Microsystem Fabrication with Advance Manufacturing Techniques
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Lecture – 20

Hello and welcome to this twentieth lecture on Microsystem Fabrication by Advance Manufacturing Processes a quick review of the previous lecture.

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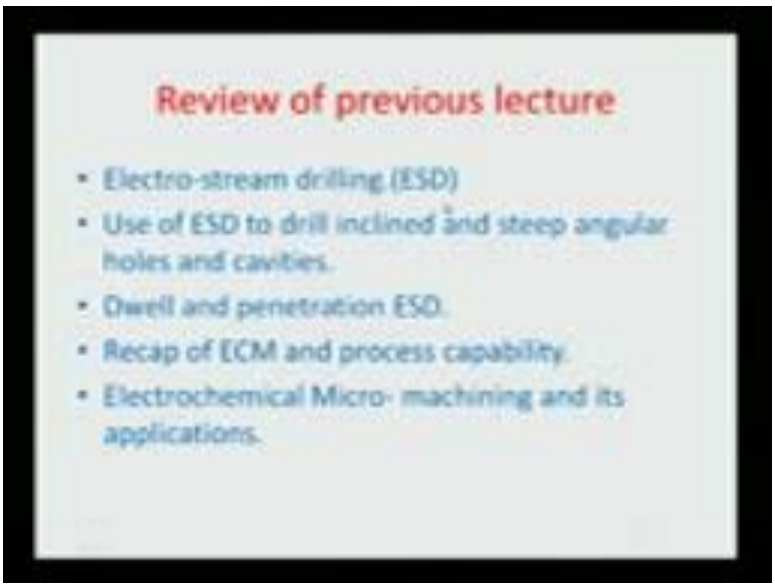

We were discussing about Electro-stream drilling in great details just like to recall that it is, a process where there is a the electrolyte itself is the electrode. So, the electrolyte is an acid stream which is negatively charged and it represents the cathode. Although it emanates out of an electrode which is otherwise, insulating in nature it generates a cathode effect; virtual cathode effect and the work piece made the anode dissolute.

And whatever ion's come out of the work pieces are precipitated or they do not react with any other constant in the acid electrolyte itself. And so they are dissolved designs and therefore, the process does not need any re flashing. Because, there is typically no new creation or no particle growth based on electro chemical processes. So, we looked at how is ESD can be used to drill inclined in steep angular holes and cavities.

We also talked about the 2 different variants: that is ESD has called the Dwell drilling and the penetration drilling depending on whether, the stream dispenser. The electrolyte

stream dispenser is a static or is moving at a constant rate or a constant feet towards the work piece.

We also sort of did a recap of the ECM basic process and the process capability associated with ECM. And then, we talked about how Electrochemical Micro machining is an absolute need for the several application in the industry and discuss some of this application and some research in the area of ECM or EMM.

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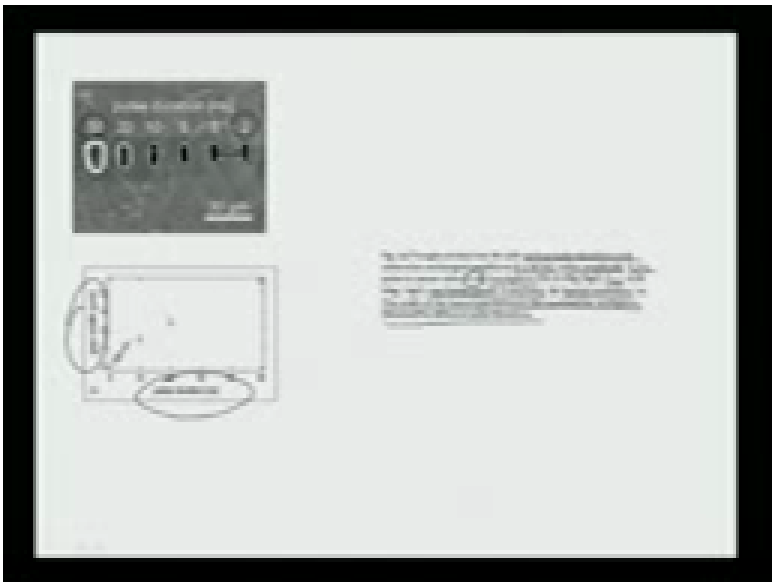

Just to recap little bit we showed this particular illustration here where with the various pulse durations in the nano seconds region varying between 50 nano seconds to 2 nano seconds. We could see how the resolution changed and how the inter penetration distance also changed proportionately. So, in this particular illustration we use the 0.2 molar HCL pulse amplitude.

