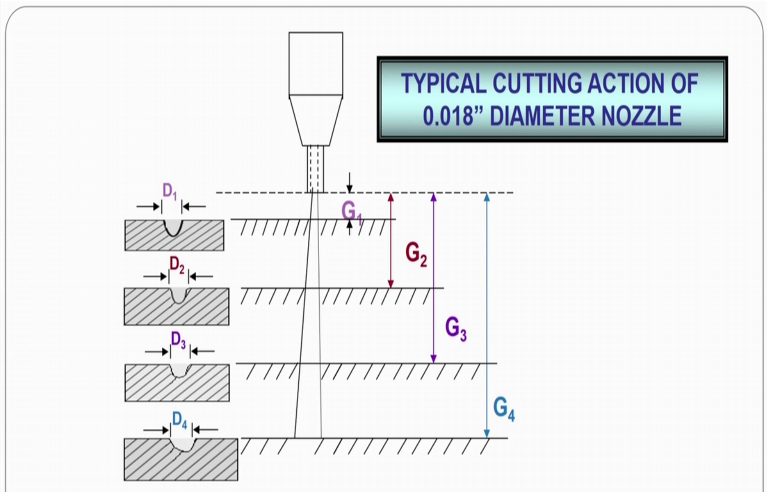

Fig. Effect of nozzle tip distance (NTD) on cavity diameter $G_1<G_2<G_3<G_4$ and $D_1<D_2<D_3<D_4$.

And if you see here so, your diameter 1 G stands for nozzle tip distance and G2 stands for the increased nozzle tip distance goes on increase. Then your diameter will increase, but your depth will decrease that is what we want to convey from this particular slide.

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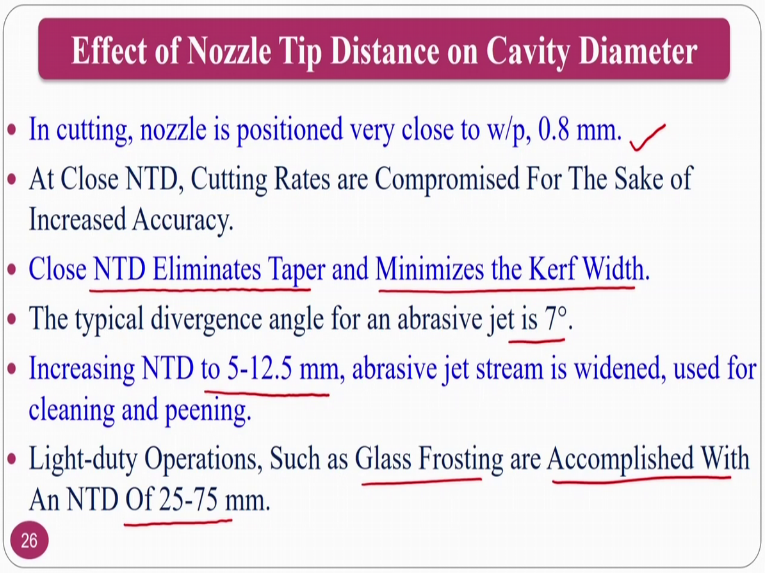

Effect of nozzle tip distance on the cavity diameter, in the cutting nozzle position by very closely to the work piece, normally the distance is 0.8mm. At the close nozzle tip distance cutting rates are compared for the sake of increasing accuracy; that means, that whenever the nozzle tip distance is low; that means, that your interest is to get the perfect cut or perfect dimensions that you want so, the accurate dimensions that you want. If the nozzle tip distance eliminates the taper and minimize the kerfs whenever you are going for smaller distances.

The typical divergence angle normally will be 7 degrees for the air. The if you are going to increase the nozzle tip distance to 5 to 12.5mm, abrasive jet stream become widened and used for the cleaning and pinning application; that means, that. So, at higher distances what is happening here is it is not going to do the machining operation. However, it is going to do the cleaning operation or the pinning operation. The light-duty operations such as glass frosting are accomplished with the normally the nozzle tip distance beyond 20.5mm.

So, whenever you want to do the glass frosting and other things you just go for far away distances like beyond 25mm. So, that it will do some texturing on the surface of the glass. So, some of the people who want to take up the research areas for texturing of the brittle materials then you can go for abrasive jet texturing process also.

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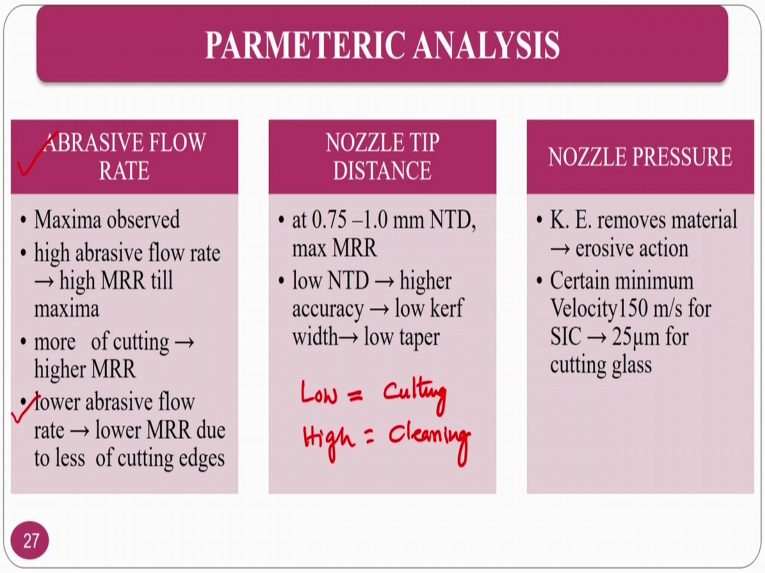

So, the parametric analysis if you see abrasive flow rate, the maximum observed normally high abrasive flow rate will lead to high material removal rate. The more cutting higher MRR, if the abrasive particle size is very big the cutting action will be very high and material removal will be very high. And low abrasive flow rate normally what will happen? To lower MRR due to less cutting edges and other things nozzle tip distance as I said.

If your nozzle tip distance is low, you can use for cutting purpose, if the nozzle tip distance is high, you can use for cleaning purpose or pinning purpose and other things. If the nozzle pressure is very high what will happen? The material removal rate will be very high. If the nozzle pressure is low what will happen? You can use for cleaning or texturing applications and other things.

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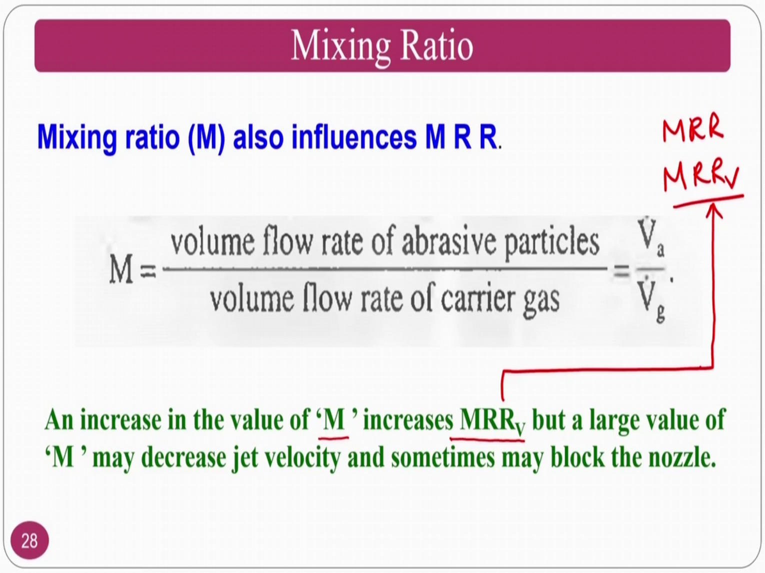

Just the mixing ratio so, the other keyword here is the mixing ratio that is nothing, but the volume flow rate of the abrasive particles to the volume flow rate of the carrier gas; that means, that you have 2 things here, one is a gas another one is a abrasive particles. If the mixing ratio is very high; that means, that your abrasives are higher in number compared to your carrier gas ok.

