Advanced Machining Processes
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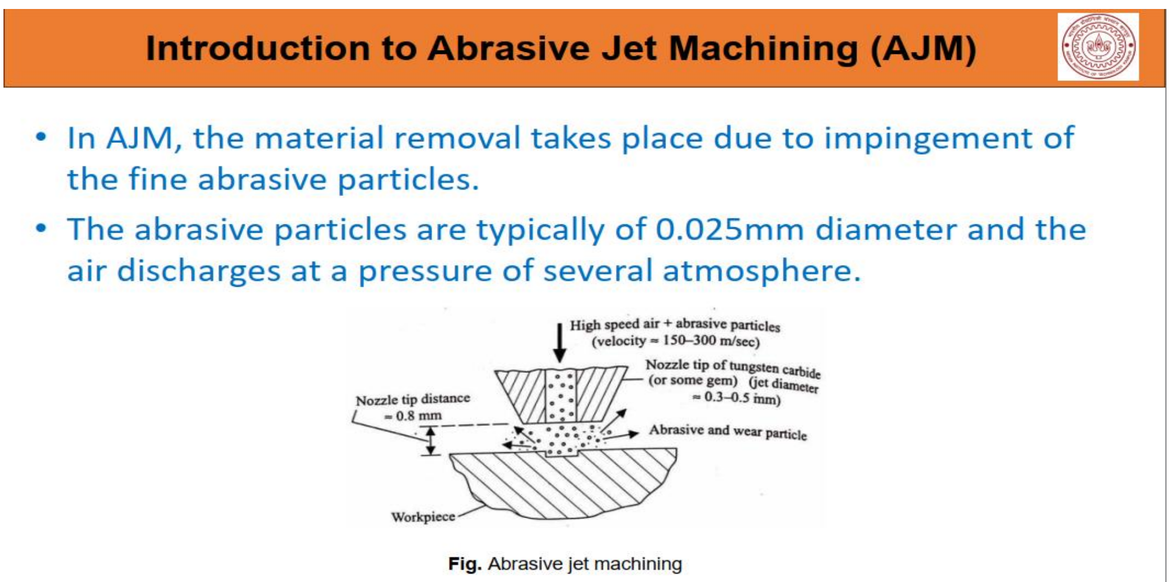
Week - 03
Lecture - 05
Abrasive Jet Machining

So, today we will now look into 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, non-conventional domain can be split up into either mechanical removal of material or thermal removal of material or chemical slash electrochemical removal of material. Meaning thereby that 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 which can impede with the surface impede into a surface and try impinge into a surface and try to remove off the material by brittle fracture. 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 which are higher than the hardness of the workpiece 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 orifice. 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 and the material gets removed. And the velocity or the high-velocity air which is flowing along with these abrasives kind of takes the material away from the surface. So, this is very prominent method, particularly for bulk micromachining 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, micromachining. One is surface and another is bulk.

Surface is a negative process for the sake of repetition and bulk machining is a subtractive process where actually removing the material from the surface. So, this is a 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 workpiece. So, if distance is varied the way that or the behaviour 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 micromachining.

The tips are normally made up of a very hard material like let us say one of the materials could be tungsten carbide or maybe some other gem can be used for making the tip. The idea is that whenever the hard abrasive particles flow around this tip 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 millimetres about 300 to 500 microns. And this gives us an opportunity to really work at a microdomain and trying to get very small areas machined using such AJM or abrasive jet machined techniques. As we will show later on there are some illustrations where you can actually see an impinging jet of abrasives creating passed through a mask, of course, to impinge the features which are there on the mask onto the surface of the material. So, the typical diameter of the grains which are used as particles here are about 0.025 meters or so, it is about 25 microns.

And the air discharges at a pressure of several atmospheres thus creating a suitable high velocity to emanate out of the nozzle in such machining processes. 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 carry it out. And that way there can be a material removal which can take place because the new area which is formulated is really this crater and it is open to another impingement and subsequently more brittle fracture.

So, basically, it is a fracture by fracture which would happen in succession for a cavity to be created within the workpiece. 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 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

Mechanics of AJM

- Abrasive particle impinges on the work surface at a high velocity and this impact causes a tiny brittle fracture and the following air or gas carries away the dislodged small work piece particle.