And then, we also considered the 0.2 Volt voltages with a 10 percent duty cycle and then, we also the authors in this particular case try to also measure the work piece and the tool voltages surface potentials. And found out a machining speed 2 millimeter per minute. Experimentally as, well as through modeling approaches. So, what also is important special resolution and the width of the lateral gap between the tools.

And the work piece obtained for different pulse duration that is the gap width is

calibrated as a function of pulse duration. And you can see the gap which steadily increases with a pulse duration meaning there by the that more is the more is the duty cycle of the pulse or more is the duration during the during which pulse remains on the work piece subjected to more voltage for greater amount of time and dissolves more.

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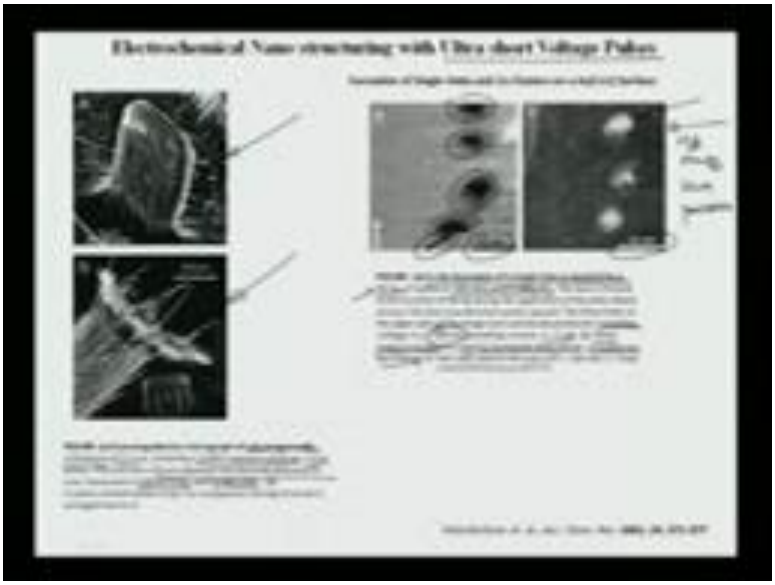

We ECM is also applied in this particular case where ultra short voltage pulses again are used for obtaining in this copper tongue. For example, this is an same images of the copper tongue. And this has a thickness of close to about 2.5 microns this is how small it is thickness voice etched by a 2 mega hertz sequence 50 nano seconds pulses of duration of magnitude 1.6 Volts.

The tool in this case is a 10 micrometer diameter mechanically flattened; piece of platinum and it just you know very nicely compares to ant leg this here right here is an ant leg. And you can see this scale is almost comparable in the same image which is above from below to each other. Which shows, the typically the process capability of the system this is 50 micron scale this is a 5 micron scale. So, it is to tenth that is about the comparison.

So, this particular machining process used an electrolyte which was 0.01 molar

Hydrofluoric HCL of 4 and 0.1 molar CU SO4. The other illustration is given by an in situ formation of a single hole on a gold sub strain, by using a voltage pulse of duration 50 nano seconds again of a 2 hole magnitude. And this is utilizing 1 molar copper sulfate at 0.5 molar Sulfuric acid solutions now the whole is formed in the location of the tip during the application pulse.

And this is represented by the black arrow the whole formation process; the initiation of the hole formation process has been showed in this particular schematic photographs and you can see that there about 3 single copper clusters on gold formed by 350 nano seconds 3 pulses to the STM tip again, in the same electrolyte solution. So, due to the formation of this kind of a copper so called electrode you can have an inverted feature hole created as in figure A.

But what is important for me to tell you, as the resolution here this is being done at a resolution of 10 nano meters which is way beyond what you have seen so far. So, with ultra-shot voltage pulses you can actually write as well as develop tools or electro chemical machining at this particular scale of few 10s of nano meters. Some other important features of this is the tunneling voltage and current.

Tunneling voltage is in the range of minus 300 millivolts and the current is about 1 nano ampere in this particular case. So, that is about how small these same process can go and still have a resolution. So, this resolves very well with1.of.the some of the current high will energy been processes like Fi b xy lithography so on so forth.

