Microsystem Fabrication with Advance Manufacturing techniques

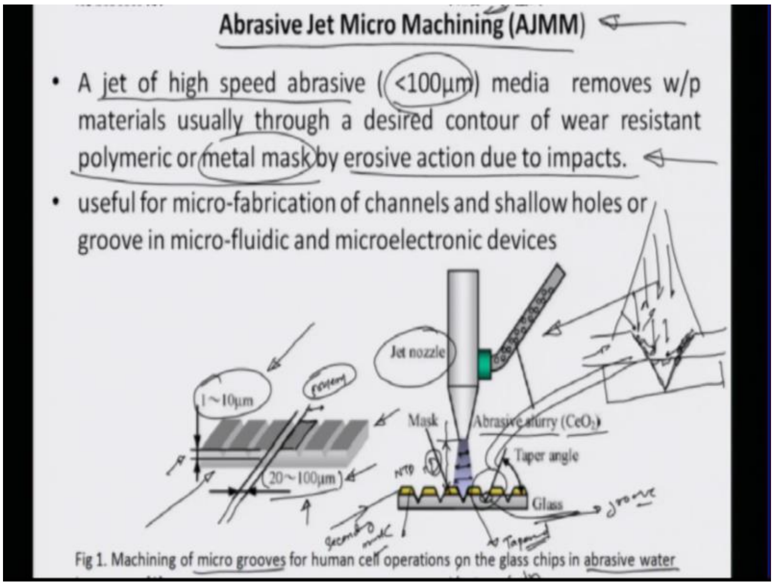
Prof. Shantanu Battacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

Lecture - 10

Hello and welcome back to this lecture ten of micro system fabrication by Advanced Manufacturing Process. Quick recap of what we have done during the last few lectures. We were talking about the mechanical form of removal of materiel as far as the traditional manufacturing process or advanced manufacturing process go, and there we mentioned about several processes including AJM – abrasive jet machining, WJM - water jet machining, or ice jet machining and also, ultrasonic machining or USM process. And in very detailed manner, we try to analyze the different aspects of the different mechanical material removable process as you some of I mean all of you may probably recall that this is actually the mechanism of material removal in such processes takes place primarily by brittle fracture introduced brittle fracture on to the surface.

And the brittle fracture is as a result of the impact energy which is given by a flowing of abrasive particle onto the surface – substrate surface. Therefore, it is worthwhile to assume that the technology can be utilized for you know during micro machining or probably structuring micro features, and grooves on surfaces. And this would be possible, because of the fact that the beam size or the jet size can be controlled as a function of the orifice dia. And therefore particularly in AJM processes, if the orifice dia suitably tailored, and on one hand, then also some kind of secondary protection is given to the exposure to the rate at which the ex posture of the substrate surface takes to the respect to the tool we can hope of making very good micro size features, and structures.
So, let us looking to the aspect of how microstructures can be fabricated using some of the technology that we have already understood in terms of the basic material removal process in the mechanical manner.

(Refer Slide Time: 02:29)



So, the first example here is actually work done by Maxmura in the year 2011, where he briefly talks about the making of micro channel or micro grooves on the surface of a glass substrate using abrasive jet micro mechanizing - AJMM process. So, as this figure right here illustrates there is a jet nozzle which is driving of the materiel which is in form of an abrasive slurry the containing of a cerinium oxide with suspended in water jet. And this is actually a a w j process which is being utilized for the purpose of micro machining.

So, in all these processes, where mechanical energy is introduced to creating a brittle fracture. As we go from the conventional macro size domain to the micro domain one has to remember that the shapes, and features either small, tiny shapes, and features which are to be incorporated on these substrates surfaces by the virtue of the impact of the jet has to be a guided impact. And this guided impact come from a mask secondary layer of a sacrificial material which has already those features, and structures negative of them embedded onto the surface, and where through holes are made by virtue of the negative of the features. So, wherever the hole created in this mask, there is the tendency just as an lithography as we discussed earlier for this abrasive jet to a go fast the mask, and hit directly on to the surface, thuscreating the material remover.

So, in this particular illustration of course, if you have a jet of high speed abrasives, where the jet size less than hundred micro meter diameter, and is used for hiding on a surface by virtue of a polymeric or metal mask. So, by the erosive action due to the impact of the particles which are suspended in the slurry, whatever is there on the masking surface made of metal or polymer gets kind of a embedded on to the surface of the glass. For example, you can see this micro grooves which have been machined on this substrate right here, and you can see that the basic features size that one is talking about twenty to hundred micro meter facing between these two walls has illustrated here in this diagram. And between two such ends of an edge as illustrated by the figure drawn here the sizes probably something of the order of four to five times the size of the channel, so maybe this is about five hundred microns or so.