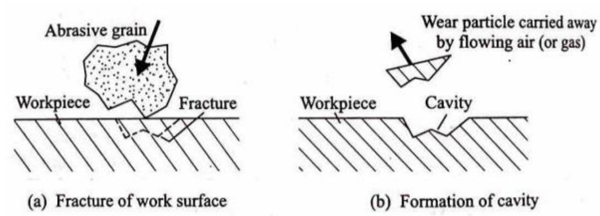


Fig. Scheme of material removal in AJM

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 observational formula it is an experimentally determined formula which has 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 impacting per unit time thereby 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 onto the flowing gas that also increases the material removal rate. And of course, the other parameters of importance are the hardness of the work material and the density of the abrasive material.

Mechanics of AJM

- The process is more suitable when the work material is brittle and fragile.
- A model for the material removal rate (MRR) is available from Sarkar and Pandey, 1980.

The MRR $Q = \chi Z d^3 v^{3/2} (\rho / 12H_w)^{3/4}$

Where
Z = No. of abrasive particle impacting per unit time.
d = Mean diameter of the abrasive grain
v = Velocity of the abrasive grains
ρ = Density of the abrasive material
H_w = Hardness of the work material
χ = Is a constant.

So, that is about it about the mechanics the process parameters which are involved in this abrasive jet machining process. 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 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 thereby meaning that the nozzle has a better working life it should be able to produce low-roughness surfaces. And then you know it 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 these process characteristics are, for example, the composition strength size mass 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 workpiece 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 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 are 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 learnt from the previous step and the composition of the gas also is very important as I just told a little bit ago because sometimes the gases can be derogatory to the surface in terms of giving its etch characteristics it may be able to soften the surface where you are actually flowing the abrasive material. And of course, the pressure and velocity of the gas is very important for illustrating what is the overall material removal rate associated with the process. So, nozzle geometry again is very important for the purpose of determining some of these process characteristics typically you know circular or square-type nozzles are the most preferred geometries in this particular case. The nozzle material 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 workpiece surface.

So, when you are basically trying to create a small crevice or a hole in a 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 best process which is available for creating such micro holes and micro features over the materials particularly from MEMS aspects. So, when we look at the quality of the abrasive mainly there are 2 types of abrasives which are commonly used in the industry 1 is aluminium oxide and 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. And basically, for good wear action on the surfaces, 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 gains out of the metal because the metal in the process of very high level of deformation and sometimes causing brittle fracture 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 onto the surface and the ploughing action would be lost sometimes the sharpness of the grain could be lost. So, therefore, reuse 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 orifice itself is very-very small which sends out particles along with let us say high velocity air.

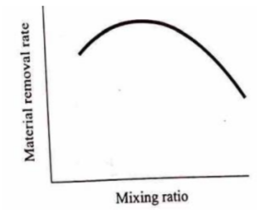
And supposing if there is a metal-to-metal contact thereof coated metal onto a grain which we have re-circulated back there is always a possibility of clogging the nozzle with such material. And therefore, you know the characteristic the process characteristics would be totally changed because of the 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 mass 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’s diameter.

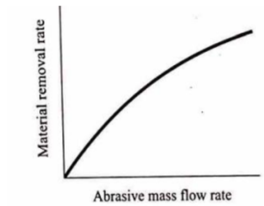
So, therefore, because abrasive particle is the main cause of moving the material away the mass flow rate the rate at which it comes and hits the surface would typically depend only on the ambient pressure and the velocity gas velocity. So, that is 1 important point about how the abrasive is loaded. 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 onto the 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 then the volume flow rate of the abrasive particle would increase, and 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 a certain optimum peak is reached there is chaos or confusion because the loading density as kind of optimized. So, these are the this is the optimized loading density.

The Abrasive

- Mainly two types of abrasives are used (1) Aluminum oxide and (2) Silicon carbide. (Grains with a diameter 10-50 microns are readily available)
- For good wear action on the surfaces the abrasive grains should have sharp edges.
- A reuse of the abrasive powder is normally not recommended because of a decrease of cutting capacity and clogging of the nozzle orifices due to contamination.
- The mass flow rate of the abrasive particles depends on the pressure and the flow rate of the gas.