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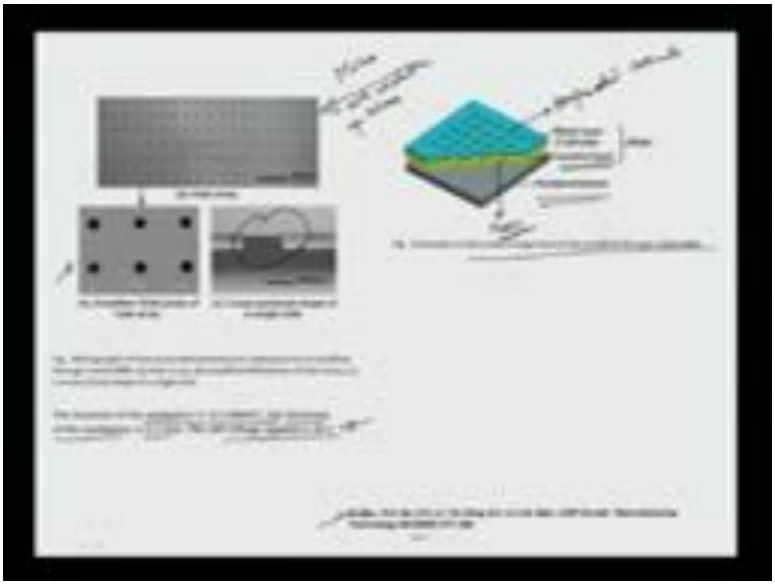

So, this is another example borrowed from zhu at all in 2009 whether, talking about a perforated cathode. So, this is a perforated cathode and the anode here is a work piece and there is an insulation layer which is in between which is also like a mask. So, there is a mask which exposes certain regions of the cathode to the work piece and viewing to this particular arrangement.

The EMM of the electro chemical micro machining is, able to drill holes which such fine resolution close to about probably 0 5 mm each of this hole must be in the range of a few 100 microns I am sure. And this is a lone of a same image of the same whole array and this right here illustrates cross sectional shape of a single whole. So, the work material in this case which is made the anode is work piece which is the chromium alloy 1 chromium 18 and i 9 titanium.

The thickness of the work piece about 0.3 millimeters that is about300 microns and the self voltage that you are applying to this machining here is 18 volts. So, this gives you some feeling of the kind of voltages resolutions and whole diameters that you can achieve with different work pieces.

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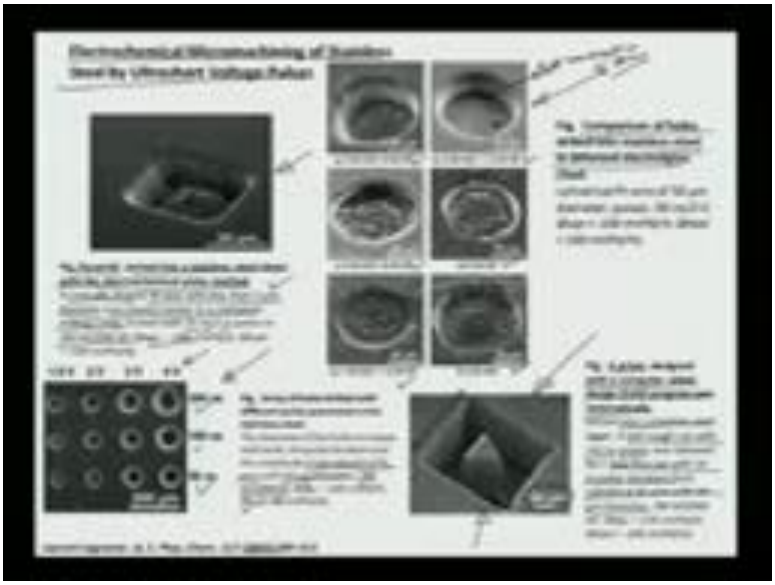

Get another example is forward from Laurent scroll as can be seen in this illustration here. So, this was reported in 2003 and this talks about again electrochemical micromachining stainless steels by ultra-short voltage pulses. The figure here is same image of a pyramid which has been etched into a stainless steel sheet and again, with electrochemical pulse method. It is a conically shaped you can see the conical shaped right about here in the center and this case is a tungsten wire with less than 5 microns diameter.

And it was moved similar to a milling cutter; that is how the process was accomplished. And as you know a milling cutter is actually a moving linearly on a surface in this case although it is not a metal to metal contact like a typical milling cutter wood with a surface in this case it is a electro chemical machining or electro chemical milling operation which does most the material removal. So, it is a dissolution material way by a circular tool.

So, this moves a although it is itself about 0.5 micron it is moves along a path here which gives you an illustration of how this cavity was made or realized in a stain less steel sheet. There was a pulse duration of 25 nano seconds that this group used and the pulse value was about 2 volts. The electrode electrolyte that was used in this case about 3

molar Hcl and a 6 molar Hydrofluoric acid combination.

