Microsystem Fabrication with Advanced Manufacturing Techniques
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Lecture – 6

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Hello and welcome back, to this lecture on microsystems fabrication by using advanced manufacturing processes. So, far we have actually seen variety of mems grade processes which are used for fabrication of the devices. And as in the introduction section, we have already mentioned in great details about the use of some of the advanced manufacturing techniques particular, the abrasive jet machining, ultrasonic machining, electro discharge machining, electro chemical machining so on, so, forth in the fabrication of mems devices.

We are going to actually review some of these basic processes, non-conventional processes before going ahead with utilizing them in the mems fabrication. So, the purpose of purpose of today's lecture really is to give you an understanding about starting from the fundamental level some of this non-conventional processes the way that you can estimate, how the material gets removed particularly in a very small area.

Then the idea is that those processes, which are learned in this manner are translated to make or fabricate micro level devices. So, there would be a section of the process of a certain kind followed by the application of the process or a group of processes to the fabrication of certain micro devices. So, let us begin today's lecture by just briefly reviewing whatever, has been done in the last class.

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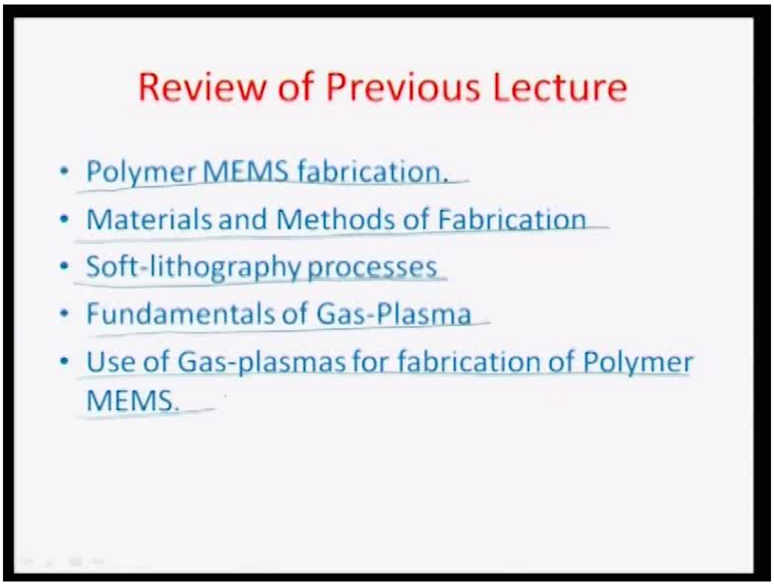

So, in the last lecture, we actually revised or understood about these polymer mems fabrication polymers like: PDMS, PMMA, Teflon so on so forth are quiet often used for fabrication of microsystems or microsystem grade devises. And some of the materials and methods were discussed, in great details of this fabrication which would include bunch of different processes called soft lithography for example, replication and molding micro contact printing micro capillary molding dip and lithography so on so forth.

Then we also learned a little bit about how gas plasmas can be used, for the fabrication of at least polymer grid polymer mems devices. So, we learned about some of the fundamentals of plasma and then uses of the plasma particular, the different how the plasmas can be formulated and how they can be used for creating wafer level bonding, between 2 or more wafers of such devises and this application is particularly very useful for hybrid devices in the mems area.

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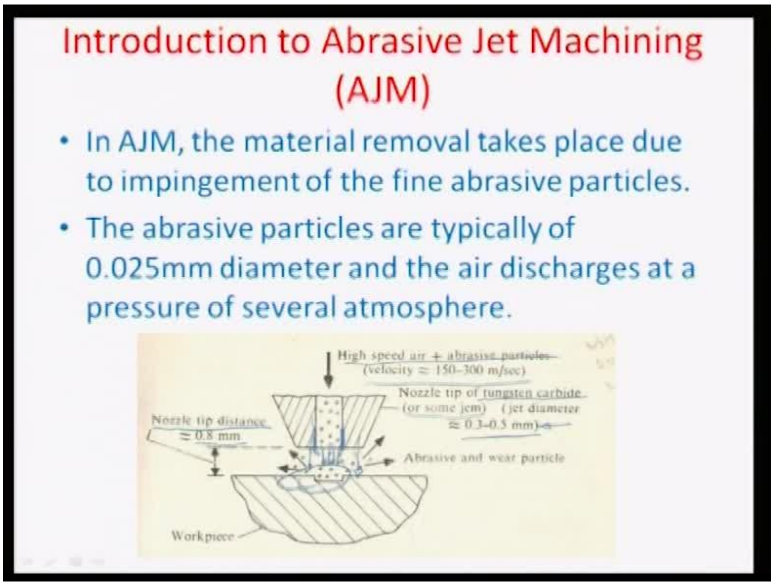

So, today we will, now look into in the one of the first fundamental mechanical non-conventional processes called the AJM or abrasive jet machining. So, as I have already illustrated in my previous lectures. A non-conventional domain can be split up into either mechanical removal of material or thermal removal of material or chemical slash electro chemical removal of material. Meaning there by the way and means in which material removal would take place by supplying energy of different forms makes these categorizations happen.

So, in mechanical removal of material, the energy mostly supplied is mechanical in nature and that can be the impact of abrasives or small grains of relatively higher hardness’s, which can impede with the surface impede into a surface and try imping into a surface and try to remove off the material by brittle fractures. So, let us look at one of the fundamental processes AJM or abrasive machining.

So, as you can see in this slide here, in the AJM process the basic material removal would take place, by impingement of fine abrasive particles. These particles would typically have hardness’s, which are higher than the hardness of the work piece surface which is being removed by the impact of such particles and the particles are carried together by means; of a jet of air with high velocity. So, that they can come with high velocity and impede into a surface as you can see here, in this particular region.

The particles are coming down through a small r f s. And they are being carried by a high speed air and abrasive mixture which is flown at a velocity of about 150 to 300 meters per second. And this nozzle is taken very close to the surface where you have to do the material removal. Thereby the impact which the abrasive grains would have there in on the surface here, causes the brittle fracture to take place the material gets removed. And the velocity or the high velocity air which is flowing along with these abrasives kind of takes the materials away from the surface.

So, this is very prominent method particularly for bulk micro machining. Where you are actually trying to subtract material from a surface as you have been taught earlier that there are 2 different kinds of machining; micro machining one is surface and another is bulk surface is a negative process; for the sake of reputation and bulk machining is a subtractive process, where actually removing the material from the surface.

So, this is the subtractive process, where you are trying to remove the material from the surface and as you can see here again back, to the slide typically there is a parameter called the nozzle tip distance NTD which means; this is the distance of standoff position of the nozzle with respect to the work piece. So, if distance is varied the way that or the behavior that, the abrasive particles would have on the surface or on the way from the nozzle into the surface would vary greatly and which will result in different kind of machining removal rates.

So, this nozzle tip distance is a very important parameter, which has to be controlled for the purpose of micro machining. The tips are normally made up of a very hard material like: let us say one of the materials could be tungsten carbide or may be some other jem can be used for making the tip the idea is that whenever, the hard abrasive particles flow around the step as you can see here, they should not be able to cause much wear. So, the wear of the tip should be minimal in nature.

