Advanced Machining Processes
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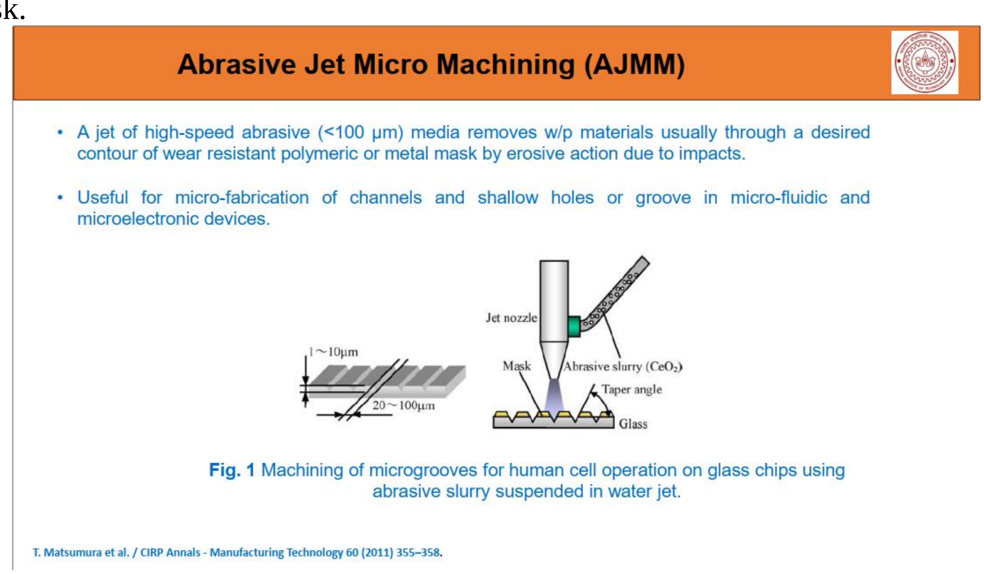
Week - 03
Lecture - 06
Abrasive Jet Micro-machining and Applications

So, the first example here is actually a work done by Matsumura in the year 2011, where he briefly talks about the making of microchannels or micro grooves on the surface of a glass substrate using abrasive jet micromachining AJMM process. So, as this figure right here illustrates there is a jet nozzle which is driving off the material which is in form of an abrasive slurry containing of a cerium oxide with suspended in some water, suspended in a water jet and thus this is actually a AWJ process which is being utilized for the purpose of micromachining. So, in all these processes where mechanical energy is introduced creating a brittle fracture as you go from the conventional macro size domain to the microdomain one has to remember that the shapes and features the small, tiny shapes and features which are to be incorporated on these substrate surfaces by virtue of the impact of the jet has to be a guided impact. And this guided impact can come from a mask a 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. And so, wherever there is a hole created in this mask there is a tendency just as in lithography as we discussed earlier for this abrasive jet to go past the mask and hit directly onto the surface thus creating the material removal. So, in this particular illustration of course, if you have a jet of high-speed abrasives where the particle size is let us say less than the jet size is less than 100 micrometres diameter and is used for guiding on a surface by virtue of a polymeric or a 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 up of metal or polymer gets kind of embedded onto 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 feature size that one is talking about is about 20 to 100 micrometres spacing between these two walls as illustrated here in this diagram.

And between two such ends of an edge as illustrated by the figure drawn here the size is probably something of the order of 4 to 5 times the size of the channel.

So, maybe this is about 500 microns or so. Also, what is important for us to understand is that the depth of machining that is obtained in case of such an abrasive water jet-based machining is about 1 to 10 microns. So, the resolution is very fine. So, you can call this a microstructure. So, you have 1 to 10-micron depth 20 to 100 micrometres width separated by a space of about 500 microns on a glass 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 you know distance from the surface of the mask D. There is a tendency number 1 for the jet to spread out as it goes nearer to the surface, which is obvious because this, I think we have discussed previously how important this nozzle tip distance NTD equal to D is as a function of the impact that the abrasive jet would create on the surface. Here, of course, one important aspect is that because the mask itself is made in a tapered manner. You can see that the mask is highly tapered.

Therefore, the grooves which are eventually being made on the glass, this is the groove which is being eventually made on the glass by virtue of this tapered form of the mask is also tapered. So, we can realize. So, let us blow this up here 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 gets exposed to the abrasive jet. The jet is coming in this direction.