•There is an optimum mixing ratio (mass fraction of the abrasive) for which the metal removal rate is the highest.

•When the mass flow rate of the abrasive increases the material removal rate also increases.

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 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 the increase Z the number of particles which are impacting per unit time which would increase because of the abrasive mass flow rate. So, this is kind of all about how you design or select the abrasive for 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 0.2 to 1.0 Newton per millimetre 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. So, if you are not loading any more abrasives per unit volume of the air still it does have a very significant effect.

Sometimes there is an automatic softening which is created by the gas because it may have some derogatory impact on to the surface that it is impacting. And so, it makes brittle fracture more prominent because of this pre-processing of the surface. So, because of all this the gas really 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 repeatedly mentioned should be hard typically tungsten carbide or sapphire aluminium oxide can be very suitable materials. And sometimes tungsten carbide material may have an average lifetime 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. So, normally for I mean sort of standard operations of the industry cross cross-sectional area of the orifice is circular in nature or it can be sometimes rectangular. And the orifice can have an area of about 50 to 200 microns or so, in terms of that small you know cross-section through which the velocity the jet actually emanates out into the workpiece. 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 carrier gas and what is the composition of this carrier gas. You also need to know about the operating pressure and the velocity of the gas. And then, of course, very important part is also the nozzle from which the jet emanates. Let us look at some other important aspects of AJM. And as I told you before that there is this term called standoff distance or nozzle-to-tip distance.

And it is self-explanatory as given in the description here that it 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 workpiece 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 a jet at a high velocity and you know at some acceleration value at some acceleration value because of the impact of the jet.

So, the acceleration is going to take this particle to a higher velocity if the distance that you are allowing it to move is 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 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 I am able to de-accelerate the particle.

And so, therefore, it is an interplay. So, in some domain, the root 2 a s the velocity is the more dominant term and in some more domain if the stand-off 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 the increase in the nozzle tip distance would really result in an increase in the material removal rate. 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 plateaued because both of them are interplaying together.

And then after the distance is 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. And so, therefore, you know you really need to choose your operating characteristics on 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 plateaued region. So, that you can actually operate at an optimum material removal rate. Since the practical limitation particularly of a microsystems, microsystem or microdevice is that you have to operate at a certain distance from this particular device. Because you are using a mask in the process and this 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 a designer. And so therefore, where you are exactly operating on the characteristics is a matter of great significance particularly for microsystems fabrication using non-conventional machining. And so, as you can see here the other aspect of a greater nozzle 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 it is shorter and the nozzle is close to the surface the spread that it would allow this beam coming from the or the jet coming from the abrasive tip would be more in comparison to maybe somewhere here where the spread is much more.