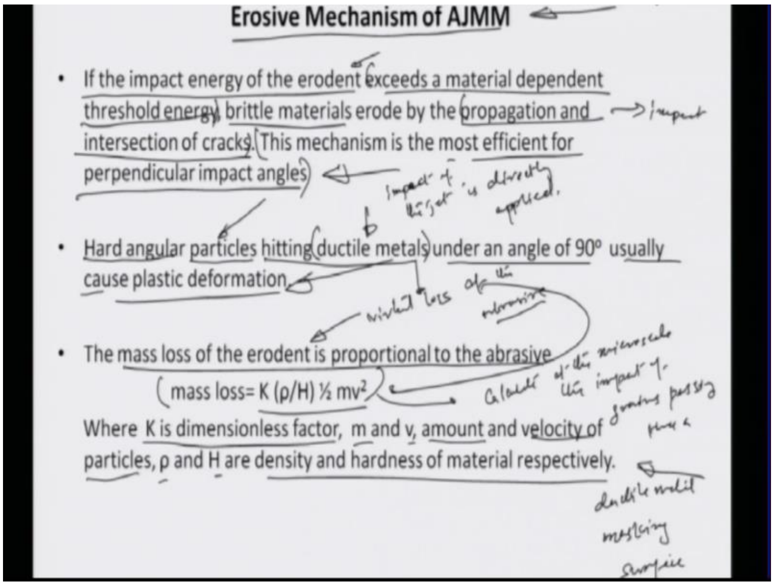
And also what is important for us to understand is that the depth of machining that is obtain in case of such abrasive water jet based matching is about one to ten microns. So, the resolution is very fine. So, you can call this micro structures. So, you have one to ten depth, twenty to hundred micro meters width separated by a space of about five hundred microns on a glasses substrate being made by an abrasive jet. What is also important here is that you know this right here is the secondary mask that we were talking about, and you can see that as the jet is positioned over the mask at a certain distance from the surface of the mask d, there is the tendency number one for the jet to spread out as it goes nearer to the surface which is obvious because this I think we have discuss previously how important this nozzle tip distance (NTD) equal to the d as a function of the impact that the abrasive jet would create on the surface.

Here of course the one important aspect is that, because the mask itself is made in a tapered manner. You can see the mask is highly tapered. Therefore the grooves which are eventually being made on the glass, this is grooves which is being eventually made on the glass by virtue of this tapered form of the mask is also tapered. So, we can realize lets blow this appear, and try to analyze what is going on. So, there is a masking surface on the top, and there is a surface on the bottom here which can exposed to the abrasive jet, the jet is coming in the direction.

So, this is the high speed jet coming, and striking of the surface, so obviously, the particle which strike these mask would also damage a deform the mask, but because you know the substrate can be either polymeric or metal, the damage may not be that much in comparison to the substrate surface which is more brittle. I guess made of glass. And so some particles would actually deflects of, and some particles which are at an angle may be would actually role of and go in a tapered manner to produce a brittle fracture somewhere in this zone, which creates a tapered micro channel eventually. That is the reason of the tapering that some particles which are deflected of the surface of the mask, and actually going and rolling along this tapered mask, and hitting the surface at high impact creating the brittle fracture also in tapered manner.

So, one of the reason why Musmura observed here in this the how beautifully the grooves can be defined, and shapes can be defined by just positioning, and structuring the mask suitably. So, this definitely gives us way of using AJMM - abrasive jet micro machining process for realizing micro grooves, and micro features.

(Refer Slide Time: 09:47)