So, this is the high-speed jet coming and striking of the surface. So, obviously, the particles which strike these masks would also damage or 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 up of glass. And so, some particles would actually deflect off and some particles which are at an angle maybe would actually roll off and go in a tapered manner to produce a brittle fracture somewhere in this zone which creates you know a tapered microchannel eventually. That is the reason of the tapering that some particles which are deflected off the surface of the mask are actually going and rolling along this taper mask and hitting the surface at a high impact creating the brittle fracture also in a tapered manner. So, one of the reasons why as Matsumura observed here in this, how beautifully the grooves can be defined, or shapes can be defined by just positioning and structuring the mask suitably.

So, this definitely gives us a way of using AJMM, Impressive Jet Micro Machining process for realizing micro grooves and micro features. So, let us look into some other aspects about the erosive mechanism of this AJMM process. If the impact energy of the erodent, of course, exceeds the material-dependent threshold energy which binds the material otherwise, particularly brittle materials. What happens is that there is a propagation and intersection of cracks which come because of this impact on to the surface of the material. So, this mechanism is most efficient for perpendicular impact angles because in that event the impact of the jet is directly applied otherwise, there would be a component of the force if there is an angle.

And therefore, perpendicular angles as you saw in the last case is typically the position at which this jet is kept with respect to the mass and the surface. And so, what happens is that this erodent particle which are angular otherwise in nature, when they hit ductile materials under an angle of 90 degrees, they do cause a plastic deformation of the material. So, therefore, because the mask is made up of such a material, ductile metals the plastic deformation of the hard angular abrasive particles are 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 a dimensionless factor m and v are the amount of mass and the velocity at which the particles are moving rho and H are the density and the hardness of the material respectively.

So, in micromachining when particularly using a mask and when particularly this business of hitting ductile metals come into picture, there is a 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. This factor has to be taken into account for really being able to calculate at the micro-scale the impact of grains passing through a ductile masking surface. Let us look at some other examples for mask materials as conventionally used in the AJMM process. So, particularly for micromachining or abrasive jet micromachining, you can use either ductile masks or you can use polymeric masks. 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 take an otherwise photo-patterned substrate and use that as a target mask by electroplating the copper on the top of that surface. So, what happens 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 deflect off 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 because of that change.

So, especially at perpendicular impacts the ductile materials would have a low erosion rate. So, the material of the mask would be untouched as it is. And the question is that how you create such micropatterns or micro-features within the masking surface. So, there are several alternate processes and that is why micromachining using or microsystems fabrication using advanced manufacturing processes is really not a one-process or a one-step approach. It is actually several steps in a hybridized 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 non-conventional techniques, of course, micro-scale drilling and milling being conventional, but even laser machining for stand-alone creating the micro patterns. So, you have a thin film of metal, and this metal is now being structured or featured according to the shape the negative of the shape that you want on the surface as a mask by using so many other methods micro drilling, micro milling, laser machining, maybe CM and EDM. And so therefore, there is a machining step which is even involved in the mask-making process of the later on step of actually creating a feature using this mask on an otherwise brittle substrate. So, there are several steps associated when you talk about micromachining using AJM.

The mask is typically magnetically clamped. So, you have to ensure that there is no relative movement between the mask and the surface. The same was the case for lithography as most of you have observed before that there is always tendency to hold the mask in case of using a photo mask in a normal stepper or a mask liner system by holding it through vacuum pressure over the substrate. So, therefore, there is no relative movement between the substrate and the mask as such. So, the mask is magnetically clamped or adhered in this case to the target to avoid any buckling or infiltration issues associated with the abrasive.

And the whole micromachining would spoil if there is some kind of infiltration in particularly the gap between the mask and the substrate surface. So, you avoid any such infiltrations, any such intrusions of an abrasive particle and you have to really ensure that the mask does not buckle. It sits straight flat on the surface. There is no gap whatsoever at any place. Otherwise, it is going to damage the resolution at which you are doing the micromachining.

So, the limitations in this kind of machining is that the machining can be done over feature size of 50 microns or more. So, going below 50 microns is a very challenging task particularly when you are using this abrasive jet micromachining. And of course, metals, of course, have this tendency of high ductility. So, there is an advantage that the mask does not get corroded that easily in comparison to some of the other probably brittle kind of materials which are used for mask mask-making process, one of them being polymers. So, when we talk about polymer masks, preferably elastic polymers need to be used because they should have, they have a high resistance being able to store more kinetic energy of the incoming powder particles without causing any brittle fracture or breaking.