So, typically the diameters of such tips; which are used are about 0.3 to 0.5 millimeters about 300 to 500 microns and this gives us an opportunity to really work at micro domain and trying to get very small areas machined using such AJM or abrasive jet machine techniques.

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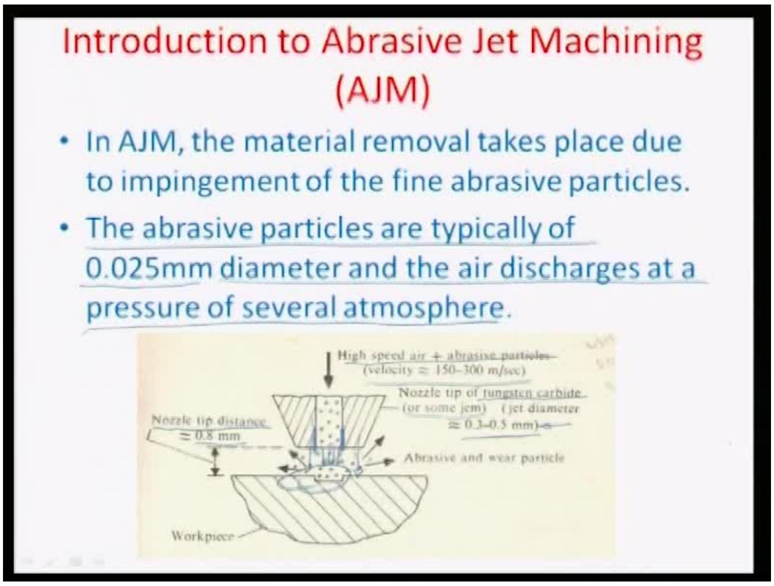

As we will show later on, there are some illustrations, where you can actually see an impending jet of abrasive's creating past through a mask, of course to impinge the features which are there on the mask on to the surface of the material. So, the typical diameter of the grains, which are used as particles here are about 0.25 millimeters or so, is about 25 microns. And the air charges at a pressure of several atmospheres; thus creating a suitable high velocity to emanate out of the nozzle in such machining processes.

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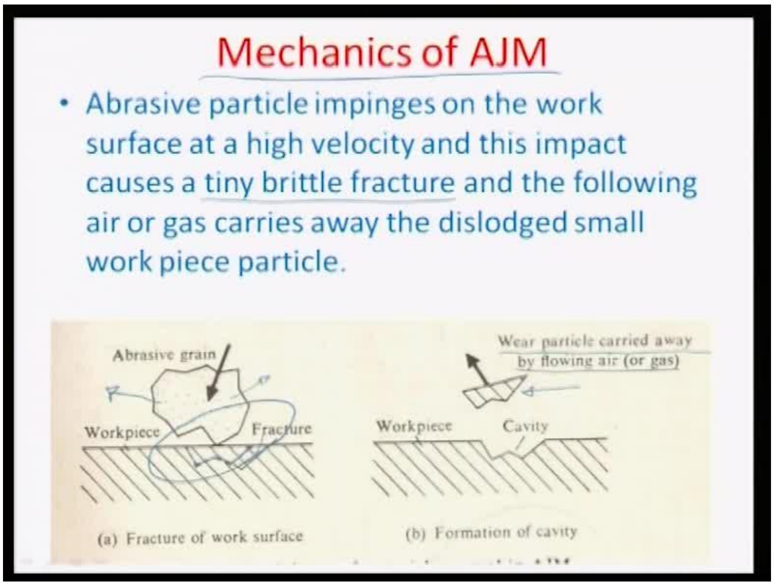

As far the mechanics of the AJM process works it really works by creating tiny brittle fracture on to the surface, which gets impinged by the abrasive particle at a high velocity and basically as I have already illustrated before for example, this is a fracture, which is happening on this particular surface by an impinging grain and the velocity of the air which flows along with this grain is sufficient to dislodge it off from the work area and carried out and that way there can be a material removal, which can take place because the new area which is formulated is really this crated and it is opened to another impingement and subsequently more brittle fracture.

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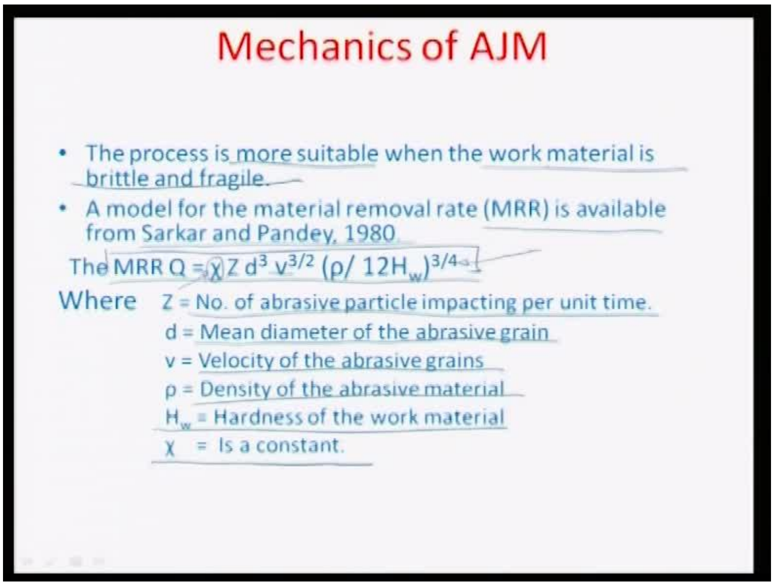

So, basically it is a fracture by fracture which would happen in succession for a cavity to be created within the work piece. So, as you can see here the wear particle here is carried away by, the flowing air or gas in this particular illustration shown. So, if you look at the process more closely. It is more suitable when the work material is actually brittle or fragile because then the it automatically promotes the process of brittle fracture.

And if you look at the various models which are available for estimation of the material removal rates; the most widely used model is that, by Sarkar and Pandey, which was formulated in 1980. And this is more on so called experimental observation where, the MRR or material removal rate is actually represented by this particular equation here. Where z is the number of abrasive particles impacting per unit time on the surface, d is the mean diameter of the abrasive grains and velocity of the abrasive grains is v rho is the density of the abrasive material as such.

Material of those grains HW is the hardness of the work material that, you are machining using this method. And the x here, is really a constant which is automatically imparted because of regression analysis. And this is a observational formula, it is an experimentally determined formula which is come out from this paper of Sarkar and Pandey in 1980. So, as you can see here the material removal rate of an AJM system is proportional to the cube of the mean diameter of the abrasive grain; which is obvious because, it is kind of giving an idea of how much volume is dislodged.

By looking at the volume of 1 grain; z is the number of abrasive particles impact in per unit time, there by meaning that; if you have more number of particles at a higher moving at a higher velocity you know there would be, a component of velocity contributed to the MRR and. In fact, the number of abrasive particles in 1 unit of time; if it is closely packed; that means, the abrasive is highly loaded on to the flowing gas that also increases the material removal rate.