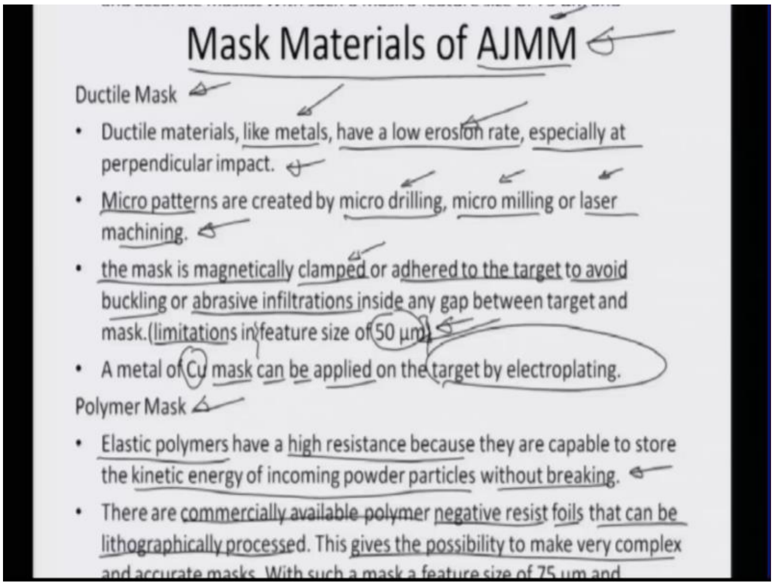


So, let us look into some other aspects about the erosive mechanism of the AJMM process. If the impact energy of the erodent exceeds a material dependent threshold energy which binds material, otherwise particularly brittle materials. What happens is that there is the prorogation, and intersection of cracks which comes, because of impact onto the surface of the material. So, this mechanism is most efficient for perpendicular impact angle, because in that event the impact of the jet is directly applied; otherwise there would be a component of the force, there is an angle. And therefore particular angle as you saw the last case is typically the position at which this jet is kept with respect to the mask, and surface.

So, what happen is this erodent particles which are angular otherwise in nature, when the hit ductile materials under an angle of ninety degree, they do cause a plastic deformation of the material. So, therefore, because the mask is made of such a material - ductile metals, the plastic deformation of the hard angular abrasive particles almost certain. So there is a mass loss factor which would happen of the erodent which is defined by this term here K rho by H half m v square. K is dimensionless factor; m and v are the amount of mass and velocity at which the particles are moving, rho H are density and the hardness of the material respectively.

So, in micro machining when particularly using a mask, and when particularly this business of hitting ductile metals comes into picture there is virtual loss calculated by this method of the abrasive in terms of damage or deformation to the total quantity of grains which emanates from the nozzle surface. So, this factor has to be taken into account for really being able to calculate the micro scale, the impact of grains passing through a ductile metal masking surface.

(Refer Slide Time: 13:07)



Let us look at some other examples for mask materials as conventionally used in the AJMM process. So particularly for micro machining or abrasive jet micro machining, you can use either ductile masks or you can use polymeric mask. There are certain advantages, and disadvantages of using both, so in case of ductile materials, let us say like metals very often copper is used as a suitable mask material. And you can actually taken otherwise a part of patterns substrate, and used that as the target mask by electroplating the copper on the top of that surface.

So, what happen is that the materials which are typically metal like, they being very ductile have a low erosion rate. So, typically whenever there is a abrasive particle which is hitting the metal mask, there is a tendency of the abrasive particle to embed or sometimes even they deflects of the surface there is a change in the angular shape, and size of the grains, sometimes grain breakage. And we already calculated the mass loss which is affected that because of that change. So, especially at perpendicular impact is the ductile materials would have a low erosion rate.

So, the material of the mask would be un touched as it is, and the question is that how you create a such micro patterns or micro features within the masking surface. So there are several alternative process that is why a micro machining using or micro system fabrication using advanced manufacturing processes really not a one process or a one step approach it is actually several steps in a advertise manner conjugated together to achieve that kind of a micro structuring of the features. So, here for example, the micro patterns are created by micro drilling, micro milling or laser machining. So, you are using so many other conventional techniques, of course micro scale drilling, and milling being conventional, but even laser machine for standalone creating the micro pattern. So, you have a think for that metal, and this metal is now being structured or featured according to shape of the negative of shape that we want in the surface the mask by using so many other methods micro drilling, micro milling, laser machining, may be CMM, EDM.

And so there for a machining steps which is even involved in the mask making process of the later on step of actually creating a features using this mask on another wise brittle substrates. So, there is several steps associated when you talk about micro machine using AJM. The mask is typically magnetically clamped. So, you have to ensure that there is no relative movement between the mask, and surface; the same was the cases for lithography. As most of you have observed before that there is always tendency to hold the mask in case of using a mask ((Refer Time: 16:27)) in normal step mask liner system by holding at through vacuum pressure over the substrates. So, therefore there is no relative movement between the substrates and mask as so such. So the mask is magnetically clamped or adhered in the case to the target to avoid any buckling or infiltration issues associated with the abrasive, and the whole micro machining would spoil, if there is some kind of infiltration in particularly the gap between the mask, and the substrates surface. So, you avoid any such infiltration any such intrusion of an abrasive particles, and you have to really ensure that the mask does not buckle it is said strait flat on the surface there is no gap whatsoever at anyplace; otherwise it is going to damage the resolution at which you are doing the micro machining.

So, the limitations in this kind of machining is that the machining can be done over feature size of fifty microns or more. So, going below fifty microns is a very changeling task particularly when you are using the abrasive jet micro machining, metal of course, have this tendency of high ductility. So, there is an advantage that the mask get corded that easily in comparison to some of the other probably brittle kind of materials, which are use for mask making process one of them mean polymers.