So, typically something like polydimethylsiloxane which is a highly viscoelastic material which is well structured, well patterned can be used for abrasive jet machining process. And the correct thickness and the correct sizes, of course, need to be defined in that particular polymeric membrane. So, there are some commercially available polymers and typically another aspect of why polymers very important aspect is that you know there are some polymers which are photo patternable. So, just by the lithography process, we have seen that there is a unique ability of these photoresist kind of polymers like SU8, S18, 13 so on so forth to be able to get photo pattern very nicely at a good resolution.

So, using a mask. So, if you have such a commercially available polymer negative resist you can use that as a coating or a layer over the substrate that you want to machine using AJMM. And then you basically pattern it in a conventional lithography way so that you have vias created where later on those vias can be exposed with the mask in place resulting in the direct exposure of the substrates at particular areas. So, you have the negative resist foils, and you can use either foils or you can actually photo pattern on the substrate. The resist actually if you are using S18, 13 comes off very easily from the substrate surface once it is dipped in acetone. And for other resist like SU8, there are some stripping agents which are commercially available which can also be used.

So, another approach is that you create a layer or a foil of this resist material photoresist material and then suitably expose it and create vias and cavities on a photo pattern manner inside that foil. So, both approaches 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 masks because this is now having or driven by the power of photolithography. And with such mask feature sizes of up to 75 microns and a very high aspect ratio of about 1.5 or so can be easily obtained. So, let us look at some examples and they are very nice images reported by Miller et al., in 2004 about what are the capabilities of an AJM and how small can really the machining go particularly by using abrasive water jets. So, there are several aspects here for example, you have profiling you can see this is a section of sort of a butterfly wing very nicely carved out of abrasive water jet machining. And you can see the sections where the smallest division of such a section is about 100 microns. So, you can really profile very thin sections with the mask which is exactly the negative replica of the wing shape, so here the maximum metal thickness profiled with a 50-micrometre diameter jet is about 9 mm.

So, it is quite thick actually this 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 millimetres per minute. So, and you are using this with a 50-micrometre jet diameter, and you can think of it that using a 50-micrometre jet diameter also is not a very easy task particularly because there are there is a water jet which is emanating. And there is a tendency of the grains to adhere to each other because there are some surface charges which are created because of the dispersion of the abrasive in the water as a slurry. And then these charges may pull them together and create clonomerates or clumps of this material sometimes blocking the nozzle.

So, there has to be a repeated flushing action and the nozzle needs to be replaced again and again particularly when you are using a jet of about 50 microns or so in size. So, with the decreasing jet diameters, there is a linear decrease in cut surface area generated per unit per minute because of obvious reasons that now you are being able to raster on a lower part of the surface at one go. And the cut depths to width ratios are much greater than are possible with micromachining lasers even. So, therefore, high aspect ratio and this is very high aspect ratio on one side you have a thickness of 9 mm another side you have this teeny tiny feature here of not more than 100 microns. So, you can think of the high aspect ratio.

So, this cannot be easily obtained otherwise on any other machining process except this abrasive water jet. So, that is the power of this process in being able to micro-size the parts. The typical process parameters of the cutting speeds vary from about 400 millimetre per minute to about 15 millimetre per minute. And you know for 400 millimetre per minute cutting speeds you can actually be able to process 50 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 the cutting speed is higher meaning thereby that the depth of cut of the material is lower. One of the reasons, of course, is the fact that you have less dwell time on a certain area. And then as you are moving ahead you are covering more in terms of length, but then the amount of depth that the jet is being able to reach is lower because of the less amount of impact time that the jet could have on one particular area of the surface and vice versa. You can see that the thickness is increased to 3 mm because of higher cutting speed. Some other materials cut with a 40 to 60-micrometer jet, this was a butterfly wing, these are actually these teeny tiny dragons as you can see here.

And these are the scale is almost about close to 100 microns or so. So, the minimum feature size on this dragon must be close to about 100 microns again with a 40 to 60 micrometre jet. And we can think of that this has been obtained from this particular sheet here by using a well-lithographed mask on the surface which would expose only those regions of the surface which are not having any protection or a coating. The other regions covered by the masks are intact as it is as you can see here. The other regions are these other regions here right here and the area which has been unshielded is what has come out after the machining process is over something like this.

Very interesting aspect of AJMM, AWJM, abrasive water jet micromachining is again illustrated here. This is, this gives a kind of futuristic way of creating micro-size features and structures for a variety of electronic and microfluidic applications. So, for example, in figure 3 it shows an array of 33 by 33 holes. So, there are exactly 33 holes here and 33 holes in this direction. And each hole has a 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 diameter. So, this tiny hole right here and the tiny hole, which is close by here, they have a distance of spacing of close to about 250 microns. And each of them have a diameter of about 50, 85 microns or so. So, you can think of the resolution given by combinatorial of the mask which has been designed and the jet in this particular case. So, this is the example of drilling using abrasive water jet micromachining processes.