So, an increase in the value of M that is nothing, but the mixing ratio increases volumetric material removal rate; normally, some people they represent MRR that is nothing, but material removal rate. And MRR V represent volumetric material removal rate. See here it is shown MRR V nothing, but it is volumetric material removal rate.

But large value of M may decrease the jet velocity and sometimes it may block the nozzle also. If you everything has its own limitation, if you are going to use more and more abrasive particles what will happen? The abrasive particles collide each other and they lose the original velocity at which they have to travel and it has to heat. At the same time there is another problem that these abrasive particles may block the nozzle.

So, if the more amount of abrasive particles are there, it will be a disadvantage. So, always as a manufacturing engineer you should think about the optimum mixing ratio. So, that you can get you required function that is a whether it is a machining, whether it is a cleaning or pinning or something.

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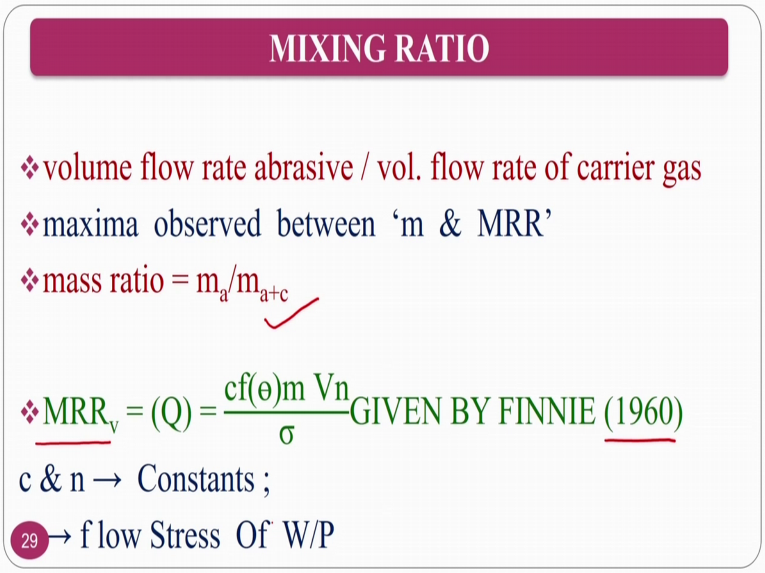

So, volumetric flow rate of abrasive to volumetric flow rates of carrier gas is nothing, but the mixing ratio. Normally, mass ratio also is there that is nothing, but mass of the abrasive particles to combination of mass of abrasive particle with carrier gas. So, volumetric material removal rate if you see here c f theta m V n which is given by the Finnie in 1960 where c and n are constant and the flow stress of the work piece is also given here.

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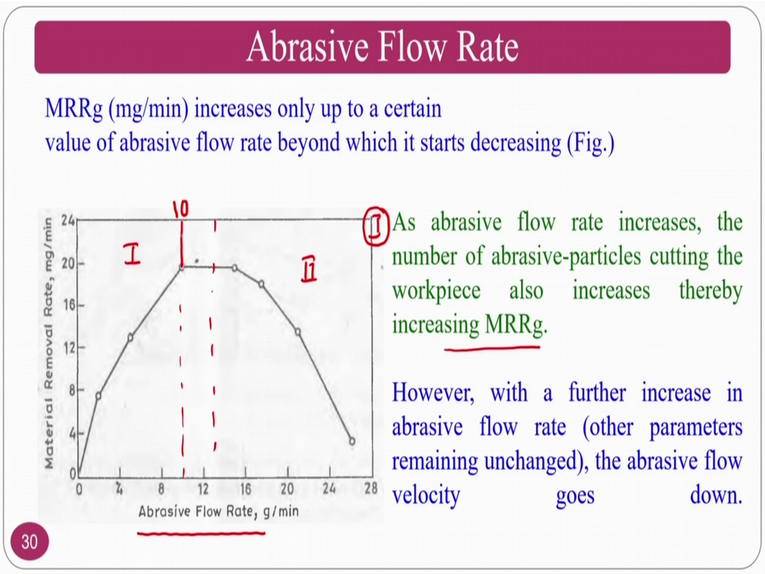

So, the flow rate, if you see the output responses that is how the abrasive jet machining works. The MRR increases only up to certain value then if the abrasive flow rate increases as I said what will happen? In the phase one, the as you increase till 12 to 16 what will happen? The value of the material removal rate will gradually increases. Because, if the abrasives are more what will happen? The number of times of abrasive particles will hit will be very high. So, the craters formation very high and material removal will takes place.

If you beyond a certain values were going to increase the abrasives what will happen? The abrasives will hit one other and its velocity will be reduced. The abrasive flow rate increases, the number of abrasive particles cutting work piece is also increases thereby material removal increases. This refers to part 1 ok.

However, with further increase in abrasive flow rate, the abrasive velocity goes down because in the section 2 what will happen? The abrasives try to collide each other and there will be a loss in the velocity. At the same time this may also clock the exit of the nozzle. If it is partially clock then; that means, that completely the velocity at which it has to come maybe completely disrupt.

So, you have that is the cost for the second portion. So, the material removal rate will be decreased if you are going beyond certain values. So, from this particular graph what is the inference is people should can go approximately this is the values where one can use for optimum. Like you can go for 10 grams per minute maximum 216 grams; if your material removal rate is good at 10 grams per minute; so, you can go for 10 grams per minute; so, that you can achieve the better material removal rate in this particle context.

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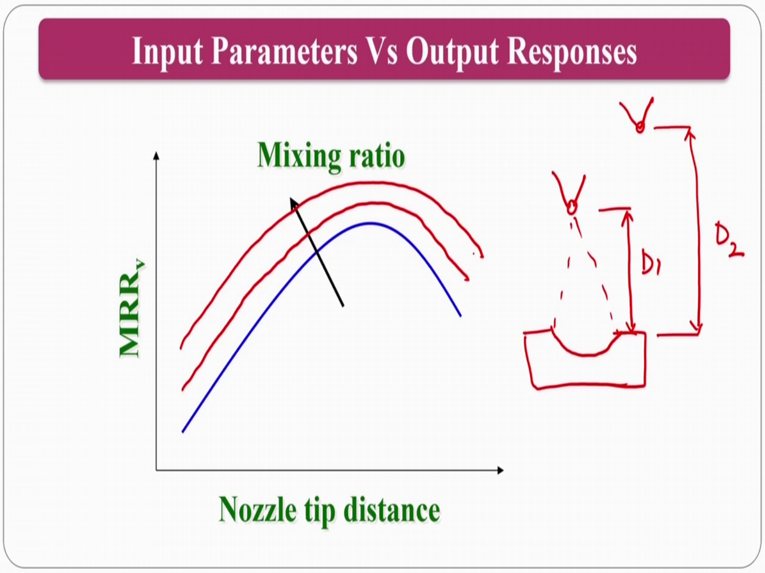

So, if you see the other parameters normally nozzle tip distance, if the nozzle tip distance is increases what is happens here is the crater diameters will. If the nozzle tip distance is low what will happen? The material removal will be good.