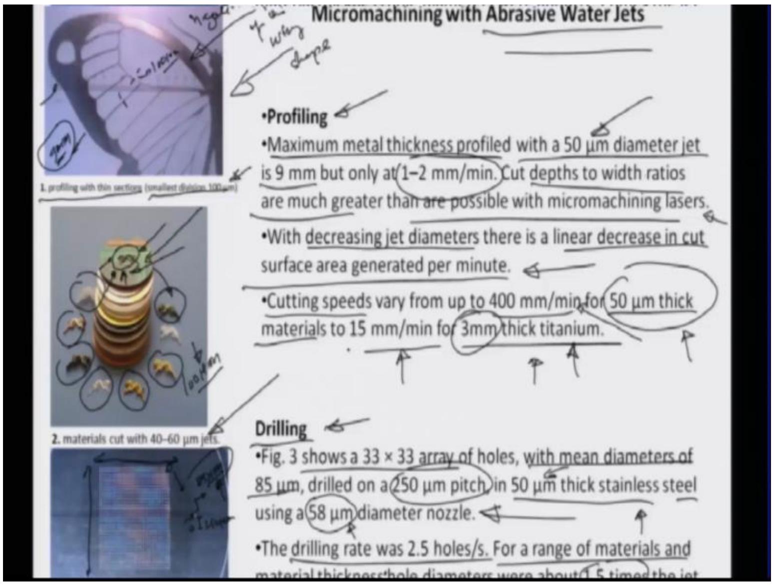
So when we talk about polymers mask preferably elastic polymers need to be used, because they have a high resistance being able to store more kinetic energy of incoming powder particles without causing any brittle fracture or breaking. So, typically something like ((Refer Time: 18:26)) in which is highly viscous elastic materials which is well structured well patterned can be used for abrasive jet machining process, and the correct thickness, and correct size of course, need to be define in that particular polymeric membrane.

So, there are some commercially available polymers, and typically another aspect of why polymer is very importance aspect that you know they are some polymers which of photo pattern able. Just by lithography process, we have seen that there is a unique ability of these photo resists kind of polymers like SUA, SA 13 and so on and so forth, to able to get photo pattern very nicely at a good resolution using the mask.

So if you have such a commercially available polymer negative resist, you can use that as a coating or layer over the substrate that you want to machine using AJMM. And then you basically patterned it in a conventional lithography ways so that you have (( )) created where later on those (( )) can be exposed with the mask in place resulting in the direct exposure of the substrates at particular areas.

So, you have the negative and resist foils, and you can use either foils or you can actually photo patterned on the substrates. The resists actually if you are using SUATE 13 comes of very easily form the substrates surface, once it in dip in acetone, and for other resist like SUATE, they are some striping agent which are commercially available which can also be used. So, another approach is that you create a layer or foil of this resist material photo resist material, and then suitably exposes it, and create (( )) and cavities on a photo patterned manner inside that foil. So, both approach are good enough direct coating as well as foil based coating for the mask making. So, you lithographically process them, and this gives the possibility to make very complex, and accurate mask, because this is now having or driven by the power of photo lithography, and which such mask feature size about to seventy five microns, at very high aspect ratio of about 1.5 or so can be easily obtain.

(Refer Slide Time: 20: 45)



So, let us look at some example, then they are very nice images reported by Millar et al, in 2004, about what are the capabilities of AJM, and how small can really machining go particularly by using abrasive water jets. So, they are several aspects here, for example, you have profiling, you can see this the section of sort of butterfly wing very nicely cared out of abrasive water jet machining, and you can see the section where the smallest division of such a section is about 100 microns. So, you can really profile very thins section with mask which is exactly the negative replica of the wing shape.

So, here the maximum metal thickness profiled with a 50 micro meter diameter jet is about 9 mm. So, it is quite thick actually the sheet is about 9 mm in thickness, and the typical cutting rates which are hit upon in this particular case is about 1 to 2 millimeter per minutes. So, you are using this with the 50 micro meter jet diameter, and you can think of it that using a 50 micro meter jet diameter is also not very easy task, particularly, because there is a water jet which is emanating. And there is a tendency of grains to adherence to each other, because there are some surface charges which are created, because of the the spurs of the abrasive in the water as the slurry. And then the charger pull them together, and create (( )) of the materials sometimes blocking the nozzle. So, they has to be a repeated flushing action on the nozzle needs to replace again and again particularly when you are using a jet of about fifty macro or so in size.

So, with decreasing jet diameters, there is a linear decrease in cut surface area generated per unit per minute, because of obvious reasons that at now, (( )) lower part of the surface and one go. And cut depths to width ratios are must greater than or possible width micro machining laser events. So, therefore high aspect ratio this is very high aspect ratio on one side, you have thickness of nine mm; in other side you have this tiny features here of not more than hundred microns.