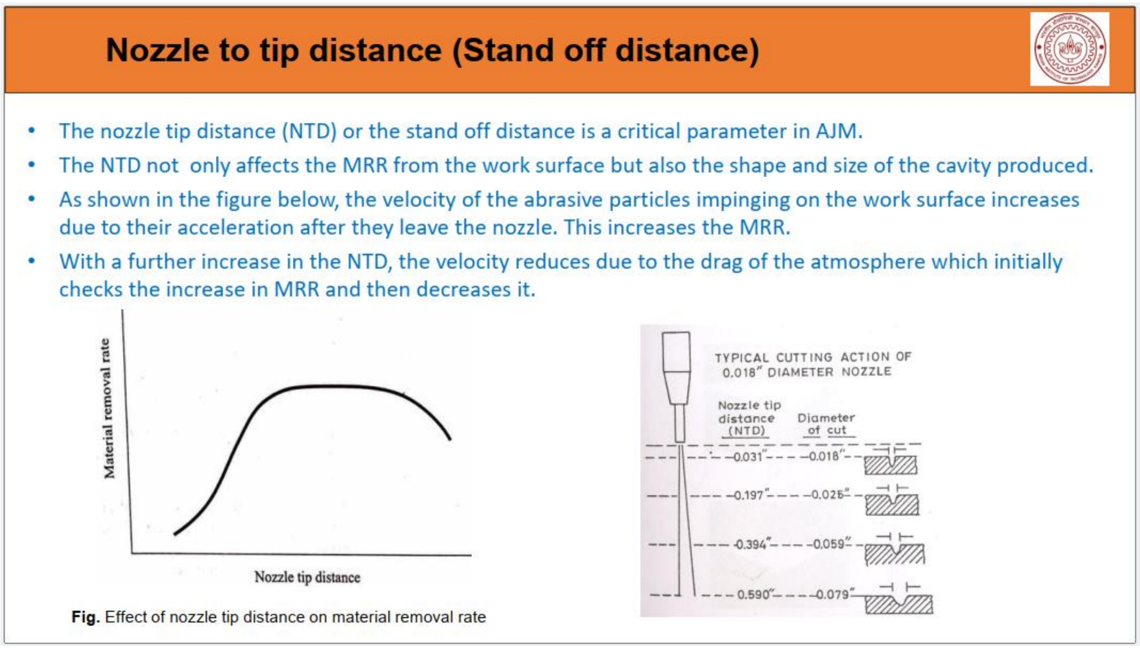


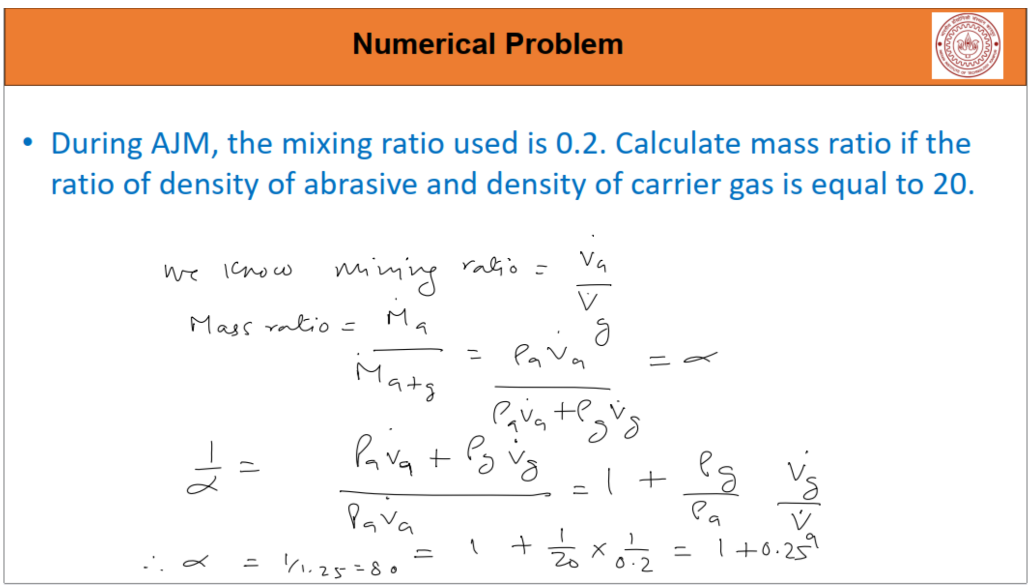
Fig. Effect of nozzle tip distance on material removal rate

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 be spread like this or whether it is a sharp feature like this depending on the situation of micromachining that you have to carry out in the surface you may have to operate at different NTDs. 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 distances shown are 2 millimetres which is corresponding to the figure a, 6 millimetres for the figure b and 20 so on so forth and 20 millimetres 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.

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 as 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 Ua or U abrasive, a is the subscript for abrasive dot meaning thereby the volume Ua is coming per unit time from the nozzle surface and Ug 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 and 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 in 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 intercalculate between alpha and m provided you are given some parameters 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 is 0.2 and I have to calculate the mass ratio of the ratio of density of the abrasive and density of the carrier gas is given and is equal to 20. So, here we know the mixing ratio already from the earlier definition as Va dot by Vg dot this is the volume flow rate of the abrasive this is the volume flow rate of the gas.