And the dependent work piece and tool potential over measured as minus 200 and minus 100 many volts respectively with respect to a standard Hydrogen electrode. This again is, another illustration of what is that process capability related to ECMM you can see for a pulse duration varying from 50 nano seconds to 200 nano seconds there are different hole diameter of the range of close to about 30 to 50 microns.

Which are obtained at different pulse magnitude. So, this is an array 4 volts 200 mean nano seconds 3 volts 200 nano seconds. These are the different hole diameters being made the different voltage nano seconds combinations. In this case, the tool was a cylindrical platinum wire and had the diameter tip diameter of 50 microns and reported values here indicate what kind of electrolyte was used.

Then, is again a Hcl Hydrofluoric acid combination and the work piece potential and the a tool potential are rated as minus 120 and 80 millivolts with respect to a standard Hydrogen electrode. There some more examples here is comparison of the holes again drilled in stainless steel with different electrolytes. So, you can see the combinatorial used here by varying the different moralities of the Hydrofluoric acid with respect to the Hcl.

And you can see various surfs topology being generated based on the different electrolyte. So, by enlarge this happens to be the best combination to do is CMM. So, a process balancing like this has to be made for good machine into happens here again is a very beautiful CM picture of a prism and this is been designed with Computer Aided Program and it was etched in stainless steel.

So, this was actually be done with fast rough cut of 143 number second pulse duration using CMM and then, there was a slow fine cut of 50 nano seconds pulse duration used in this particular case. The tool in this was again a cylindrical tungsten wire with 30 micro meter diameter. So, typically the movement here is an similar manner has happens in most of and the computer driven tools where there is a path geometry which is provided in terms of a CAD file and the x y g stage is set in a manner.

So, that it course between def coordinate values in a in a manner that CNC also happens. So, it is a sort of computer numeric control; which is directs the tool move in a certain path which would relate to the fabrication of the eventual feature shape and size. So, this is otherwise very hard to achieve you can look at the scale here it is about 50 microns meaning there by, this 1 side alone is close to about 50 microns.

The whole depth or the whole width here is about 100 by 100 microns and the depth also as you cannot be figure out here SCM. But it is actually about 100 microns or so. So getting such a feature using non-lithography, non-energy been techniques is highly you go for electro chemical micro machining.

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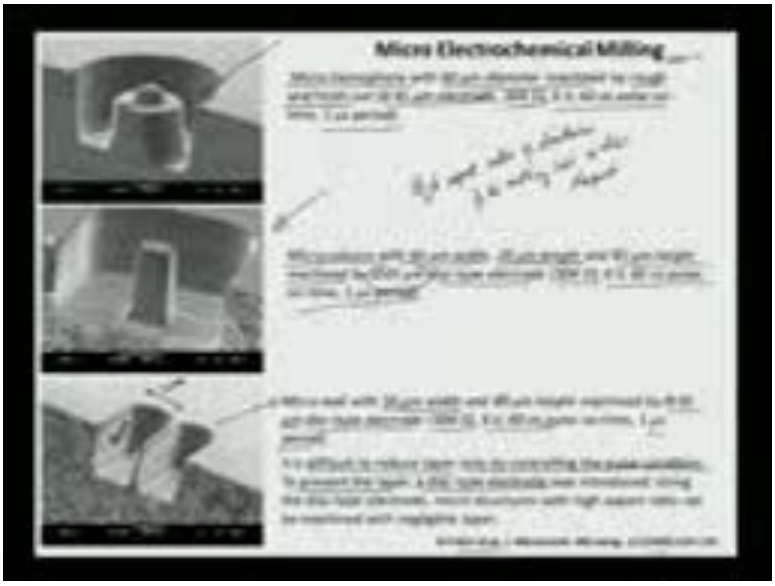

So, some beautiful illustrations of milling electro chemical milling here you can see this is borrowed by Kim at al work published in 2005. Where he talks about the fabrication of a Micro Hemisphere with about 60 micro meter diameter machined by, rough as well as finish cuts. The electrode used here is about 45 micron diameter electrode wire and the material that you are using of the electrode is stainless t 304 and basically using a 6 volt 60 nano seconds pulse on time duration for a 1 micro second period to a sheep.

This particular feature right here beautiful again micro feature illustrated on stainless

steel. Similarly, by this again is another example where a micro column has been with a width of 14 microns and a 20 micron length, an 85 micron high so very high accept ratio this been machined by again a 65 micrometer disc type electrode and this is again example of milling. Where the electrode is rotated because of which there is machining taking place at this mic this nano metric level.