So, you can think of the high aspect ratio. So, this cannot be easily obtain otherwise any other machining process except this abrasive water jet, so that is the power of this process in the able to micro size the parts. The typical process parameter or the cutting speeds vary from up to four hundred millimeter per minute to above fifteen millimeter per minute. And you know for four hundred per millimeter per minute cutting speed, you can actually be able to process fifty microns thick materials; and for this lower cutting speed, you can go up to about 3 mm thick titanium. But still it does matter at what speed you raster on the surface. And as you can see here, and to the cutting speed it is higher meaning there by that the depth of cut of the material is lower.

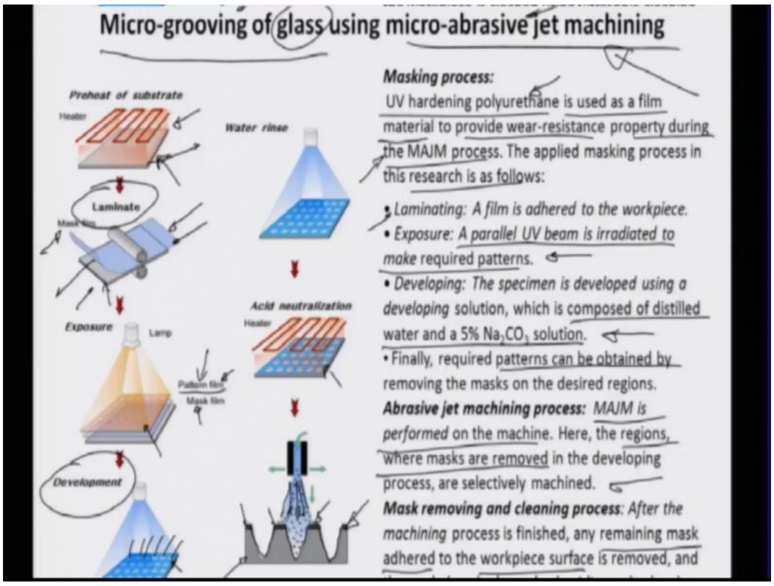
One of the reason, of course, is the fact that you have less (( )) on a certain area. And then as you are moving ahead your covering more in terms of length, but than the amount of depth that jet is being able to reach is lower, because of the less amount of (( )) of time that the depth of the have one a particular area of the surface and vice versa. And you can see the thickness is increase to 3 mm, because of higher cutting speed. Some other materials cut with the 40 to 60 micrometer jet, this was butterfly wing, these are actually this tiny dragons as you can see here, and these are the scale is almost about close to hundred microns or so. So, the minimum feature size on this dragon must be close to about 100 microns, again with 40 to 60 micrometer jet. And we can think off that this has been obtained from this particular sheet here by using well lithographed mask on the surface, it would exposed only those regions of the surface which are not having any protection or a coating. The other region covered by the mask are intact duct as the can see here. The other regions are the right here, the area which has been unshielded is what has come out after the machining process over something like this.

Very interesting aspect of AJMM, AWJM - abrasive water jet micro machining is again illustrated here. This is this gives kind of futuristic way of creating micro size features in structures for (( )) electronic, and micro fluidic applications. So, for example, in figure 3, it shows an array of 33 by 33 holes, so there are exactly 33 holes and 33 holes in this directions. And each hole as the mean diameter of about 85 microns, and it is drilled on a 250 micrometer pitch meaning thereby that the distance between two such holes of diameters. So, this tiny hole right here, and the tiny hole which is close by here, they have a distance of pacing of close to about 250 microns.

And each of them have a diameter of about 50, 85 macron or so. So you can think of the resolution given by combinatorial of the mask which has been design, and the jet in the particular case. So, this is the example of drilling using abrasive water jet micro machining process. And this is actually done in a 50 micrometer thick stainless steel. So, you can think of it that even the power of the jet is so enormous in this particular case that even very high strength material like stainless steel is being corroded easily by this process. And this particular process uses about 50 to 60 about 58 microns or so in terms of the nozzle dia. So, in nozzles size of 58 micron resulting in a jet which is of identical size is creating a 85 micron over a 50 micron thickness steel sheet it is actually amazing capability that water jet machining as shown in this particular example.

So, of course the drilling rate in this particular case was about 2.5 holes per second. So, you can think of the (( )), or the scanning rate of the beam in this particular case. And for a range of materials, and the material thickness, and the hole diameters, the thickness to the hole diameter ratio for a range of a material and you know the abrasive jet machining, water jet machining process that is to be used. So, the material thickness to the hole diameter is typically about 1.5 times the aspect ratio, the jet diameter. So, if the jet diameter is about close to 120 micrometer, the holes size in the particular case you can see here is about 85 micro meter or so. So, such is the power of abrasive water jet for doing micro structuring, and micro processing.