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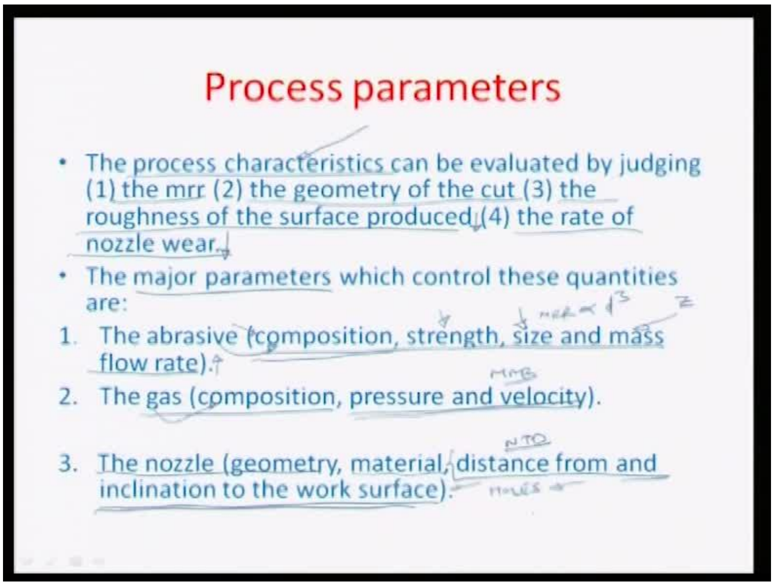

And of course, the other parameters of importance at the hardness of the work material and the density of the abrasive material, so that is about it. About the mechanics, the process parameters which are involved, in this abrasive jet machining process the you know you can evaluate the process by characterizing the of course, the material removal rate MRR you can also illustrate or you can also characterize the process, by the geometry of the cut that you would need to formulate, you can also characterize the process by the amount of surface roughness; which is produced by this the process in relation to a surface and of course, the rate of nozzle wear.

So, any good process machining process, would need typically a lower wear rate there by meaning; that the nozzle has a better working life. It should be able to produce low roughness surfaces and then you know, you should be able to do complicated geometries in terms of machining and the MRR should be high yield meaning thereby the MRR should be higher.

So, the major parameters, which are the controlling parameters for some of this process characteristics are for example, the composition strength size mask and flow rate of the abrasive material. So, if the abrasive is; what is the hardness level of abrasive for example, with respect to the work piece on which you are machining. What is the size for example, of the grains because, as you know the MRR typically, is dependent on cube of the diameter of a grain what is also the mass flow rate of the abrasive which gives an indication of the numbers per unit time.

If you are packing the grains more thereby increasing the mass flow rate, a basically increasing the z value of the machining and then of course, the composition also is very important as to what is the quality of the gas; which is flowing along with the abrasive or does it have its own etching effect on the surface which is being machined. The other very important aspect is the composition of the gas, the pressure and the velocity of the gas.

So, the composition of abrasive is important as, we learned from the previous step. And the composition of the gas also is very important as I just told little bit ago because sometimes, the gases can be derogatory to the surface in terms of giving its h characteristics, it may be able to soften the surface where you are actually flowing the abrasive material and of course, the pressure in velocity of the gas is very important for illustrating, what is the overall material removal rate associated with the process.

The nozzle geometry again is very important for the purpose of determining some of these process characteristics. Typically you know circular or square type nozzle are the most preferred geometries, in this particular case the nozzle materials should be having a higher hardness than the hardness of the abrasive grains therefore, reducing the nozzle wear rate and of course, the distance of and this is very important the distance from an inclination to the work piece surface.

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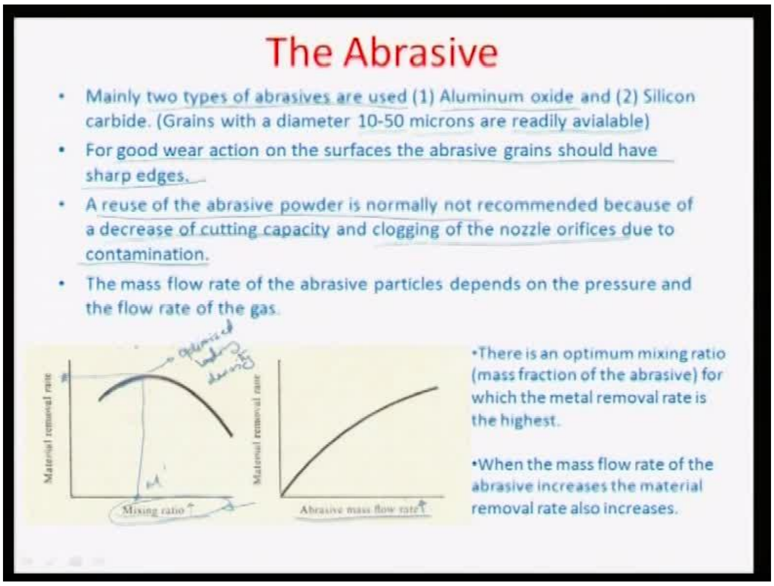

So, when you are basically trying to create a small cravious or a hole material. What is important is that, what is the standoff distance or the nozzle tip distance NTD which would create you know, the MRR would vary, as per this distance. And also what is the inclination at which the nozzle is placed with respect to the work surface. And for example, some of the cases where, holes are needed to be etched in a inclined manner this would suit to be the nest process; which is available for creating such micro holes and micro features, within materials particular from mems aspects.

So, when we look at the quality of abrasive mainly there are 2 types of abrasives, which are commonly used in the industry 1 is the aluminum oxide and a silicon carbide and the diameter, as we already mentioned are about very often 10 to 50 microns range of these grains although 25 to 30 microns is really what is most commonly used.

Basically for good wear action on the surface is the abrasive grains should have sharp edges. Because sharper is the profile of the grain better is the impingement of these grains on the surface and more typically would be the MRR, because of that the use of abrasive powders is normally not recommended, because as you are machining the surface along with. Let us say an abrasive jet and there is continuous material removal.

So, whatever is the waste collection unit for this whole system would have metal which has been removed; as well as the grain along with it. And after a while when the grain gets completely loaded with metal, it is very difficult to filter out or clean the grains out of the metal because, the metal in the process of very high level of deformation and sometimes causing brittle fraction, there is a level at which the metal is coming or removing.

There may be a case where, the particle may get actually softly sticking to the metal or you know it may plastically weld to the metal. And it is not easy to clean the particle of the metal and. So, when you are using that material, the grains may not be able to impinge more on to the surface and the plowing action will be lost sometimes, the sharpness of the grain could be lost.

So, therefore, use is normally not recommended. And because there would be a decrease of the cutting capacity and then sometimes the issue of clogging of nozzle is also very important the r f s itself is very small which sends out particles along with, let us say high velocity air. And supposing if there is a metal to metal contact there of coded metal on to a grain, which we have re-circulated back there is always a possibility of clogging the nozzle with such material.