If you are going to increase beyond which what will happen? The crater depth will reduce, but crater diameter will increase. But, whatever the problem here is if you are going to increase the distances between the nozzle and the work piece, what is going to happen here is the velocity it loses the velocity. As the distance is D1, if you go for D2 what is going to happen is it loses its velocity.

So, the losses will be there because it is coming into the far fear, the pressure difference is there because of the pressure difference the velocity will lose. If your mixing ratio is high; that means, that abrasive particles are high. Normally, what you are going to expect is the curve will move like this ok. Beyond certain value again it will goes down because as you have seen the same reasons in the previous slide that it decreases the velocity and it may block the nozzle also.

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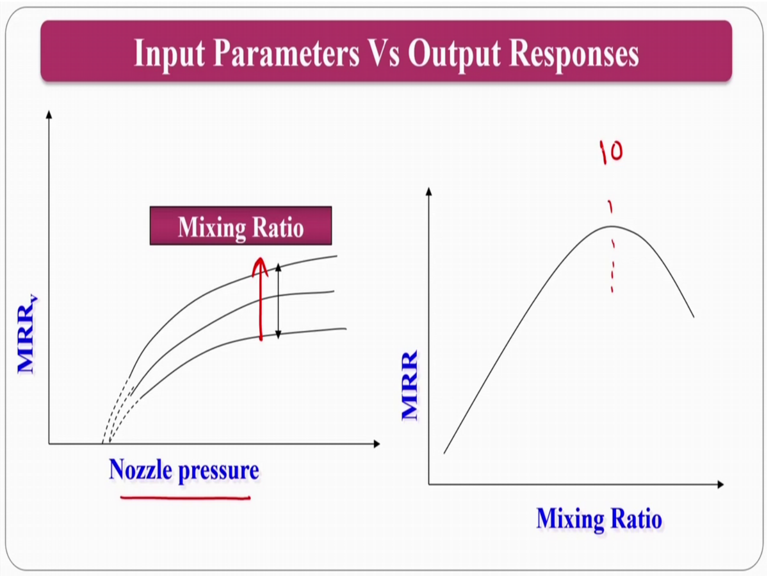

If you see here mixing ratio with respect to nozzle pressure that mean that how much pressure you are increasing. If you are increasing the pressure the jet will come and hit with high velocity. For that purpose the material removal completely increases. At the same time if you are going to increase the mixing ratio; obviously, the material removal increases. If the nozzle pressure increases what will happen? The velocity at which the abrasive particle hits will be very high and the crater size will be very high and the material removal volume will be very high.

Mixing ratio as you have seen in the first slide that mixing ratio if your mixing ratio is up to certain value like what the 10 is a value if it is increases beyond which it blocks and internal collection of the abrasive particles will lead to the pressure, velocity decrease and other things will takes place.

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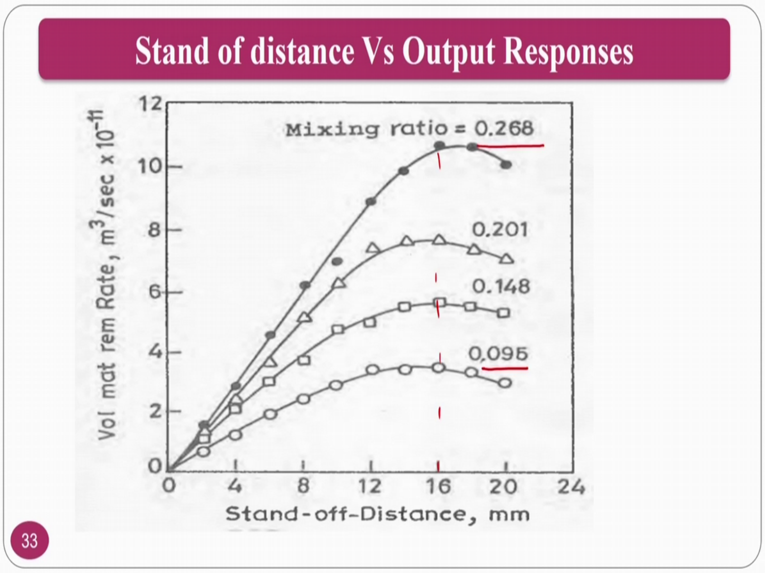

If you see the standoff distance, if the standoff distance is increasing for the mixing ratios; here you can see the mixing ratio 2 point, previously whatever you have seen is a qualitative things those are taken, but if at all correct values are required quantitatively and other things.

Better material removal is achieved if your mixing ratio is very high. At the same time for the standoff nozzle standoff distance is approximately 16. For this particular thing you can achieve better value. So, the mixing ratios are ranged from 0.05 to 0.268. So, the mixing ratio; that means, that abrasives are increased, if the abrasives are increase normally the number of craters generation will be also increased ok.

So, the material removal; obviously, increase. If the standoff distance is increased, if the standoff distance is too less what will happen? You do not have sufficient velocity to carry. So, you also need the standoff distance a optimum value so, that you can hit the work piece.

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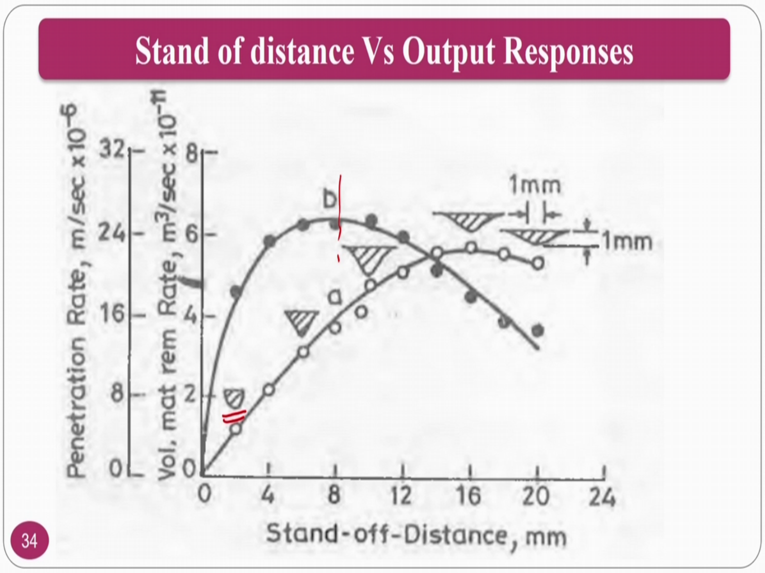

If you see the standoff distance with respect to volumetric material removal rate and the penetration rate is the penetration rate. If the standoff distance is too low, the normally the penetration rate is also somewhat low. But, if your penetration rate will be slightly increased if you give sufficient space are to the nozzle. If you give sufficient space to the nozzle what will happen? It has certain distance where it can carry the velocity and hit the work piece.

For that purpose normally the penetration rate will increase and beyond which the penetration rate will decrease. If the penetration rate decreases what will happen? The volumetric material removal also will go on decrease that is what you can see in this particular slide.