So, use a 304 ss stain less steel electrode in this case with 60 volts 60 nano seconds pulse on time duration and for a 1 microsecond period. This another is an illustration of micro wall with 10 micron width. So, this is about close to 10 microns and 80 micron height; which is this height right here machine by a 65 micrometer diameter disc type electrode. Again using, the same material 304 stainless steel with 6 volt 60 nano seconds pulse on time duration for a 1 micro second period.

So, 1 aspect which is learning experience from this particular work is there it is very difficult to reduce the taper only by controlling the pulse condition. Because, electro chemical machining has I think I have illustrated many times earlier as a self-tapering process. And so at typically a better idea would be to use a disc type of electrode; which in this case they have used, chemetal has used. And you can actually have high aspect ratio of your micro structures if the milling tool is disc shaped.

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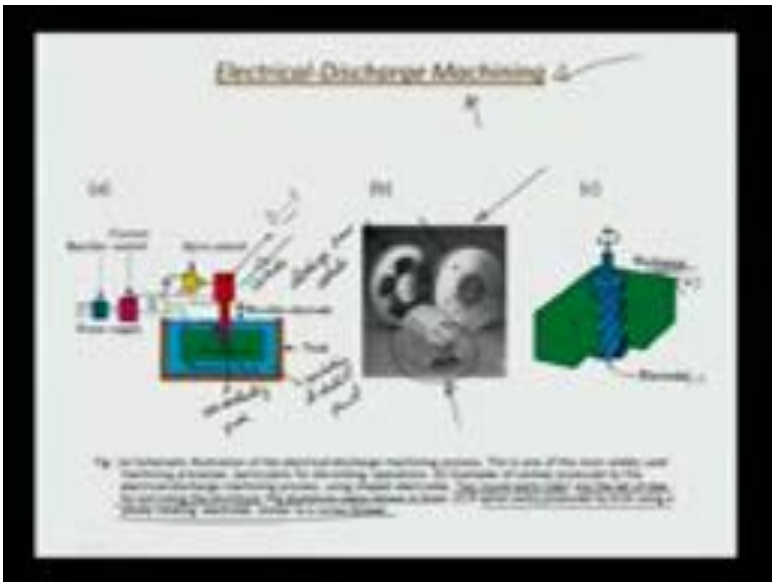

So, again some very nice illustrations of ECM . So, let us now look at a little bit different process EDM I think I had detailed in the last lecture why we need to look at this particular process because, although we are going to do the numerical modeling in the process details later, but in from an application stand point.

ECM is combined with this EDM process to formulate hybrid making machining strategy which is called ECDM which is electro chemical discharge machine. So, you must understand the basic principles etcetera here and some applications stand point what dm does and how ECDM would be different from ECM or ECDM or EDM. So, that is the reason for using this right here.

So, just a brief summary of what this processes about. So, there is a electrode which is mobile in nature and it is basically, the cathode. And the work piece is made the anode here and instead of putting a electro chemical or electro in instead of putting an electrolyte here or electro chemical agent here you put a insulating the electric fluid. The advantage of the electric fluid is that it provides a path between the tool and the work piece right about in this particular gap which has non-conducting in nature.

So, as this path is non-conducting you keep in charging this potential to a higher negative potential. There is the tendency that the medium which is very small in this case; which is an insulating medium breaks down. And there is it is charged which happens because of the charge difference from the cathode in this particular case. So, discharge is typically momentary stream of electrons which is released by the cathode.

So, they are driven by the field and the positive potential of the anode and they are accelerated. And then, in this condition they heat upon the work piece of which leads to the discharge of the at least to a situation, where this charge creates an ablation or a thermal; thermally ablated zone with a melt pool. And as the electron pressure reduces on the surface there is a tendency of cavitations to happen because, the medium itself is not so fast as the electron velocity and it has high inertia.

So, it takes some time for the medium to come back in to that portion. So, for a momentary instant there is a creation of a low pressure zone; which creates full of the

melt pool which has been formulated. And that is how you remove the material in this particular process. So, it is a useful tool electro discharge machining just as like electro chemical machining I am going to give this details of the modeling process etcetera and later on lecture.

But here from a stand point of what EDM can do; you look at some of the components high aspect ratio systems you know examples here. For example: you can have the small cavities or this gearings produced by the EDM process of the electro electrical discharge machining process. So, for example: here there are 2 round parts here and set of dies for extruding the aluminum.

The aluminum piece which shown in the front. So, this is the piece and this is the die these are the dies which are used for extruding this particular piece. So, such examples are very common place where EDM is used. For these applications this for example, is another a illustration where there is a work piece made the anode and the electrode made the cathode. And there is spiral cavity been produced by either ECM or EDM type of operations.