Therefore, you know the characteristics, the process characteristics would be totally changed because of the reduced area from which the grains emanate out. So, contamination is really prevented and also reuse of the abrasive powder is normally not recommended in some of these processes. Also the mask flow rate of the abrasive particles depends on the pressure and the flow rate of the gas. As you have already seen before that MRR also is heavily dependent on both the velocity of the gas, as well as the volume; which is proportional to the cube of the abrasive particle is diameter.

So, therefore, because abrasive particle is the main cause of moving the material away; the mass flow rate the rate at which it comes and hits the surface would, typically depend only on the ambient pressure on the velocity gas velocity. So, that is one important point about how the abrasive is loaded. And if you look at the various parameters like, let us say how you are mixing the abrasive with respect to air and there is something a parameter called mixing ratio.

Which I will just define: basically it only indicates that, if you are increasing the mixing ratio there is of course, an optimal best of material removal rate as can be illustrated by this point here, at a certain mixing ratio m dash meaning thereby that this is probably the optimum you know case of mixing or loading of the abrasive on to a gas. So, the mass flow rate you can define: basically the mixing ratio you can define: basically by looking at; the volume flow rate of the abrasive particles per unit the volume flow rate of the carrier gas. So, if you are loading more than the volume flow rate of the abrasive particle would increase in the mixing ratio would increase.

So, if you look at various mixing ratios, the more you are loading the air abrasive slurry and as such increasing the mixing ratio in the process. The material removal rate would first increase and then after the certain optimum peak is reached there is chaos or confusion because loading density has kind of optimized. So, these are the this is the optimized loading density. And then it kind of comes down at a lower mixing ratio. So, this is the optimum best in terms of material removal rate.

So, there are there are some other interesting factors like for example, if the abrasive mass flow rate is increased the material removal rate, would almost always increase because of increase z; the number of particles which are impacting per unit time, which would increase because of the abrasive mass flow rate.

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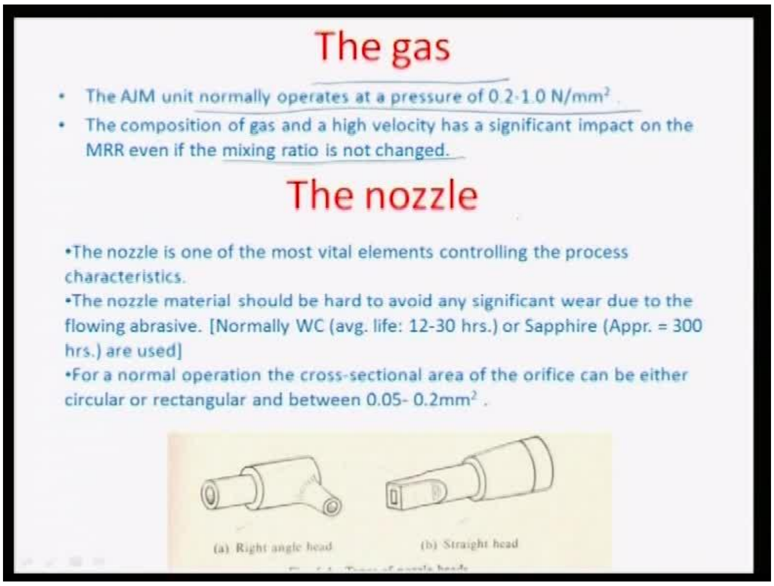

So, this is kind of all about, how you design or select the abrasive for the operating the process the other aspect which is involved is the gas; which is actually the most important component sometimes in the AJM process. And typically, the AJM unit normally operates at a pressure of about point 2 to 1.0 newton per millimeter square. And the composition of the gas and a very high velocity, has a significant impact on the MRR as you have seen before, in the Sarkar and Pandey's MRR estimation method even, if the mixing ratio is not changed ok.

So, if you are not loading anymore abrasives per unit volume of the air; still it does have a very significant effect. Sometimes there is this automatic softening, which is created by the gas because it may have some derogatory impact on to the surface that, it is in impacting and. So, it makes brittle fracture more prominent because of this preprocessing of the surface. So, because of all this the gas heal is a very important component. The other important component is the: nozzle in abrasive jet machining. And the nozzle materials as, we have already again repeated dimension should be hard.

Typically tungsten carbide or sapphire aluminum oxide can be very suitable materials. And sometimes tungsten carbide material, may have an average life time of about 12 to 30 hours whereas, sapphire may have about approximately 300 hours or. So, so sapphire is. In fact, much more harder than tungsten carbide.

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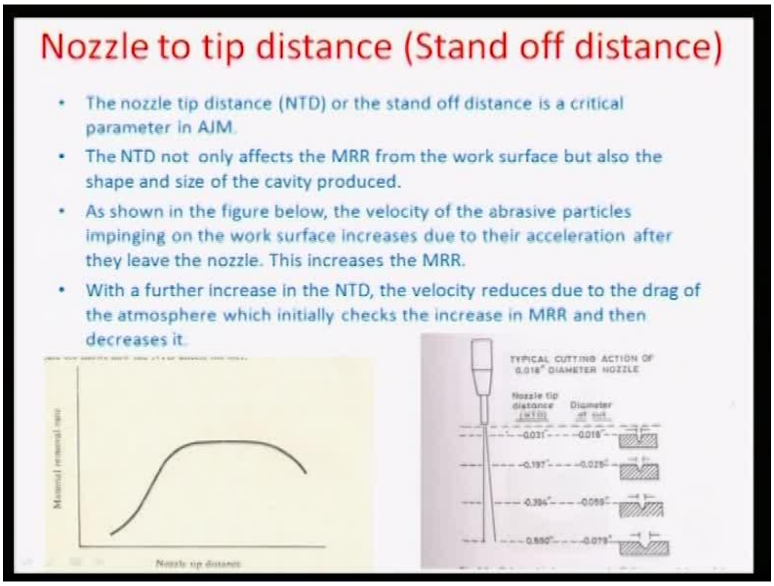

So, normally for I mean; sort of standard operations of the industry cross sectional area of the r f s is circular in nature. Or it can be sometimes rectangular. And the r f s can have an area of about 52 200 microns or so in terms of the small you know cross section through which, the velocity the jet actually emanates out into work piece. So, these are some of the important aspects of the AJM process.

In summary you need to know about the abrasive particles, the selection of that you need to know about what is the carry carrier gas and what is the composition of this carrier gas, you also need to know about the operating pressure, then the velocity of the gas and then of course, very important part is also the nozzle from which the jet emanates. Let’s look at some other important aspects of AJM. And as I told you before that, there is this term called standoff distance or nozzle into tip distance and its self-explanatory as given, in the description here is the distance at which the nozzle rests with respect to the surface which you are machining.

So; obviously, in between the nozzle and the surface there is full atmosphere and there is air, which is around and it is obvious to logically or intuitively see that as this distance keeps on increasing. The air resistance which comes between the work piece and the nozzle to the particles, which are impinging out of the jet would also increase. Thereby reducing their velocity; although there are 2 different factors, which would interplay here 1 is that: if you are shooting a particle out of jet at a high velocity and you know at some acceleration value because of the impact of the jet.