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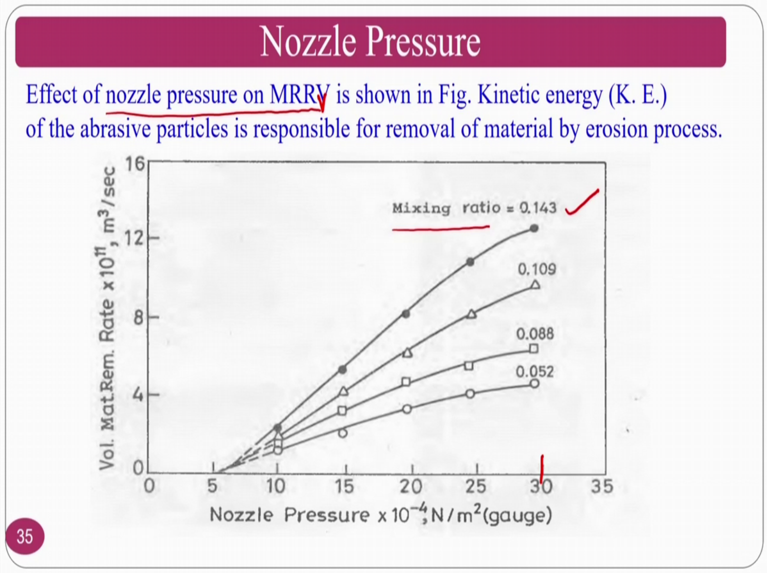

So, nozzle pressures, nozzle pressures with the volumetric material removal rate here you can see all the values. So, previous slide similar slide we have seen, but the thing is that there it is a qualitative one. As you increase it will increase, but how much increase of the input parameter will increase the how much output response that we are going to see here. Here 0.143 mixing ratio gives the highest value; that means, that mixing ratio is high.

So, the higher material removal rate is achieved for the higher nozzle pressure. If the nozzle pressure is 30 you are getting the higher value. So, if your nozzle pressure is very high. So, the impact will be very high; that means, that the abrasive particles will be hit with the high velocity.

So, the material removal will takes place; that means, that the nozzle pressure that is volumetric material removal is shown in the one. What is the kinetic energy of abrasive particle is responsible for material? So, if your nozzle pressure is very high, the kinetic energy of the abrasive particle will be very high and the material removal rate will be increased. Now, we see about the material removal models for the brittle and ductile materials using abrasive jet machining process.

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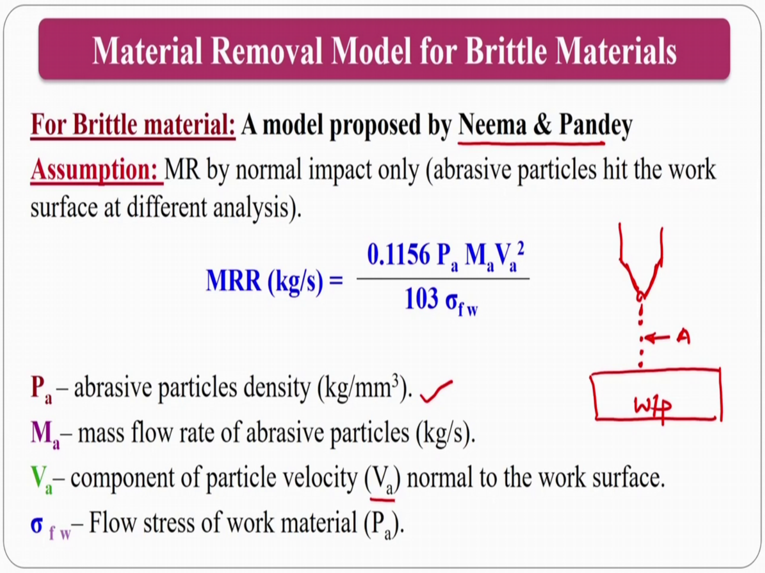

Material removal model for the brittle materials which is proposed by Neema and Pandey [FL], Professor Pandey; so, assumption material removal by normal impact only; that means, that there is no additional things involved. So, abrasive particles hit the work piece and the work piece material will be removed that is a simple assumption.

So, MRR is taken in kg's per second. So, 0.1156 P a M a and V a square so, by upon 103 sigma f w. Where P a stands for abrasive particles density, our M a is stands for mass flow rate of the abrasive particles, V a is a component of particle velocity that is in and normal to the work surface. That means, that assume that my work piece is like this and my jet is like this and abrasive particles are coming and hitting perpendicular to this particular surface ok.

So, this is how it is and sigma f w is the flow stress of the work piece material. The normally what are the flow stress of this work piece material these are the abrasive particles and this is a nozzle from where the (Refer Time: 55:30). So, this is normally what Professor Pandey has proposed for the brittle materials.

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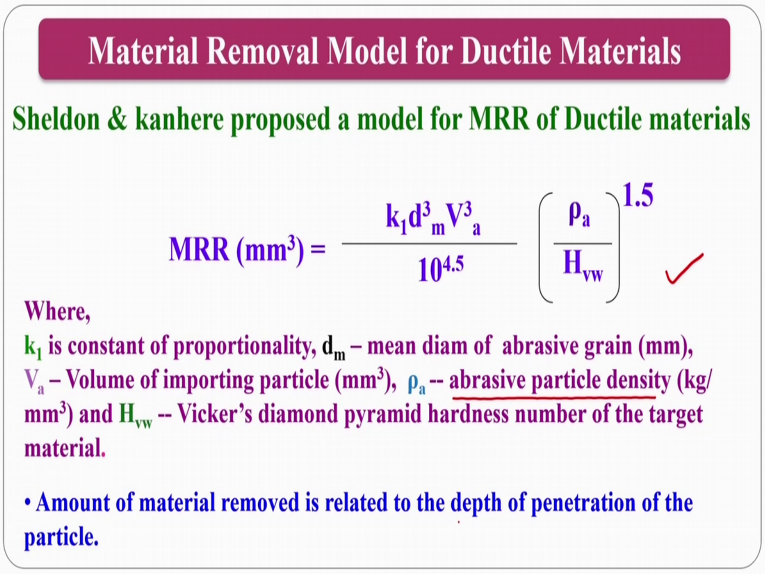

So, if you see the material removal model for the ductile materials, as you have seen this particular process is mainly suitable for the brittle materials because abrasives are coming and hitting. So, the fracture and small-small fragments of the chips, then it will goes off. That is the most major mechanism or this is suitable for the brittle materials, but people have used for the ductile materials also. As I discussed in the previous, as I discussed in the previous slides, that the where the flow stress will be equivalent to your fracture and then it will goes off as a chip.

So, in the same way the ductile materials also proposed here the material removal model. Sheldon and Kanhere is proposed the model for MRR for the ductile materials. If you see MRR in the volumetric material removal normally k one d cube and V a cube and whereby the various terms are given here. The rho a and H V W this is the one equation.

So, where k1 is a constant of the proportionality and d m is the mean diameter of the abrasive particle or abrasive grain. V a is the volume of importing particle; that means, that the how much material is going away and rho a is abrasive particles density that is kg per mm cube. And H V W is the Vickers diamond pyramid hardness number of the target material; that means, that indirectly you are is saying about the hardness of the work piece material.

And the amount of material removed is related to the depth of penetration of the particle; that means, that how much particles are hitting it is generates the deformation, then act and prolonged abrasive particles will hit, hit, hit, then the fracture will be a removed. So, that is what the amount of material is removed related to the depth of penetration; that means, that how much penetration is taking place in the work piece material will be taken into consideration for this particular model.

These are the 2 mathematical models that are proposed by different different authors. So, this may be useful for the people who want to do some of the possible research or some of the relative research. If at all you want to move ahead with this particular model you can move ahead also as considering these equations of the base equations.