(Refer Slide Time: 29:05)



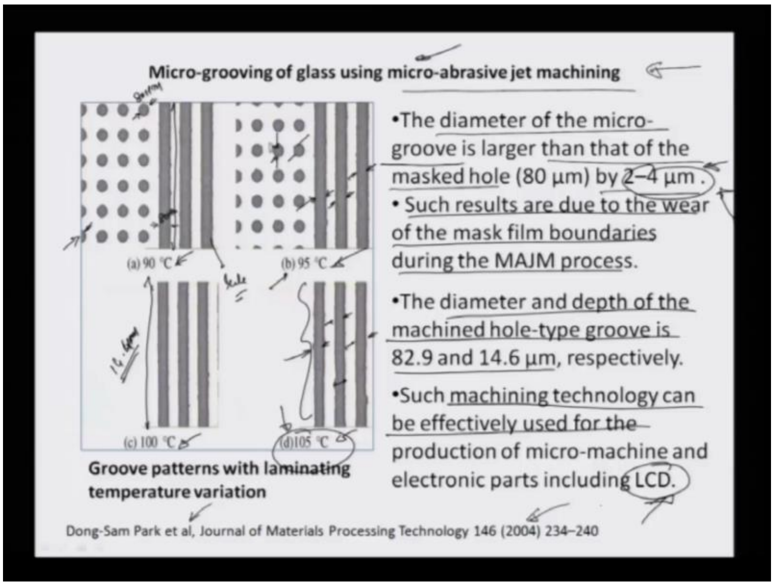
Let us look into another aspect of how grooves can be created on the glass using again micro abrasive jet machining system. So, here for example, you can see has been borrowed from work by park at all in 2004, which talks about a process of AJM using the same masking techniques. So, it is start with the preheating, and the uv hardening of a polyurethane which is actually the material which would be eventually develop by MAJM process - the micro abrasive jet machining process. And this uv hardening polyurethane is used the film material to provide wear resistance property during the MAJM process. The applied masking process is illustrated here, you laminate you create a small mask film, and laminate the substrate which is preheated, and uv exposed hardened polyurethane.

And basically exposure using a pattern film on the mask film which is this laminate right here, and what it ensure is that, because of this lamination, there is the perfect alignment between the mask film, and the surface on the top of it. And essentially a parallel uv beam is irradiated over the pattern film to make identical kind of future exposed on the mask film which is underneath. So, after the exposure is done, and the developing provided by a solution which is composed of distilled water and five percent sodium carbonate solution. The holes which are exposure through this pattern film on the mask film come off, so they are now empty curvature which are created on this blue masking film or this laminated films right here. And finally, these patterns are used for exposing the substrate which is down below here you can this is the substrate to the abrasive jet running through the nozzle onto the substrate surface. So, MAJM is performed using the pattern on the machine. And as you can see here regions are mask removed in the developing process are selectively machined off. So, you have this (( )) which are crated in those regions where the mask has been removed by photolithography done earlier.

So, there are some remaining materials of the mask which adhered to the work piece surface, because as you know it is laminated onto the surface. And there is amount of a pressure as well as temperature which is given onto the plastic, so that adherence is complete over the whole flat surface without any gap or air pocket in between. So, therefore, sometimes diction is major problem, and the mask remains back to the parent substrate, and one of the ways to cleaned its by using ultrasonic machining, or ultrasonic bath where ultrasonic frequency are used than a water bath to create enough kinetic energy. So, that anything like an impurity which is on a surface, and may be layer of this surface is taken off.

And as the result probably this is the one which adhered this layer on the surface this is one which adhered onto the mask. So, as soon as this layer is eliminated, it releases the mask. So, at places where there is rennet of the mask as you can see here, this black region typically are further process using ultrasonic cleaning techniques, this is very commonly used techniques in all microelectronic MEMS fabrication aspect. So that is how you actually create micro grooves on a glass surface. So, the parent surface here is (( )) the glass.

(Refer Slide Time: 33:32)



So, here in this particular example, this micro grooves all of diameter intend diameter 80 microns are so. This is of course the depth of the micro hole talking about. It is on a different scale, this has a different scale. So, this has been cart on such a surface using the techniques that was illustrated before that lamination techniques. And we can see that masked holes here is typically 2 to 4 microns larger in diameter. Probably in this case the mask was a polymeric mask as you saw in the last step; other was the lamination which was involved. And because of that the change of dimension of the polymeric mask would be reflected in terms of change of dimension of the surface concerned as such.