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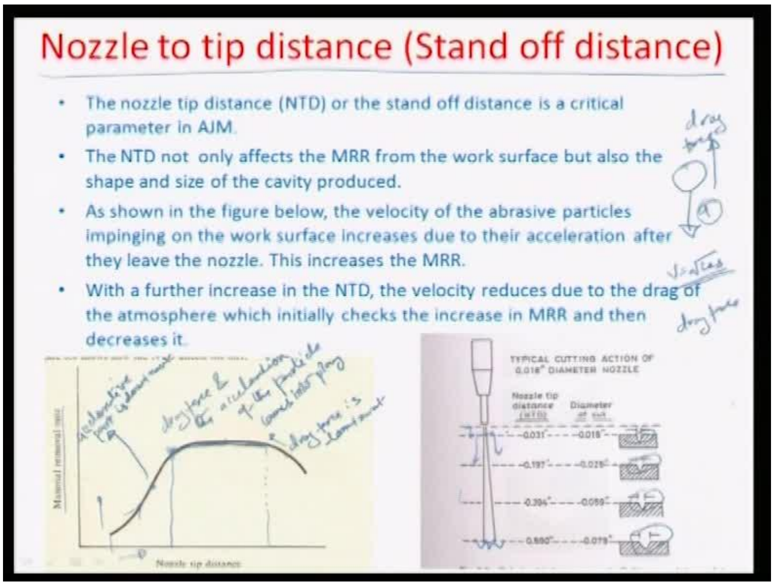

So, the acceleration is going to take this particle to a higher velocity of the distance that, you are allowing it to move this more. As you know v square minus u square is equal to 2 a s keeping acceleration constant the velocity at u equal to or initial velocity equal to 0. The final velocity that you can achieve is really proportional to the root of in the distance.

But at the same time a particle, which is accelerated as you can see here, in the downward direction at an acceleration a meets a drag force. And this drag force is typically because of the air around the particle. And which is the atmosphere around the particle. And this drag force is able to de accelerate the particle and. So, therefore, it is an interplay.

So, in some domain the route to a s. The velocity is the more dominant term and in some more domain, if the standard of distance is increased further and further the drag force, becomes the more dominant part. So, it is an interplay between both the forces. Therefore, if you have a lower nozzle tip distance or at low nozzle tip distances and increase in the nozzle tip distance, would really result in an increase in the material removal rate ok.

But, then this really is the point from which the interplay between the drag force and the acceleration of the particle comes into play. And you can see that, the material removal rate is kind of plat hoed because both of them are interplaying together. And then after the distances increased any further from this particular point the drag force becomes dominant. So, drag force is dominant this of course, is the point where the accelerative force is dominant right.

So, therefore, you know you really need to choose your operating characteristics from this particular trend. So, if you are placed somewhere here, you can still increase the nozzle tip distance to have an optimum best, if you are placed somewhere here, then you need not really do much and then if you are placed here then you should rather move back to this plat hoed region. So, that you can actually operate at a optimal material removal rate.

Sometimes, the practical limitation particularly of a micro systems or micro device is that you have to operate at a certain distance from this particular device because, you are using a mask in the process and those mask is actually a hard material and it has a certain thickness through which the abrasive is being routed. So, there are openings on the mask or windows of the mask through, which the abrasive is being routed and this strikes and removes the material, where it makes an impact by creating brittle fracture.

So, the NTD the nozzle tip distance is really something that may not be that, much in control of designer and. So, therefore, where you are exactly operating on the characteristics is a matter of great significance particularly, for micro system fabrications using non-conventional machining and. So, as you can see here, the other aspect of greater nozzle length tip distance, is in terms of the sharpness of the feature or the resolution of the feature which would come here.

For example, if supposing the nozzle tip distance is close or its shorter and the nozzle is close to the surface. The spread that it would allow this being in coming from the jet coming from the abrasive tip would be more in comparison to may be somewhere, here where the spread is much more and. So, therefore, if you are at a different nozzle tip distance you may have to also take care of the fact that, what really would be the eventual shape, whether it will spread like this or whether it is a sharp feature like this. Depending on the situation of micro machining that, you have to carry out in the surface you may have to operate at different entities.

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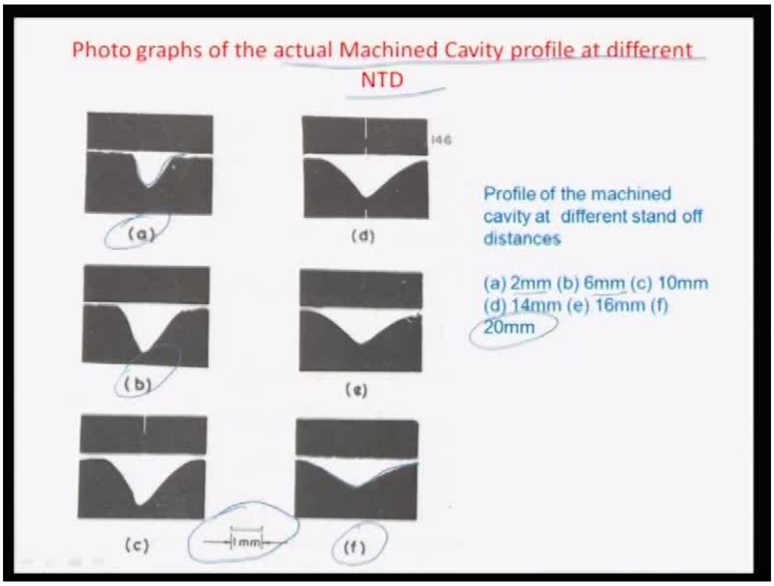

So, that is about it regarding the AJM process. We would just like to illustrate some more examples here; for example: you can see photographs of an actual machined cavity and for different nozzle tip distances the distance is shown at 2 millimeters, which is corresponding to the figure a 6 millimeters, for the figure b and 20 so and so, then 20 millimeters for the figure f. So, you can see that, the spread of the cut profile would happen; obviously, because of a higher nozzle tip distance. So, these are real experimental results, where this 1 mm shows the scale at which these photographs have been taken.