And this is actually done in a 50-micrometre-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 a 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 nozzle size of 58 micron resulting in a jet which is of identical size is creating a 85 micron over 50 micron thickness steel sheet. It is actually amazing capability that water jet machining has 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 rastering or the scanning rate of the beam in this particular case. And for a range of materials and material thickness and hole diameters, the thickness to the hole diameter ratio for a range of materials and you know the abrasive jet machining, water jet machining process that is being used. So, the material thickness to the hole diameter is typically about 1.5 times aspect ratio the jet diameter. So, if the jet diameter is about close to 120 micrometres the hole size in this particular case as you can see here is about 85 micrometres or so. So, such is the power of abrasive water jet for doing micro structuring and micro processing.

Let us look into another aspect of how grooves can be created on glass using again a micro abrasive jet machining system. Here, for example, you can see this has been borrowed from work by Park et al in 2004, which talks about a process of AJM using the same masking technique. So, it starts with the preheating and the UV hardening of polyurethane which is actually the material which would be eventually developed by the MAJM process, and this UV hardening polyurethane is used as a film material to provide wear-resistant 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, exposed using a pattern film or the mask film which is this laminate right here and what it ensures is that because of this lamination, there is a perfect alignment between the mask film and the surface on the top of it. And the masking process is used essentially a parallel UV beam is irradiated over the pattern film to make a identical kind of feature exposed on the mask film which is underneath it. So, after the exposure is done and the developing provided by a solution which is composed of distilled water and 5 percent sodium carbonate solution the holes which are exposed are then exposed through this pattern film on the mask film come off.

So, they are now empty crevices which are created on this blue masking film or this laminate film right here. And finally, these patterns are used for exposing the substrate which is down below here you can see this is the substrate to the abrasive jet running through the nozzle onto the substrate surface. So, MAJM is performed using the patterns on the machine and here the regions where the masks are removed as you can see here regions where the masks are removed in the developing process are selectively machined off. So, you have these vias which are created in those regions where the mask has been removed by photolithography done earlier. So, there are some remaining materials of the mask which adhere to the workpiece surface because as you know it is laminated onto the surface and there is an amount of pressure as well as temperature which is given onto the plastic.

So, that the adherence is complete over the whole flat surface without any gap or air pockets in between. And so therefore, sometimes the stiction is a major problem and the mask remains back to the parent substrate. And one of the ways to clean it is by using ultrasonic machining or ultrasonic bath where sonic frequencies ultrasonic frequencies are used in a water bath to create enough kinetic energy. So, that anything like an impurity which is on a surface and maybe a layer of the surface is taken off and as a result probably this is the one which adheres this layer on the surface is the one which adheres on to the mask. So, as soon as this layer is eliminated it releases the mask.

So, at places where there is a remnant of the mask as you can see here these black regions typically are further processed using ultrasonic cleaning techniques. This is very commonly used technique 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 really the glass. So, here in this particular example, these micro grooves all of diameter intended diameter 80 microns or so.

This is, of course, the depth of the micro hole we are talking about it is on a different scale this has a different scale. So, this has been carved on a such a surface using the technique that was illustrated before that lamination technique. And we can see that the masked holes here is typically 2 to 4 microns larger in diameter probably because in this case the mask was a polymeric mask as you saw in the last step there was a lamination issue which was involved. And because of that the change of dimensions of the polymeric mask would be reflected in terms of change of dimensions of the surface concerned as such. So, such results are due to wear of the mask films therefore, there is a increase in the overall size of the hole because of this change in mask boundary.

And of course, the diameter and depth of the machined hole-type groove comes out to be 82.9 and 14.6. So, essentially this is a different scale you have to remember this is about 14.6 micrometres on a much blown up or magnified scale. And this here right now right here is about 82.9 microns on a relatively reduced optical magnification. What is also important here is that at different temperatures the laminating has been done. So, at one instance it has done at 90 degree Celsius and other instance at 95 and other instance at 100 and 105 respectively. And then you basically try to see the impact at different temperatures.

For example, you see that at 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 topsy turvy. So, the surface roughness suddenly increases. One of the reasons why this can be so is that at a higher temperature, there is a tendency at some probably points to formulate air pockets as far as the lamination is concerned because of heated up nature of the 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 roughen the surface up. Similarly, if it is at about 95 degrees or so 90 to 95 degrees you can see that the features are quite smooth in nature depth-wise if you look at and also cross-sectionally at a different magnification on a scale.