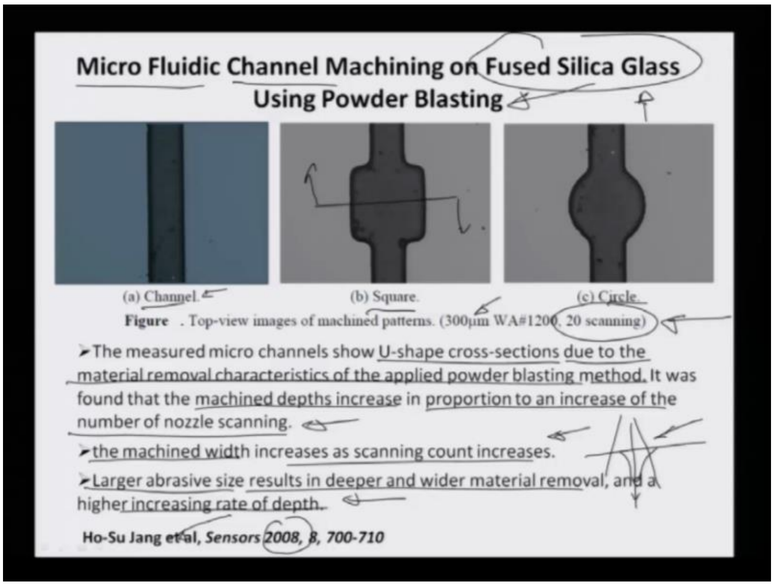
So, such result are due to wear of the mask films, therefore there is the increase in the overall size of the hole, because of this change in mask boundary. And of course the diameter, and depth of the machine hole type groove comes out to be 82.9, and 14.6 essentially this is the different scale. You have to the remember this is about 14.6 micro meters on much blown up a magnified scale, and this here right now right here is about 82.9 microns, so on relatively reduced optical magnification.

What is also important here is that at different temperatures the laminating has been done, so at one instance is that 90 degree Celsius. In another instance at 95, another 100 and 105 respectively. And then you basically try to see the impact at different temperatures. For example, you see that 105 degrees the groove which is created essentially, and this is the sectional view of the groove across the thickness of the substrate is actually very (( )), the surface roughness suddenly increase. What are the reasons why this can be so that at higher temperature, there is a tendency at some probably points to formulate air pocket as per as lamination is concerned, because of heated up nature of material medium between the laminate as well as the substrate.

And this air pockets may lead to the formulation of some crevices at some point where there is a tendency to overall rough in the surface off. Similarly if it is that about 95 degree or so, 90 to 95 degree, you can see that the future are quite smooth in nature depth wise if you look at and also cross section at a different magnification order of scale. So, this kind of machining technology, you can really be very effectively used for applications like developing of liquid crystal displays - LCDs. And in fact these processes have been tailor to the test of microelectronic industries for some of the very peculiar kind of high aspect ratio manufacturing application that the industry (( )).

So, for example, in a LCD monitor, you need to probably have this kind of a 80 micron diameter by about 40 micron depth structure on this on the top of display. So, such example of numerous impact where non-conventional process have been merged, the produces something, because of interest to the microelectronic industry.

(Refer Slide Time: 37:26)



This for example, is other very powerful powder blasting techniques, is same as abrasive jet machining in different manner. And here it is used for carving out micro fluidic channels on fused silica glass again one thing, which is observable here is the most of the substrate material that we are talking about either glass of one form of rather where the brittle fracture on the crack propagation is bit easier. So, as we learned before in our fundamental process learning of the fundamental process that as the principle mechanism is the brittle facture, therefore, the material which are unable to brittle fracture are the more well machined substrate. So, all the example that we have seen so far in the literature research literature are on such brittle materials on micro machining on them.

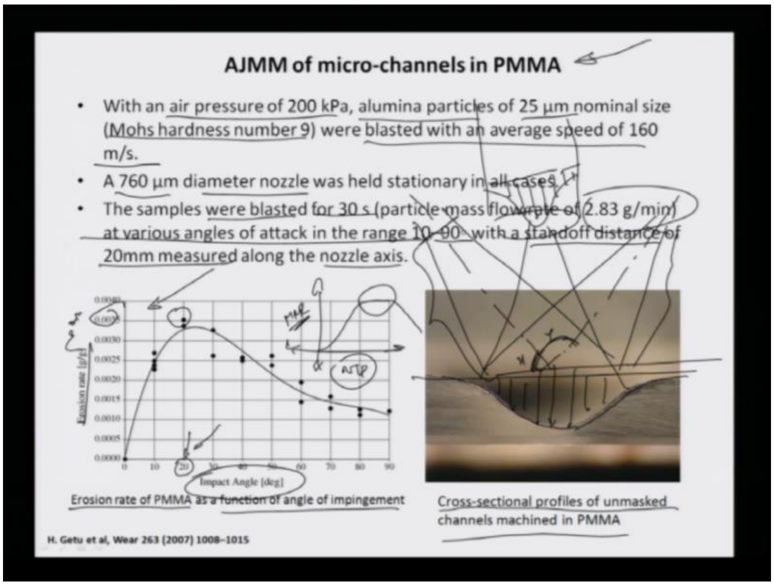
So, this right here example has been reported from work by Jang et al, published Sensors in 2008, it talks about making of this different square circle, and stress channel shape on top of the fused silica glass. So, if you look at cross sectional what happen meaning there by that you cut this across the section, and try to imagine depth wise, you will see that it show the U shape cross sections. And this is typically due to the material removal characteristics of the applied powder blasting method. When you talk about a powder blasting on jet of abrasive, it is really follows a normal distribution, and this I think I had illustrated before when talking about process basics.