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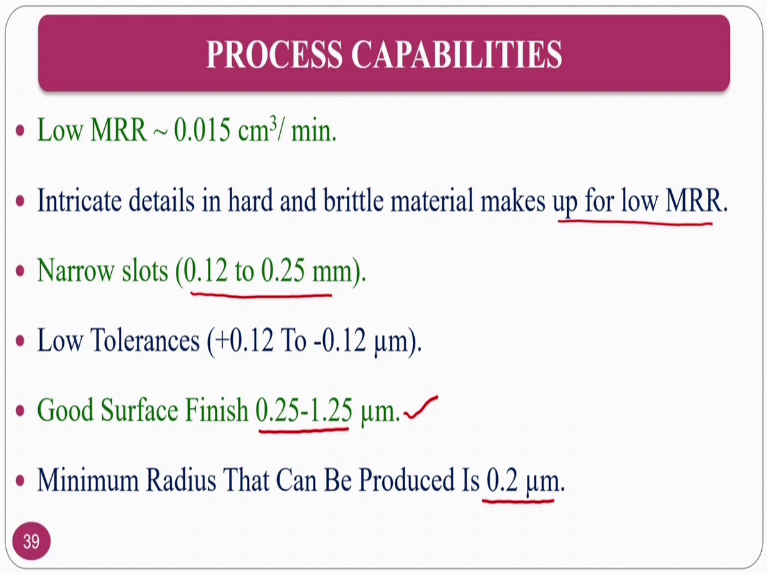

The process capabilities: if you see the low MRR normally 0.015 centimeter cube per minute is the material removal. So, intricate details in hard and brittle materials can up to for the lower material removal rate; that means, that normally if at all you want to do the abrasive jet machining for intricate shapes and you do not bother about much MRR that is material removal rate. Because, the intricate shapes it has to go and it has to do. So, for that purpose you do not look for the material removal that is why the material removal is very low for that one.

Narrow slots, you can cut a narrow slots normally 0.0 0.12 to 0.25mm slots you can cut using abrasive jet machining. You can achieve low tolerances ranging from plus 0.12 to minus 0.12 microns you can achieve. And the good surface finish normally from the nano surface point of you this is not a good value, but for the machining purpose the surface finish that you are going to get is minimum is 0.25, which is a good surface finish from the finishing point of view.

But, this particular process is dominated by the material removal mechanism that is nothing, but it is a machining process. That is why we are considered this abrasive jet machining as one of the advanced abrasive machining processes. So, minimum radius that can be produced is 0.2 micrometer. So, this can produce a good amount of a good radius ok.

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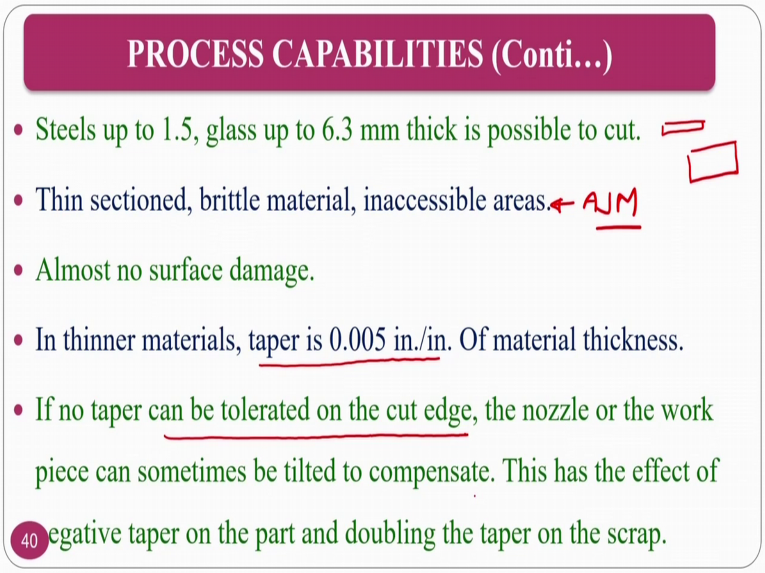

So, process capabilities still there are some more process capabilities, steels up to 1.5, glass up to 6.3mm thickness you can cut; that means, that if at all you have a steel plate of very small thickness, you can cut or your glass plates with big thickness you can cut using the abrasive jet machining. Thin sectioned, brittle materials, inaccessible areas can be machined by this particular AJM process.

So, these are the capabilities of abrasive jet machining process. Almost no surface damage because there is a gap between abrasive particles. At the same time heat generation in this particular process is normally low because you have air which is a lubricant or which act as a coolant in this particular action of the abrasive jet machining and there is no surface or subsurface damage.

In the thinner materials taper is 0.005 inch per in of the material thickness; that means, that normally if you are going for 1 inch, 0.005 inch is the taper that normally observed. So, this is if the requirement to the customer is very minimal, then you have to think about some other processes. If this is within the limits of their requirements then you can go for abrasive jet machining process.

Low taper can be tolerated in the cutting edge. So, the nozzles or the work piece can be sometimes tilted to the component compensate this; that means, that. So, if at all you do not want this type of tapers then you can tilt it. Nowadays you can tilt the nozzle assume that if this is your nozzle you can tilt as per your requirement if at all you do not want. Assume that some microns taper is coming, just you move your nozzle or you give some tilt to your nozzle in opposite direction of that much micron; so, that you can compensate it.

This effect of negative taper or the part double the taper than scrap; that means, that you can improve and if at all you want the tapered holes are something then you can use; obviously, this particular process with slight experience and other things.

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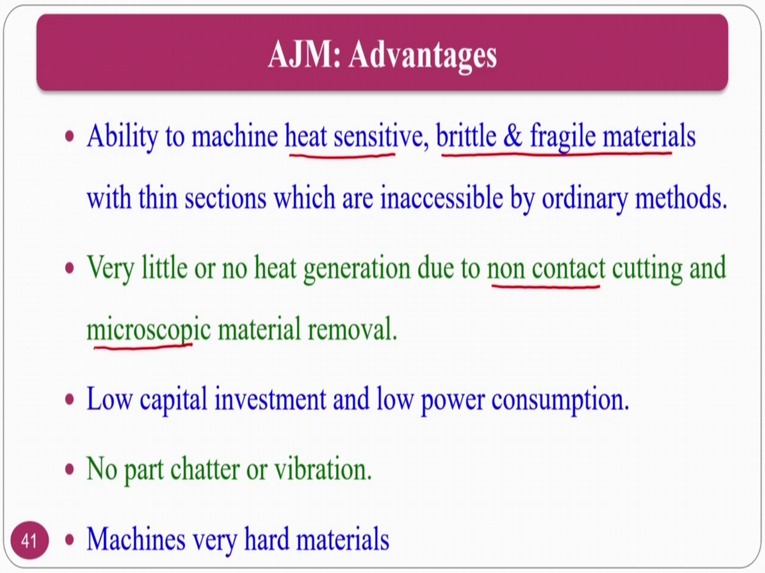

Advantages of abrasive jet machining, if you see the ability to machine heat sensitive, brittle fragile materials; that means, that if it is heat sensitive material assume that any materials are mostly subjected to heat sensitive then those can be machined by abrasive jet machining because, this particular process do not develop any heat during the machining process.

Very little or no heat generation due to non contact cutting and microscopic material removal; that means, that the material removal is very very minute. At the same time non contact cutting tool that is nothing, but you have abrasive particle, abrasive particle in between there is a air gap. So, air will act as a lubricant or a coolant or something. So, it is a sufficient time or a ample time is there between one abrasive particle to another abrasive particle if your mixing ratio is slightly less.

So, there would not be any generation of heat in this particular process. So, low capital investment and low power consumption; that means, that you can develop this abrasive jet machining in your laboratory with a very minimal cost. That mean that if you have a if you do not have funding also you can develop, you need a one compressor. So, normally compressors are not that much costly. So, you can have different different ratings of compressors and you can get those compressors, then you just put a feeder, abrasive feeder and you can mix it in a mixing chamber and you just impinge on the work piece.