So, this kind of machining technology can really be very effectively used for applications like developing of liquid crystal displays LCDs. And in fact, these processes have been tailored to the taste of microelectronic industries for some of the very peculiar kind of high aspect ratio manufacturing applications that the industry poses. So, for example, in a microelectronic monitor, you need to probably have this kind of a 80-micron diameter by about 14-micron depth structure on the top of a display. So, such examples are numerous in fact where non-conventional processes have been merged to produce something which is of interest to the microelectronic industry. This, for example, is another very powerful powder blasting technique is same as abrasive jet machining in a different manner.

And here it is used for carving out microfluidic channels on fused silica glass. Again, one thing which is observable here is that most of the substrate materials that we are talking about are either glass of one form or another where the brittle fracture and the crack propagation is bit easier. And so, as we learnt before in our fundamental processes, learning of the fundamental processes that as the principal mechanism is brittle fracture therefore, the materials which are amenable to brittle fracture are the more well-machined substrates. So, all the examples that we have seen so far in the literature, research literature are on such brittle materials and micromachining on them.

So, this right here example has been reported from a work by Zhang et al. and published in sensors in 2008 which talks about making of these different square circle and straight channel shapes on top of a fused silica glass. So, if you look at cross sectionally what happens meaning thereby that you cut this across this section you know and try to image it depth wise you will see that it shows a U-shaped cross-section. And this is typically due to the material removal characteristic of the applied powder blasting method. When you talk about a powder blasting and a jet of abrasives it really follows a normal distribution. And this I think I had illustrated before when talking about process basics where the central particles in the beam are actually having maximum impact on to the substrate and thus causes maximum brittle fracture or damage.

As you move along the periphery of the beam it is like a normal distribution the velocities fall down rapidly as you move away because of the undue interference of the environmental particles typically air which collides with some of these materials creating huge amount of drag forces. And also, the very fact that in a nozzle also the you know pressure if you look at the velocity distribution coming out or emanating out of the nozzle it is really parabolic in nature. So, you have the axial velocities as the most prominent velocities or higher velocities and as you go from the axial centre to the sides because of no-slip boundary conditions the velocities 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 they kind of increase in proportion the number of nozzle scans.

So, if you have only one scan and as opposed to 10 scans, the 10 scan of course, the amount of thickness that would be covered by means of brittle fracture the depth that would be covered of the channel would be higher in nature. So, the Zhang et al also found out that the machine width increases as scanning count increases. So, both depth and width at the cost of that the scanning count is increased and the larger the abrasive size it results in deeper and wider material removal of course, because of higher impact of the grains because of higher mass. So, it typically increases the rate of depth-based etching you know if the particles are higher in size. So, is another very wonderful example of micromachine patterns of course, the patterns are corresponding to about 20 scans on a surface and the beam diameter that is used in this particular case is about 300 micrometres.

This right here is another very interesting example of micromachining done in poly methyl methacrylate PMMA. If you can see here this is the cross-sectional profile of an 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 centre the removal rate is maximum and as you go towards the sides 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 a function of the angle of the impingement supposing the jet were to turn in this manner between let us say angle x here to angle y. There is a variation in the erosion rate and the erosion rate here is mentioned in terms of gram per minute.

This is misprint, this is minute. So, if you look at that there is a 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 gives a basis which really talks about standoff distances as of the nozzle as measured from this plane surface right about here. So, probably around this 20 degrees range the standoff distance is the optimum best. If you may recall, there was a relationship that we derived before in terms of the nozzle tip distance and we said that the machining rate increases and then plateaus of and falls down as far as the variation of MRL is concerned with the NTD. So, as we raise this angle from x to y there is a tendency that the nozzle tip distance nozzle somewhere being located here in case of x and here in case of y.

So, the nozzle tip distance is actually quite large I should say for or vary I should say as a function of the angle. And so far, probably a 20-degree angle the nozzle tip distance is the optimum best which falls along somewhere in this region of the curve which 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-micron nominal size with the most hardness number of 9. They were blasted with an average speed of 160 meter per second and a 760-micron diameter nozzle was held stationary in all the cases. The samples were blasted for about 30 seconds particle mass flow rate in this particular case is 2.

83 gram per minute and at various angles of attack in the range of 10 to 90 degrees with the stand-off distance of 20 millimetres measured along the nozzle axis for the optimum angle. So, that is

how AJMM has been used in this particular case for working on poly methyl methacrylate. Thank you.