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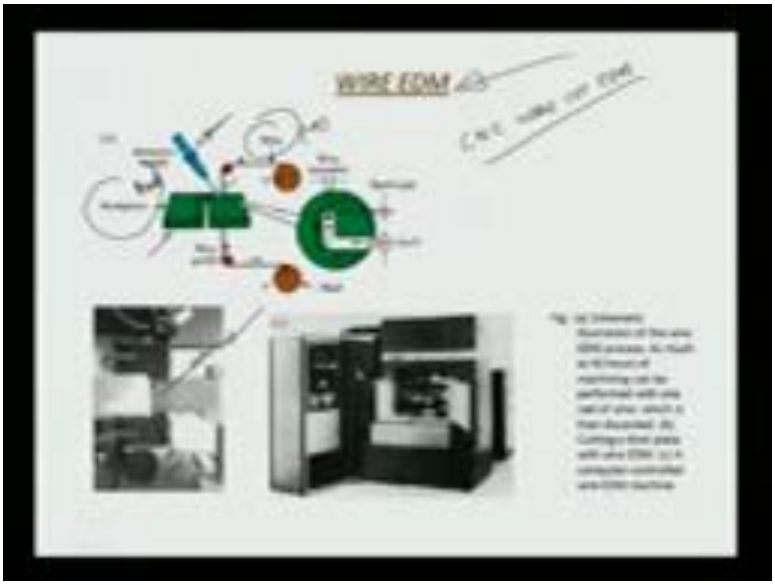

So, having said that a slight variant of this process is found in very common place and

very handy tool for having complex shapes like l slots or Cam profiles being cut and this is called wire cut EDM. And typically the process is driven by a CNC system. So, that is why we call it CNC wire cut EDM. So essentially what it means is, that you have a coordinate layout which is there and there between the coordinates there i e movement of the particular tool.

So, that creates its machining in fact, on the work case. In this particular case there is a work piece which is made the anode. So, the work piece is made the anode and there is a supply; dielectric supply of direct fluid insulating fluid in the work zone. And that is a wire and this wire is normally made the cathode. So, the wire actually spread from a role you can see between this role here and this role here the wire is being fed.

So, as the wire slowly emanates out it there is a discharge which happens between the wires. The cathode and the work piece anode and where ever the wire moves, so this slot write here the l slot which is otherwise seen in top view. So, the wire actually the motion of the wire path would be first in this direction and then in this directions. So, the wire comes all the way into this and then goes like this.

Wherever the wire a proceeds there is a arcing because of this complex else lot depending on the path of guide of the wire would formulate on the workplace. So, this is very interesting high capability process which is used in the domain of a advance manufacturing processes for doing extremely complex shapes and features. And I just like recall that if we are talking about micro gearing or if we are talking about very small features of high aspect ratio.

There is a possibility that if the stage itself which is feeding the wire in this particular case. The wire being about close to 80 micron diameter or so if this stage has a fine resolution of movement then, you can actually be able to make small features or components utilizing the effect of such small motions, such precisions motions of this stage itself.

So, the stage needs to be very finitude. So, this is how a wire cut EDM system look like in the laboratory this right. Here is that wire and it is past between the roles 1 role can be

seen here, the other role is probably out of the picture and there is a way to mound the work piece in this particular case; which gives in the bases of a EDM.

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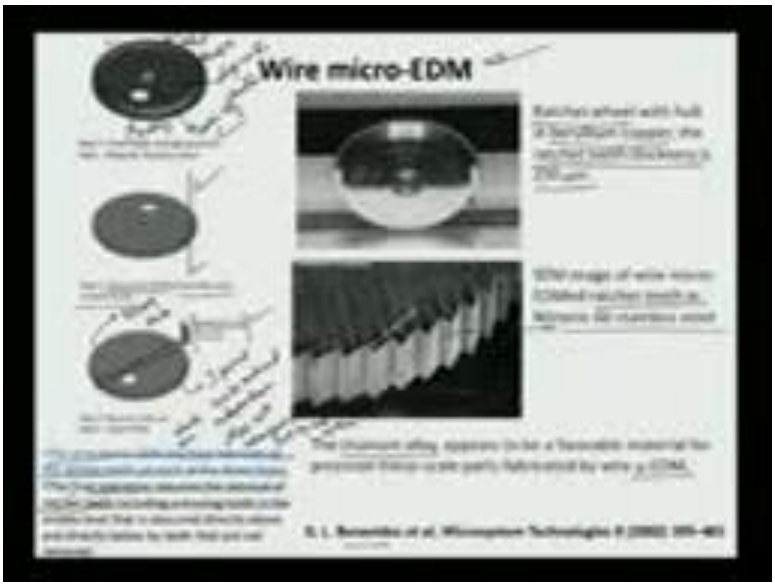

So, let us now look at some of the micro structuring being done by wire micro EDM operations. Some very nice illustrations by Benavides group in 2002, where he talks about is the creation of a small ratchet wheel with diameter of with thickness close to 250 microns in beryllium copper. So, the way to make it is that they take a blank and then, turn a blank on a high precision lathe.