So, you can start work basic research with low investments which assume that if your institute or university can give a minimum amount of some amount. A minimum amount if they can give then you can develop this abrasive jet machining and power consumption also very less.

So, I think the universities will higher authorities of universities will allow you for going ahead of this particular process. Low part chatter or vibration is observed because there is no chance of vibration. So, if at all what you have to do is you have to firmly hold your work piece. So, that if at all there is anything such small small minute things are there from the point of chatter or something then can be avoided.

So, machines are very hard, it can machine very hard materials; that means, that hard to brittle materials normally brittle materials are hard materials also. So, you can do the machining of these hard materials

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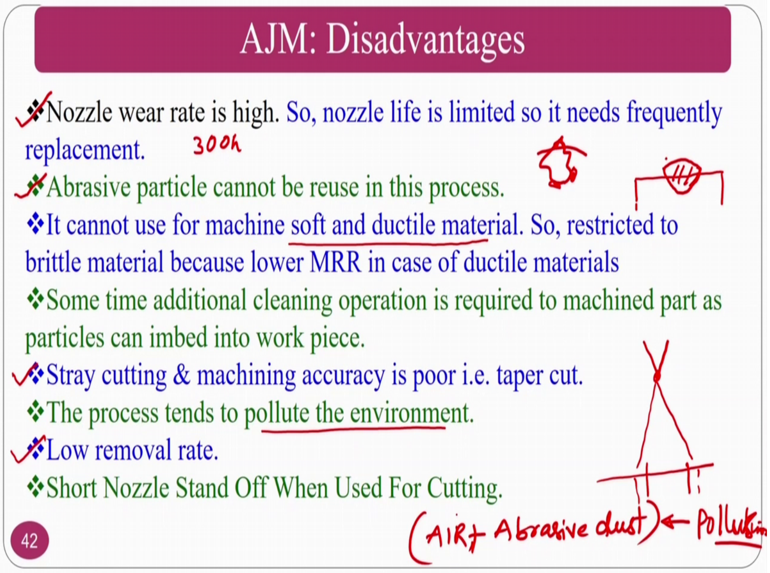

Disadvantages of this particular process, nozzle wear rate is very high as I said you have to go for sapphire. If you go for sapphire normally you go for 300 hours ok. If you are going for the tungsten carbide or some other things now you it will be reduced by 10 times, that is maximum you were going to get is 20 hours or 30 hours. Abrasive particle cannot reused that is the biggest problem because, this abrasive particles once hits the work piece it loses it is cutting edges. At the same time assume that I have a short cutting edge here. So, after uses what will happen? This will goes off.

So, that mean that will become blunt, at the same time this will catch up some of the chips of the work piece material and this chips are hardness compared to the tool material, that is abrasive materials. For that purpose what will happen? You cannot reuse in most of the cases. It cannot use the machines for soft and ductile materials because, whenever you use a soft and ductile materials these abrasive particles go and indent, sometimes it will stay also.

So, assume that I have a soft material here abrasive particle can come and hit to the work piece and can stay like this only ok, it will stay like this. So, in a soft material this is a biggest problem ok. So, you may not recommend this particular abrasive jet machining to machine soft materials. Sometimes, additional cleaning operation is required on a machine part. Because, if assume that some of the indentations are generated or some of the abrasive particles are stayed there. So, you need a post processing that is nothing, but the cleaning.

Stray cutting and machine accuracy is poor; that means, that because of the divergence assume that my nozzle is here because of the divergence what will happen? The stray cutting also will takes. Assume that I required only in this region so, I am getting a stray in this region which I do not want because, the air is a gas, gas try to expand because of that problem the divergence will stay and the stray cutting will takes place. Because of that what will happen? Accuracy of that particular hole or accuracy of that particular part which has to be generated will go beyond what was the customer require. So, the customer has every chance to reject that particular part.

The process tend to pollute the environment because abrasive particles are brittle materials whenever the abrasive particles are hitting the hard materials of the work piece, hard work piece material. So, it will generate some dust like gas is there already you have air plus abrasive dust this will lead to pollution ok.

So, low material removal rate at the same time the short nozzle standoff distance when used for the cutting purpose; that means, that if at all you want to go for cutting. So, you have to use nozzle tip distance or the standoff distance very low ok. This has to be taken care if at all you are going for a cutting operation. If you are going for a pinning operation or surface cleaning operation you have to go for high standoff distances.

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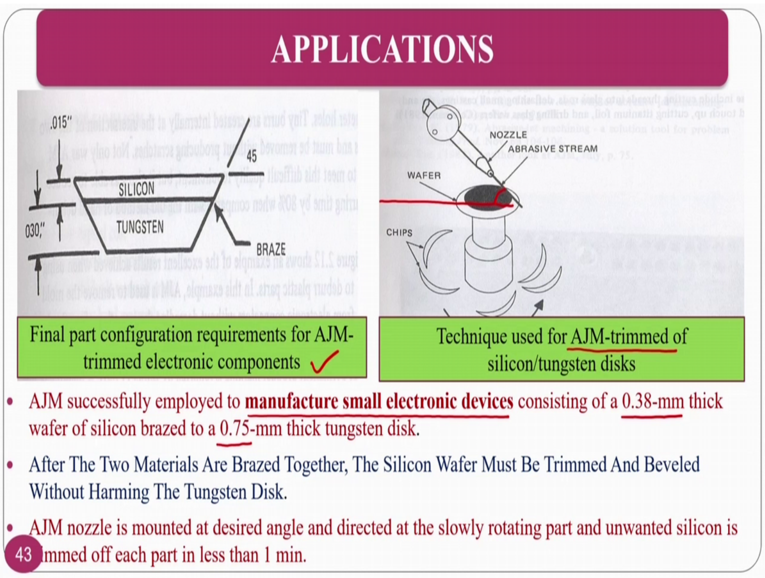

Applications, if you see the applications normally silicon or tungsten carbide configuration requirement for AJM for the trimming of electronic components. At the same time you can use AJM trimmed for the silicon you can use at different angles ok. You can use at different angles for trimming application this is one of the technique that you can use. AJM is successfully employed for manufacturing of small electronic devices consisting of 0.38mm thickness.

Silicon wafer brazed to 0.75mm thickness tungsten disk and other things you can use for the brazing then you can do the trimming also. After the 2 materials are brazed together the silicon wafer must be trimmed and beveled without harming the tungsten disk. And AJM nozzle is mounted at desired angle and directed slowly rotating part and unwanted silicon is trimmed off for the part ok. That means, that you can trim off as per your requirement, this is the one of the special thing about this particular process ok.

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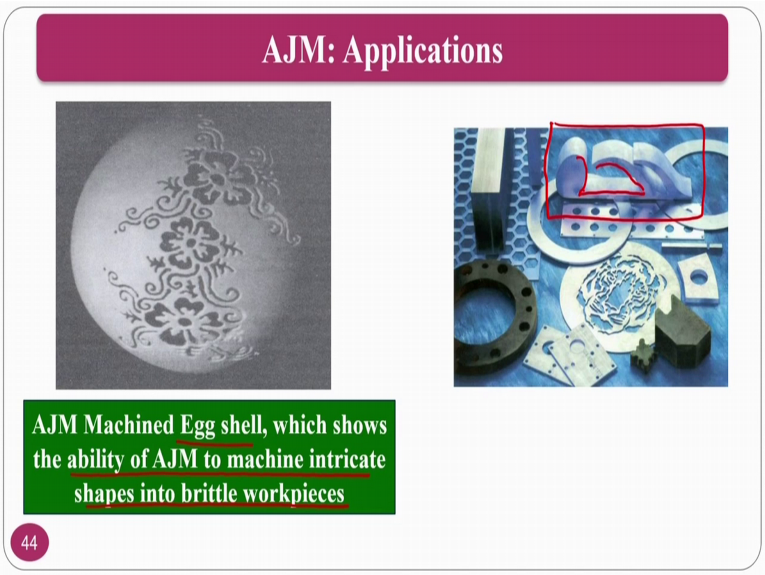

The applications, if you see the applications as I said you can see the capability how beautiful capability by drawing or by creating some sculptures on egg shells. So, egg shell is to brittle material on and it is a very thin material also. So, if you can generate a beautiful sculpture on top of it; that means, that it has tendency to not break any type of physical brittle material so; that means, that it is very superior process to make in a brittle and thin sections any type of sculptures.