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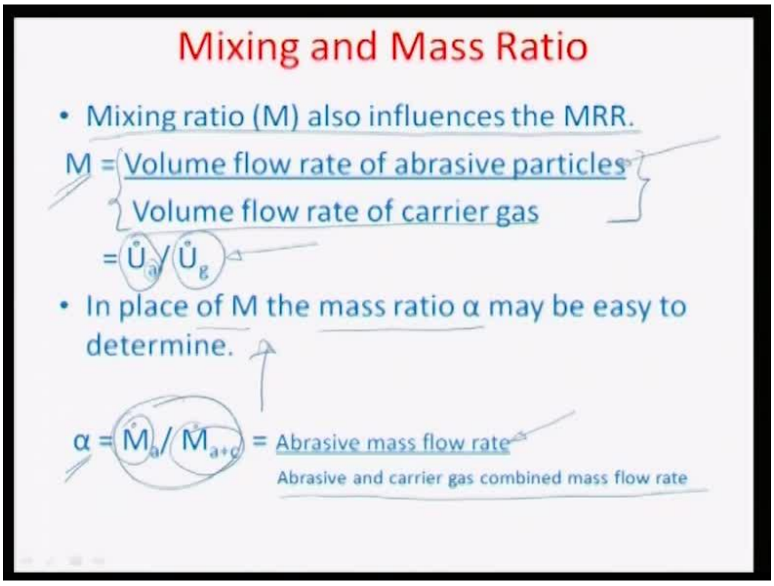

So, I already discussed in great details about the mixing ratio and also the influences, on the material removal rate of the process and. So, the mixing ratio has I earlier defined is known by this quantity here, the volume flow rate of abrasive particles by the volume flow rate of the carrier gas and. So, if you are loading more than this mixing ratio goes up and vice versa.

So, we can categorize this as u a or u abrasive a is a subscript, for abrasive dot meaning thereby the volume u a is coming per unit time from the nozzle surface and u g dot is basically the: volume flow rate of the carrier gas. And in place of the mixing ratio there is another parameter called the mass ratio alpha, which may be more easy to determine sometimes and it is given by this mass of the abrasive to the mass of the abrasive in carrier gas the ratio between that.

So, it is typically because, it is mass it is a function of the abrasive mass flow rate this is m dot and both the cases. And this is the abrasive and carrier combined mass flow rate. So, it is a ratio between the 2 and you can actually inter calculate between alpha and m provided, you are given some parameters.

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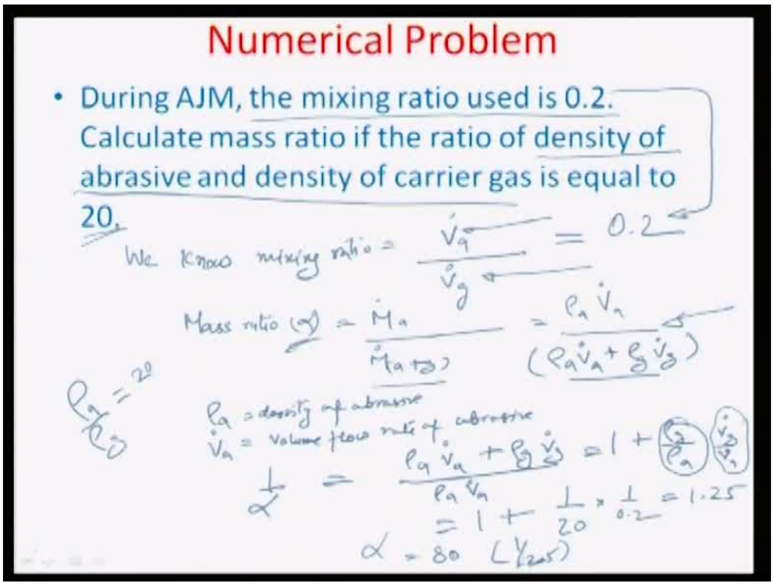

And I will just like to show you 1 or 2 example problems, where we calculate this. So, during an AJM process for example, the mixing ratio is that is used 0.2 and I have to calculate, in the mass ratio of the ratio of density of the abrasive and density of the carrier gas as is given, it is equal to 20. So, here we know the mixing ratio already from the earlier definition, as v a dot by v g dot this is the volume flow rate of the abrasive this is the volume flow rate of the gas.

We also know that the mass ratio alpha is given by the mass flow rate of the abrasive by the mass flow rate of the abrasive and gas taken together. So, if we just do a simple calculation here that the mass flow rate is nothing, but, the density of the abrasive times of the volume flow rate of the abrasive. So, we can call it lets say rho a is density of abrasive and v a dot is volume flow rate of abrasive. And this can be written down as the density of abrasive volume flow rate of abrasive plus density of the carrier gas that, you are using times of the volume flow rate of the carrier gas that is really the mass flow rate of the abrasive gas mixture and that is really what alpha is.

So, somewhere around this mixing ratio which is given to be equal to 0.2 in this case in the question is somehow embedded in this term for the mass ratio. So, we can calculate the mass ratios inverse 1 by alpha by looking at you know this particular inverted equation rho a v dot a plus rho g v dot g divided by rho a v dot a. And this becomes equal to 1 plus rho g by rho a times of v g dot by v a dot. And therefore, we already have the density of the abrasive and carrier gas that ratio typically is given here, in the inverted manner and then we also have, the inverted ratio of the v dot g by v dot a.

So, this becomes equal to 1 plus density of abrasive by density of the carrier gas is given to be 20. So, this becomes 1 by 20 times of 1 by 0.2 and that is really equal to 1.25. So, therefore, calculating the mass ratio by inverting this is actually 80 or so, the inverse of 2. 1.25. So, that is how you can calculate some of these problems and these are very important tools, because you will be able to use that in mems fabrication as I will show you little bit later.

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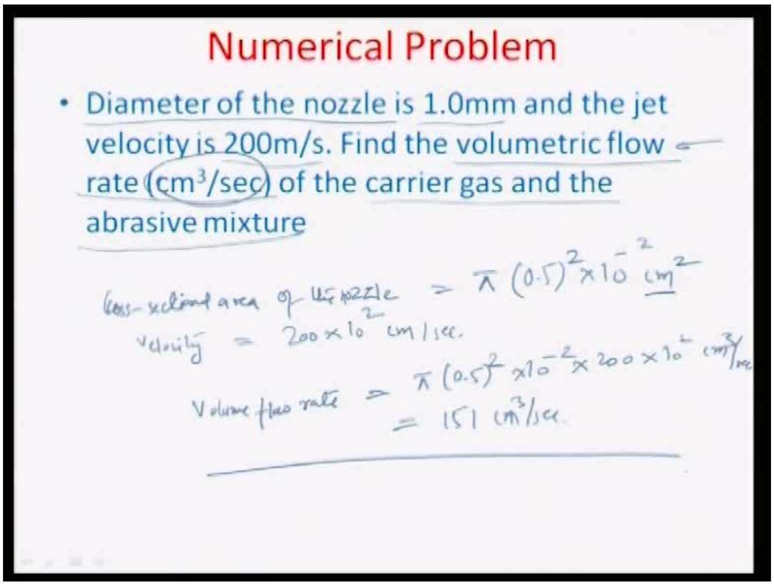

Let us do another problem, numerical problem on AJM. So, in this particular illustration for example, the diameter of the nozzle is given is 1mm and the jet velocity is also given to be 200 meters per second and. So, you will have to find the volumetric flow rate just for, the estimation sake from a practical problem how you get these things of carrier gas and abrasive mixture.

So; obviously, the fluid mechanics teaches you, the cross sectional area times of velocity becomes the volume flow rate. So, in this case it is a circular cross section. So, the cross sectional area of the nozzle is given by pie times of square of the radius and of course, we converted into a reasonable CGS system, so centimeter square and we also. So, the volume flow rate has to be estimated in centimeter cube per second. So, we are just converting everything into CGS system. And the velocity is again; a velocity of the gas is again 200 times of 10 to the power of 2 centimeters per second.