And are able to structure it in a manner so that, there is a cup at the center here. And then, my other fine operation like drilling etcetera these mounting holes or the center mounting of these blank has been formulated. Once this is formulated the use wire here this right here is a wire between the 2 tick marks and they perform a micro wire EDM on off all possible teeth at the 3 levels of the blank. The blanks are cut into 3 different levels can be illustrated here.

So basically, you can also use another electrode for removing the teeth from each other. So, once the blank has been formulated in 3 already some machining has been done here, but the extent to which the machine can go is very limited in the radial direction in this

particular case. And therefore, the tooth removing electrode sort cleaves it diametrically. So, the electrode goes all the way to the other side here and cleaves it diametrically.

So, those 3 pieces can be realized, which are independent discs with micro gearing cut on each of them. So, the wire micro EDM machine fabricate all the ratchet teeth on each of the 3 levels and the final operation requires, the removal of ratchet teeth including a missing tooth in the middle level that is obscured directly above directly below by teeth that are not removed.

So, this right here shows a detailed view a same image of the wire macro EDM the ratchet teeth structure. And this is in Nitronic 60 stainless steel and they have also done it for titanium alloy and they have seen that the process is quite favorable for titanium machining titanium alloy also by micro wire EDM. So, this is very high capable process now for doing this micro features and structures.

So, you can imagine the ratchet teeth thickness of 250 means this 1 section here is only 250 micro meter thick, and there are 3 such sections and different levels of this particular mechanism.

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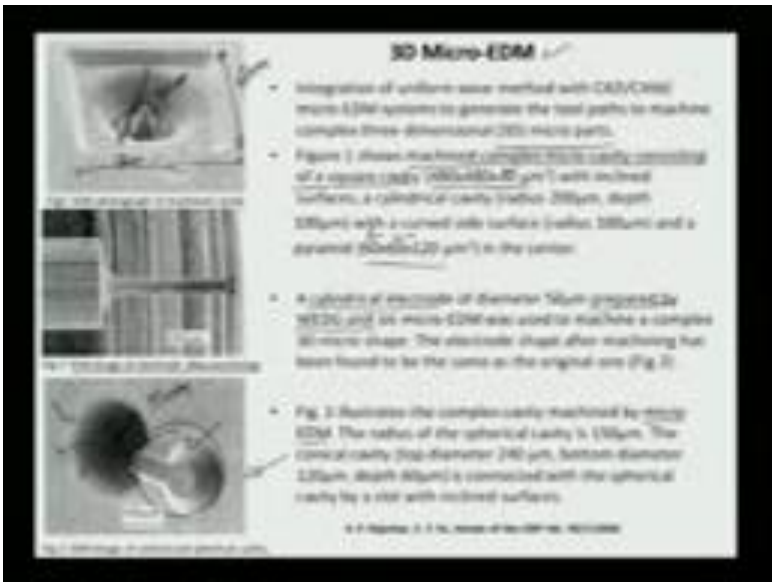

So, this is 1 very fine, example of what CNC work EDM can do apart from that there are many other applications of the micro EDM process 1 of the examples here shows a machined complex micro cavity consisting of a square cavity. Which is about 480 microns wide and 480 microns long with a depth of about 40 microns. And there is a small pyramid at the center which is been made by, the whole machining is made by micro EDM operation.

Use a radius of the cylindrical cavity of the extent of about 200 microns and the depth of this cavity about 100 microns. So, and if you look at the pyramid structure; the pyramid is about 120 micron tall and is square pyramid so each side of the square is about 60 micron, 60 microns. So, this comment highly about the way that EDM of the capability process capability EDM to do 3D micro structured architecture of parts.

Figure 2 again is a electrode, circular electrode the same image of a circular electrode and this tip size here mast be close to about all the 10 of 10s of microns. So, this is double again using a micro EDM process this cylindrical electrode was prepared by you know a wire electro discharge grinding a unit the electro discharge machining process. I think I had illustrated further earlier that with another kind of an identical wire assistant ECM process we had produced about 2 microns of tip size.