That means that this particular AJM has ability to machine intricate shapes into a brittle work pieces with low thickness. At the same time you can see some of the metals that are being cut using this. So, thin sections also you can go if you see this particular work piece material, see how much thick it is. So, you can cut the thick sections, you can cut the thin sections, at the same time you can cut multiple types of geometries ok. So, some of the geometries are you can cut like some of the complex geometries you can cut on a some of the thick sheets also.

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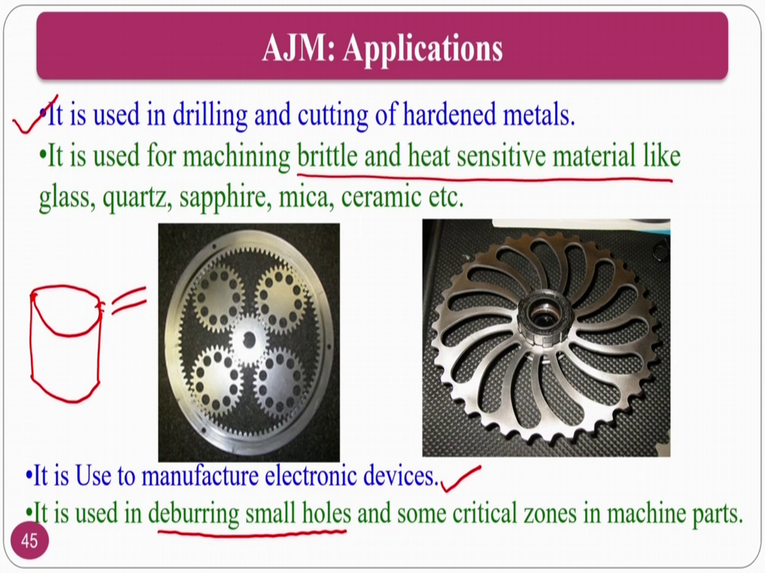

It is used to drill and cut the hardened metals normally you can do the drilling or cutting of the hardened metals also can be possible. It is used for machining of brittle and heat sensitive materials like glass, quartz, sapphire, mica, and ceramic. These are the some of the advanced materials where you can generate where you can make without any heat generation.

So, that if these are heat sensitive it may change it is metrological structures morphological structures or something. So, if at all you do not want all this metallurgical changes which are changing with respect to temperature you can use for this in this particular abrasive jet machining. So, that this there is would not be any heat generation because of which there would not be any changes in a thermo sensitive materials.

It uses the manufacturing of electronic devices which we have seen in the advantages. It is used for the deburring of micro holes also. So, if there is a bur assume that this is my hole on a surface there are there are burse. So, you can use by some tilting of your nozzle you can remove the burse ok. This type of applications also you can use for the, this type of deburring applications also you can use, this type of deburring applications also can be done by the abrasive jet machining process.

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So, some of the applications as you can see the butterflies, dendrites structures, cycle structures and gears can be manufactured; at the same time many complex shapes with the thin structures and as well as thick structures can be made ok. Thin as well as thick structures one can cut using the abrasive jet machining process.

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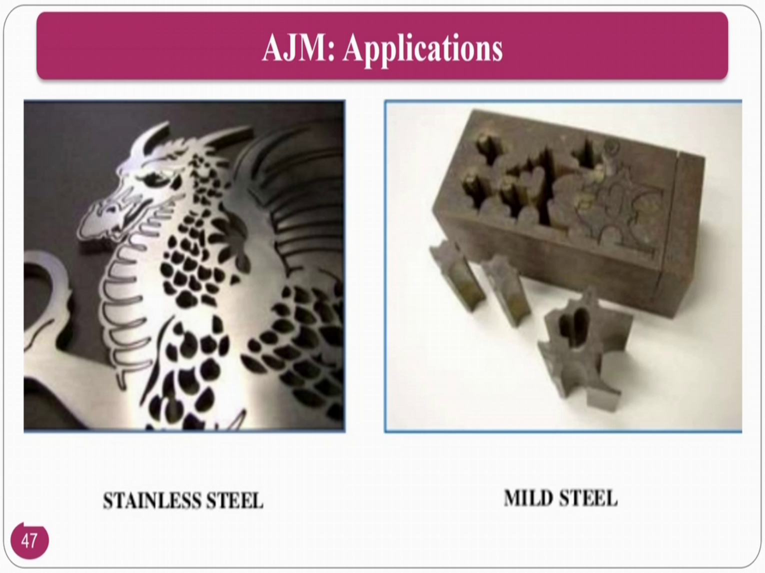

Stainless steel work pieces, you can see the good and complex structures are fabricated. At the same time thin structures and mild steel also can be cut. You see the thickness of this particular material, it is too thick material and you can cut using abrasive jet machining for this particular material, if some of the people might have used for by abrasive water jet machining also.

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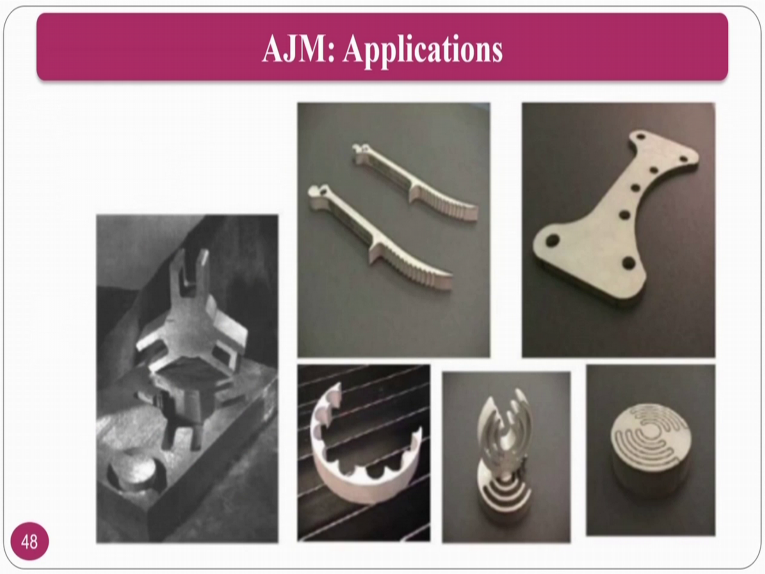

These are the same applications.