So, the volume flow rate equals the cross sectional area times of the velocity centimeter cubes per second, which is actually equal to about 151 centimeter cube per second. So, you can actually this way compute the various aspects of an AJM process and you can use that further for mems applications. Now, let us look into another aspect of how this abrasive jet machine normally is or what kind of parameters, we need to monitor while designing such a machine or a system.

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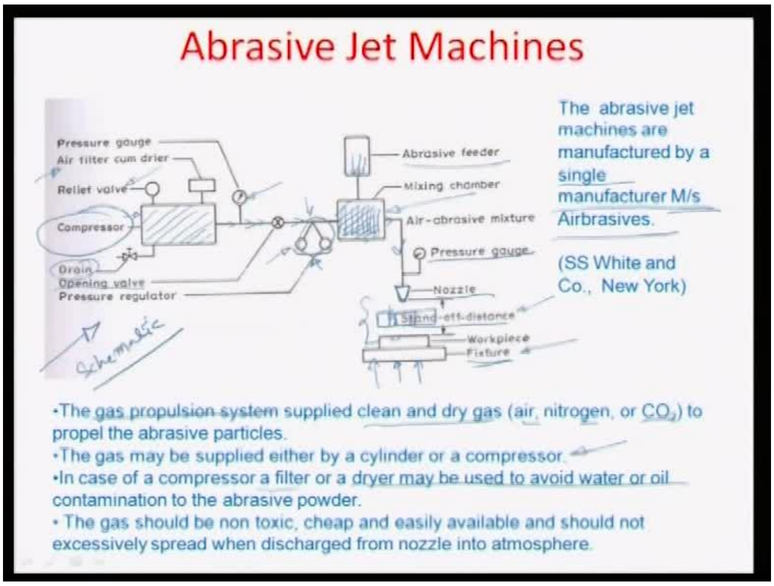

So, typically all these abrasive jet machines are manufactured by these company called Airbrasives in Newyork. And they are probably one of the single manufacturers for this particular system. If you look at the details of the system here, this schematic is very well illustrative of what all components go into abrasive jet machines.

So, you have a compressor unit here, as you can see which would give out pressure pressured air; high pressure air. And then there is of course, a drainage port, which ensures that the pressure is maintained within a certain level there is a relief valve also which has been given into this chamber, which contains the air at high pressure and then of course, when there is another aspects like: the air filter come drier, which is used for circulating the air into the chamber for cleaning it.

Then this once this compressed air is stored, in this particular tank here. You can monitor the pressure of this by a gauge which is fitted towards the end of this compressor tank. And you have another opening valve for this air to proceed further, in this direction and there are certain regulators here, which you can manually controls. So, that you can actually change the pressure of the inlet air, at which it should come and this is the available pressure really for the mixing process, which happens in this chamber here.

So, the chamber contains you know an abrasive feeder as you can see here, which down ports the abrasive material on to the air at the pressure, which has been regulated by means of these manual valves and the air abrasive mixture is really created within this particular chamber as you can see. And is fed into the nozzle, in this direction there is again a pressure gauge, which is very close to the tip to find out what is the pressure, at which the abrasive would emanate from the nozzle.

And this nozzle is at a certain standoff distance from the surface in consideration the work piece surface in consideration of course, is newly affixed on a fixture. So, that it does not move and it is capable of x y z motion particularly, at the micro systems fabrication case you may have to design this friction in a manner. So, that it can give you a good resolution in terms of movement of the various features over above the nozzle.

So, in the microsystems fabrication case the only other component, which is useful here is a mask which is like a open mask and this open mask is used for guiding the abrasive particles on to the surface; thus creating certain feature in structures on the surface. So, they are like small wells and the remaining area of the mask is pretty hard. So, it is not amenable to much wear and the particles, which strike this are the particles which do not have any machining.

So, they are the free particles and the particles which actually create the fracture go through this small cavities on the mask and the h of inside the or they or they remove or machine the features on the work piece exactly of the size of the mask with some limitations. So, the standoff distance can be controlled by varying the nozzle position or t he work piece with respect to 1 other.

So, typically the gas propulsions system should be able to supply clean and dry gases, could be air nitrogen carbon di oxide and thus used for propelling the abrasive particles and of course, the gas may be supplied other by a cylinder or a compressor, if it is a heavily used machine then typically it comes with the in built compressor unit. In case of a compressor there has to be a filter.

So, the gas has to be somehow filtered here before feeding. So, that you can have clean samples of abrasive mixing with clean gas sometimes the dryer is used because, there is a moisture or some oil content which is there. So, therefore, there has to be stages of filtration before the air can be proceeded into this mixing chamber. Also 1 more important factor in abrasive machining is that: whatever, gas you are using has to be a very nontoxic in nature because, you are exposing the operator whoever is using this machine to the gas.

So, therefore, 1 aspect is of course of the operator safety and prevention the other aspect is how you can have a safe system with absolutely, you know safe gas which is non-poisonous in nature and therefore, this aspect has to be kept in mind while designing the system as such. So, this is all about abrasive jet machines and I would like to now, go to another process. The other mechanical method of importance that I would like to proceed with before actually looking into the applications aspects of some of these methods for micro devices is the ultra-sonic machine or USM process.

So, as I told you before that there are various ways and means; in which you can deliver energy in a non-conventional process to onto a work surface. There can be a mechanical means; there can be means; where you can use thermal way of removal by interaction with high energy beams laser so on so forth. And then there can be a chemical electro chemical way and means of removal of material.

So, here the second part of the process, which is important for understanding some of the micro devised fabrication as well come later, is the USM or the ultrasonic machining.

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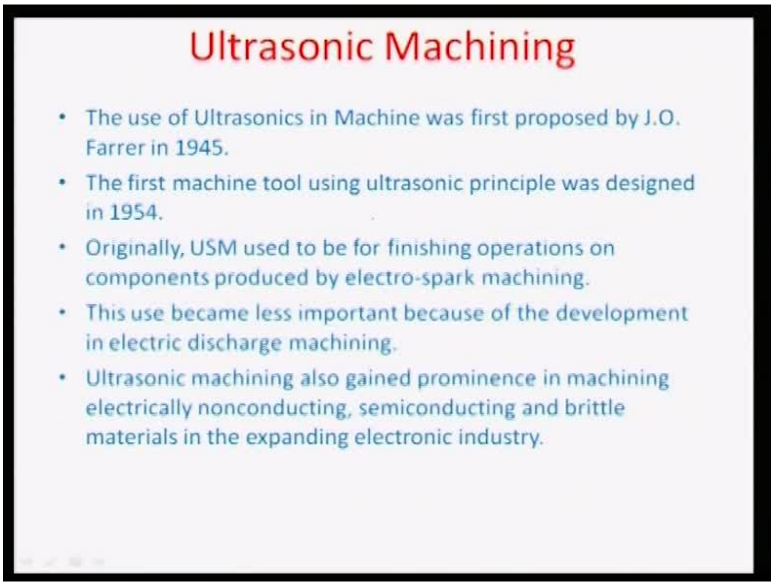

The ultrasonic machining basically, was developed in about 1945 or so, by J.O. Farrer. And the principle, in this particular machining is very simple than instead of having a direct impact of the grains that typically, happens with like for example, you saw in AJM with the velocity of air. In this particular case, the grains are squeezed between the surface the work surface and a tool head. And these squeezing action is sort of hammering action, which is the primary material removal mechanism in this process.