Where this central particles in the beam are actually having maximum impact onto the substrate that is causes maximum brittle fracture or damage as move along the periphery of beam. It is like the normal distribution velocity is fall down rapidly as you move away, because of the interference of the environmental particles typically air which collides with some of these materials creating huge amount of drag forces. And also in very fact in the nozzle also the pressure, if you look at the velocity distribution coming out or magnetic out of the nozzle, it is really parabolic in nature. So, you have the axial velocity is the most prominent velocity or higher velocity as you go from the axial center to the sides, because of no slip boundary condition, the velocity would fall down.

So, typically that is what is reflected here also in terms of the abrasive jet machining process, and you can see that the machined depths, the kind of increase in proportion the number of nozzle scans. So, if you have only one scan, as suppose to ten scans, the ten scans of course the amount of thickness that would be covered by means of brittle fracture to the depth that would be covered of the channel would be higher in nature. Also found out that the machine with increases, scanning count increases, so both depth, and width at the cost of that thus scanning count is increased, and the larger of the abrasive size at results in deeper, and wider material removal.

Of course, because of higher impact of the grains those of higher mass. So, it typically increases the rate of depth based achieve, if the particles are higher in size. So, it is another very wonderful a example of micro machine patterns. Of course, the patterns are corresponding to about 20 scans on surface, and the beam diameters that is used in this particular cases about a 300 micrometers.

(Refer Slide Time: 41: 22)



Here is another very interesting example of micro machining done in polymethyl - PMMA. If you can see here, this is the cross sectional profile of unmasked channel which is machined in PMMA. So, I would like to urge you to look at the profile created by the impact of powder blasting, and exactly what I was saying that in the center the removal rate is maximum, and as we go towards the size, the removal rate is minimum. Typically, because the jet which is emanating out of someplace here also has that parabolic distribution, because that is how the velocities are distributed in a parabolic flow.

So, here for example, what is also important for me to share is that if you look at the erosion rate of PMMA as the function of the angle of the impingement, supposing the jet toward to turn in this manner between let us say angle x here to angle y. There is the variations in the erosion rate, the erosion rate here is mention in terms of gram per minute, this is miss-print and this is minute. So, if you look at that there is the certain impact angle, in this particular case it is about 20 degrees or so, where the erosion rate is the highest.

So, this kind of a gives the basis, which really talk about standoff distance as of the nozzle as measured from this plane surface right about here. So, probably around this 20 degrees range, this standoff distance optimum best. If you may recall there was relationship that we derived before in terms of the nozzle tip distance, and we said that the machining rate increases, and plot of falls down as for as the a variation (( )) concern with the NDT. So, as we raise this angle from x to y, there is tendency that the nozzle tip distance, nozzle somewhere being located here in case of x, and in case of y. So, the nozzle tip distance is actually quite large I should say for or vary I should say as function of the angle. So, probably twenty degree angle the nozzle tip distances is the optimum best which falls along somewhere in this region of the curve with results in a higher erosion rate.

In this particular case, the parameters that were used was a air pressure of about 200 kilo pascal's alumina particles of 25 micro nominal size Mohs hardness number of 9 were blasted with an average speed of 160 meter per second. And 760 micron diameter nozzle was held stationary in all the cases. The samples were blasted for about 30 seconds. A particle mass flow rate in this particular cases 2.83 gram per minute. And various angle of attack in the range of 10 to 90 degree with a standoff distance of twenty millimeters measured along the nozzle axis for the optimum angle. So, that is how AJMM has been used in this particular case for working on (( )).

Now there are several other examples the interest of time these lecture needs to be a finish now, but then there are several other examples of use of such a powder blasting or abrasive jet machining or water jet machining techniques, for doing micro system fabrication or micro system processing. So what I am going to do is to now start a new topic in the next lecture, which is about ECM or electro chemical machining. And, then towards the end of all the processes, I am again going to revisit this topic, and gives a few slides of what powder blasting or abrasive jet machining can do in terms of material removal from this surface.

Thank you.