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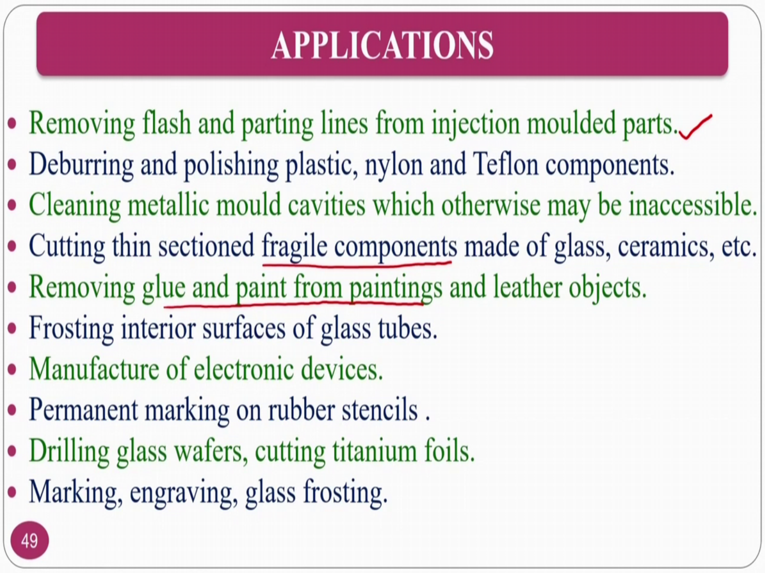

And if you see the applications removing of the flash, parting lines of the injection moulded parts can be done. And deburring and polishing plastic, nylon, Teflon components can be done and the cleaning of metallic mould cavities which otherwise may be inaccessible by other processes can be done by this abrasive jet machining process.

Cutting thin sectioned fragile component that is brittle component made up of glass, ceramics can be machined using abrasive jet machining. Removing of the glue paint from the paintings and other leather objects can be easily fabricated. Posting interior surface of the glass tubes normally if at all you want to generate some textures can be done by using this particular process.

Manufacturing of electronic devices as we have seen the silicon and other things can be done or trimmed by using this abrasive jet machining by giving some tilt to the nozzle. Permanent marking on rubber stencils can be done by the abrasive jet machining. And drilling of on glass wafers, titanium and other foils can be done. Marking and engraving and glass frosting is another application of this one. So, other part I just want to touch here is abrasive jet machining you can manipulate or you can modify to abrasive jet polishing also.

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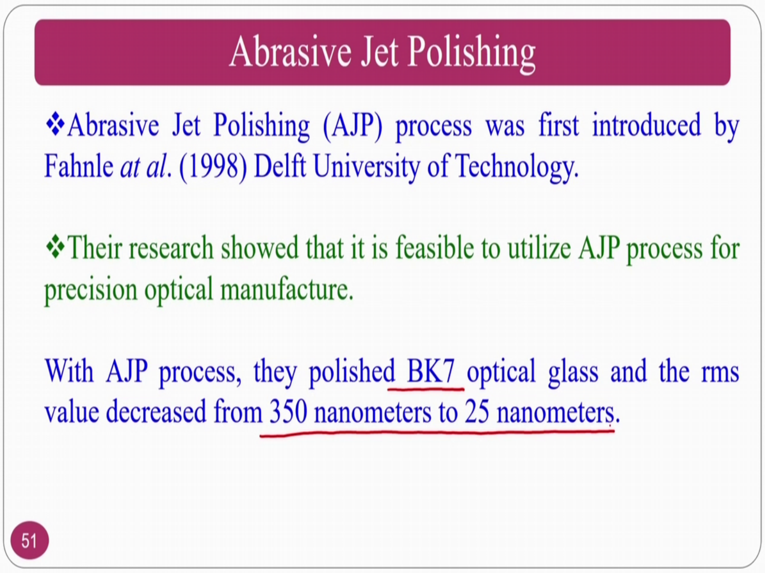

So, just I am going to give you 1 or 2 slides of the glimpse. Abrasive jet polishing process was the first introduced by Fahnle in the Delft University. Their research showed that this is feasible to utilize abrasive jet polishing for the precision optical manufacturing and abrasive jet process they polished BK7 optical glasses and rms values are decreased from 350 nanometers to 25 nanometers.

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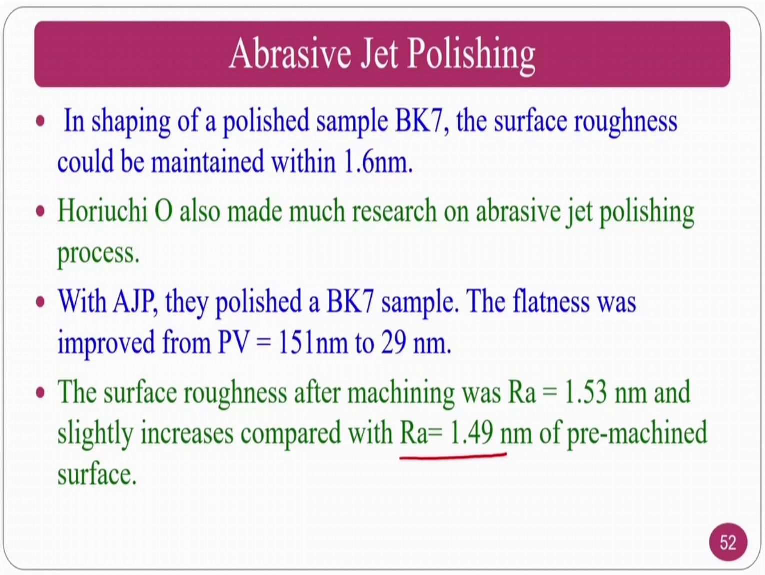

That is the best value that they have achieved. So, that mean that if you are looking for the abrasive jet polishing techniques it will be also can be done, but make sure that BK7 is one of the brittle and is brittle and material ok.

So, Horiuchi O also made such research and abrasive jet polishing process. And these are the some literature that I am giving because not much research work is done on abrasive jet polishing. That is why you can go through this particular thing and if at all some people want to take up or modify the existing abrasive jet machining process to abrasive jet polishing that can be done. And if the roughness values are 1.49 nanometers and pre machined can be done from the surfaces also ok.

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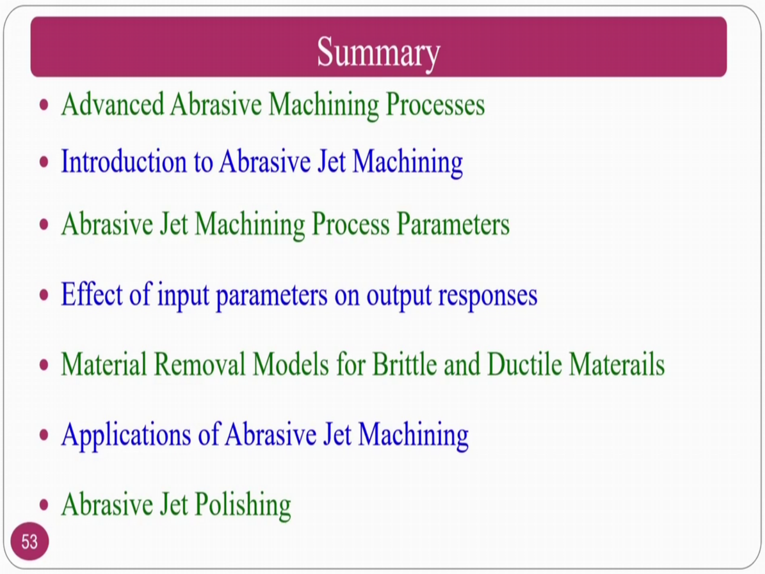

The summary of this abrasive jet machining can be summarized like this, advanced abrasive machining processes I just give you what are the process that I am going to cover in this particular section. Introduction to abrasive jet machining, then abrasive jet machining process parameters, what are the parameter, input parameters and what is needs to influence and output responses.

Effect of input, material removal models for brittle and ductile materials, applications, as well as at the same time I have just touched the abrasive jet polishing ok. So, this is about the abrasive jet machining process. Thank you for your kind attention and we will see the next process in the next class.

Thank you.