This USM process and the material, the abrasive material typically comes in a slurry format. And the slurry is posted between the work piece and the tool and therefore, there is a zone between the work piece and the tool, which is continuously flooded by slurry which is re-circulated back and forth which of which contains these abrasive particles.

So, in a nutshell, the only difference between, the abrasive jet machining in the USM ultrasonic machining is that, in this case there is a positive impact of a tool head on to the abrasive circle particles; which does plowing action on the work piece. And in the other case that is: AJM there was the impact of the standalone grain, which is being carried with the certain pressure with the particular jet.

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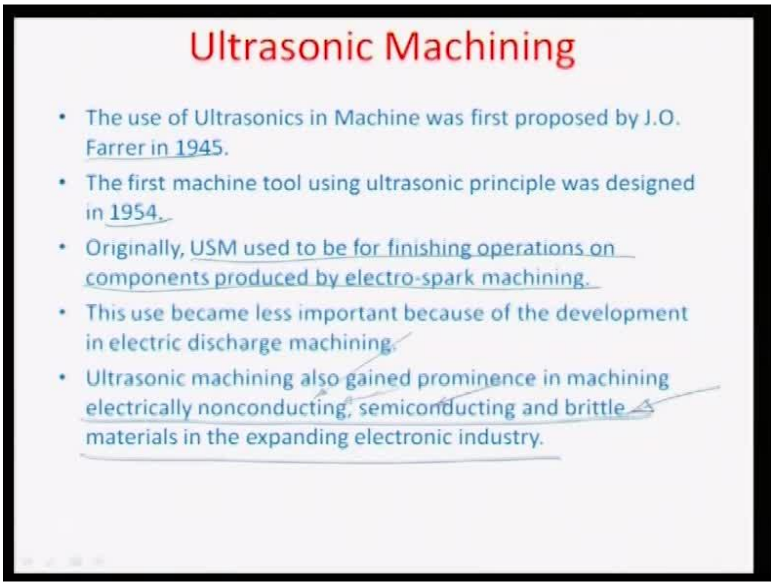

So, the first machine tool as I already mentioned, was developed in you know 1954 after J.O. Farrer first proposed about that this can be done, in the you know machine tool technology and originally USM used to be for finishing operations, on components produced by electro spark machining and basically that was. So, because you could give short strives of very high ultrasonic frequencies of impact. Thus creating a averaging effect because, every impact would create some kind of a brittle fracture.

But, if the time for which it the impingement would happen, would be very less depending on the frequency and then there would be a cyclic impact there would be, an average planerizing of the surface and it would be used mostly for a as a finishing process. Of course, it was superseded by other more developed processes like: EDM, electro discharge machining processes; which were developed later on which are, in fact, much more you know in terms of planerizing a surface then an USM process stand alone.

So, ultrasonic machining also gains, the some prominence particularly, electrically non conducting or sometimes even semi conducting and brittle materials in expanding the electronic industry. And that would actually have, its own connotation because there were not many methods, which would really be able to finish or sometimes polish materials, which would not have a conducting property .And because this is a mechanical means: of addition of energy therefore, all materials which would otherwise be moved or removed with an electrical method would, actually be now planerized or machined using mechanical method in the u s m process.

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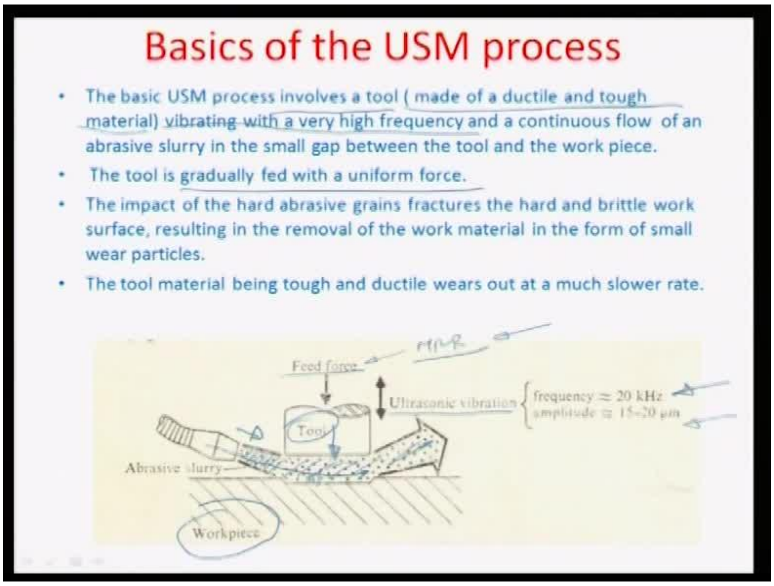

So, this is how the process looks like: you have a tool head which comes in strikes, on the slurry. The slurry is moved between the work piece and the tool head at a certain rate and the slurry typically, can contain mixture of a abrasives and water and this tool had forces down at a certain frequency and the squeezes, the abrasive grain against the work piece thus causing brittle fracture.

So, typically it should involve a tool for example, which is made up of a ductile and tough material. And because, it vibrates with the very high frequency, it has to be amenable to the process as such, by having a high modulus of elasticity and a continuous flow of the abrasive slurry is made in a small gap, to ensure that a material removal that is happening is carried away along with the grain; which has been used for the impingement.

The next, set of grains come with in this region. So, it is a dynamic equilibrium that establish that the grain comes here gets squeezed between the tool and the work piece it causes a brittle fracture material moves away. And the slurry actually moves along, with the grain and the material outside. So, that new slurry can occupy its place for a better cutting action on the next cycle of the tool.

So, the tool is gradually fed with, the uniform force and the impact of the hard impressive grain fractures the hard and brittle work surface. And that results in the removal of the work material. So, 1 important aspect that, I would like to say is that: typically, frequency is as high as about 20 kilo hertz and very small amplitudes in the level of microns are preferred for the feeding tool. And a continuous feed force is given to this tool, which is very important part in determining the MRR as we will just see the model the theoretical model that will create a little bit later.

They also important are things or aspects like: what is the velocity of the flow of slurry or what is the material of the work piece that, you are trying to machine on material of the tool, with which you are trying to impact the abrasive grains. So, you know, we you now kind of understand the basic of both the AJM and the USM process in the. So, I would like to end my lecture here today, but then I would like to continue, next time. With the theoretical model of estimation of the material removal rate for such an USM process. Once both these processes are well defined and fundamentally clear, then I will tell you some aspects about how you can use these processes, for developing microsystems, micro devices so on so forth; which would be, subsequently available in a lecture.

Thank you.