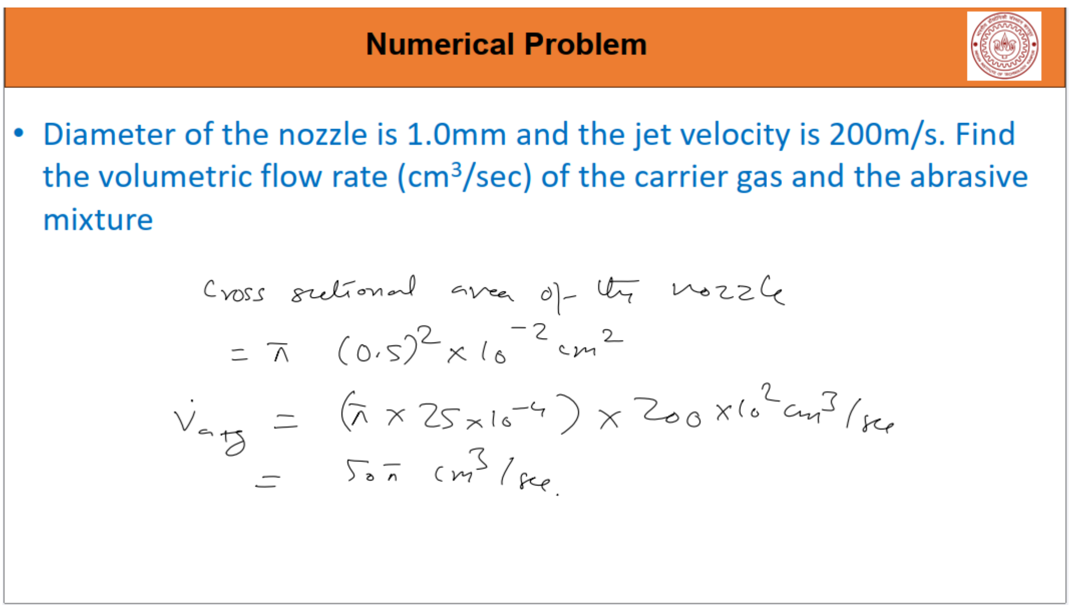
And we also know that the mass ratio alpha is given by the mass flow rate of the abrasive by the mass flow rate of the abrasive and gas taken together. So, if we just do a simple calculation here that the mass flow rate is nothing, but the density of the abrasive times of the volume flow rate of the abrasive. So, we can call it let us say rho a is density of abrasive and Va 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. And 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 Vg dot by V a dot. And therefore, we already have the density of the abrasive and carrier gas, and 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 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.

Let us do another problem numerical problem on AJM. So, in this particular illustration for example, the diameter of the nozzle is given is 1 mm and the jet velocity is also given to be 200 metres 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 that 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 pi times of square of the radius and of course, we converted into a reasonable CGS system centimetre square.

And we also, so the volume flow rate has to be estimated in centimetre cube per second. So, we are just converting everything into CGS system. And the velocity is again, velocity of the gas is again 200 times of 10 to the power of 2 centimetres per second. So, the volume flow rate equals the cross-sectional area times of the velocity centimetre cube per second which is actually equal to about 151-centimetre 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. So, typically all these abrasive jet machines are manufactured by this company called Airbrasives in New York. And they are probably 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 an abrasive jet machine. 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, there are some other aspects like the air filter come dryer which is used for circulating the air into the chamber for cleaning it. And 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 control so that you can actually change the pressure of the inlet air at which it should come.

And this is the valuable 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 force the abrasive material onto 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 workpiece surface in consideration.

The workpiece, of course, is duly fixed on a fixture so that it does not move, and it is capable of XYZ motion, particularly at the microsystems fabrication case you may have to design this fixture in a manner so that it can give you a good resolution in terms of movement of the various features 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 onto the surface thus creating certain features and 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 these small cavities on the mask. And they etch off inside the or they or they remove or machine the features on the workpiece exactly of the size of the mask with some limitations. So, the standard of distance can be controlled by varying the nozzle position or the workpiece resistance with respect to one another. So, typically the gas propulsion system should be able to supply clean and dry gases, gases could be air, nitrogen, carbon dioxide and this is used for propelling the abrasive particles.

And of course, the gas may be supplied either by a cylinder or a compressor. If it is a heavily used machine, then typically it comes with an in-built compressor unit. And 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 abrasives mixing with clean gas. Sometimes a 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, one more important factor in abrasive machining is that whatever gas you are using has to be very-very non-toxic in nature because you are exposing the operator whoever is using this machine to the gas. So, therefore, one 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. Thank you.