In this particular case although, a the tip size is slightly higher it is about 5.2 micro meter, but it is still is a very high improvement over the other machining processes, which exist figure 3 here illustrates a complex cavity machine by again a micro EDM tool the radius of the spherical cavity this particular region is about 150 micro meters. On the conical cavities having a top diameter of 240 microns and a bottom diameter of 120 microns the depth of about 60 microns. And this conical cavity further is connected with this spherical cavity.

So, such inverted features in 1 case probably this part is through a die sinking operations, where the a tool is a negative replica of the cavity. And this particular case the tool is a projection coming out to the tool surface they can be done parallel on a surface. So, that is the capability of producing a 3 dimensional structured, highly structured surface of at the microscopic lens scale. Then, such kind of operation demonstrates the capability of

the micro EDM process, micro electro discharge machine process.

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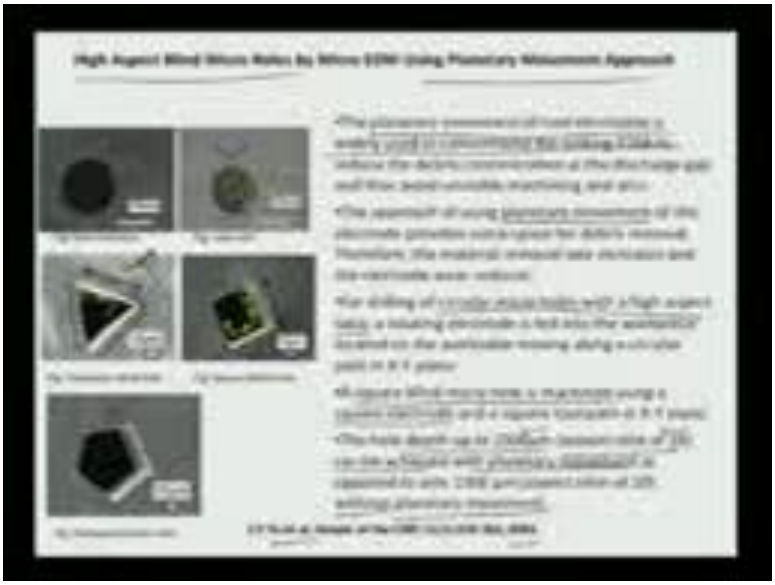

Another you know aspect of EDM reported by you at all in 2002, which talks about high aspect ratio blind micro whole kind of structures. These are the micro hole structures and the holes can be other triangle of wholes or square wholes or even pentagonal holes depending on the electrode that does been used. And this is using planetary movement approach of the tool.

So, the planetary movement is in this case basically smaller electrode moving or following across the hole the internal control of the hole. So, the planetary movement of tool electrode is widely used in this conventional die sinking EDM process. And 1 of the reasons why that is used to give a sufficient gap debris removal or take place. So, the machining is always stable because of non accumulation of the debris any part of the machining zone.

So, particularly in cylindrical cases or in circular cases you can really follow this planetary motion and you can with this drill circular micro holes with high aspect ratio. A rotating electrode is put inside the tool. So, similar kind of machining cannot be done if the holes concerned have non-circular cross sections. For example: in this case it is a

triangle hole or a square hole, but in that event a square blind micro hole can be machined by using a square electrode, you just develop a electrode.

So, which is very close to this and may be a good idea would be if this square is reasonably small in comparison to the square that is being illustrated. So, if in this particular case as I was saying, if the square electrode is reasonably small it can follow a square path of motion something like this. Just as in this case there was a circular which was follow a circular path even you could have rotated in the tool while following it. The square tool can follow square path and that would give you a very good machining of in this case.

For example: there can be a triangle a small triangle and this triangle can follow a triangular path. So, that this whole thing can be machined accordingly. So, there was different strategies that now people use for doing this micro EDM with planetary movement, planetary motion. In fact, all these holes are to the depth of about 2500 micro meters. And in fact, if you look at 1 of these edges here or for example, this particular edge they must be close to if this is 10 microns, this mast be close about 130 or 140 microns.

Having said that a very good aspect ratio of the order of about close to 18 or, so a is generated using a this kind of a process. It is actually very good and capable process for doing high aspect ratio structure at the micron scale. So, if you had no planetary movement. For example: if same process would have been produced by a normal electrode of a same size as the whole etcetera, the aspect ratio would then come to about close to 10.

So, in a way it illustrates what the planetary emotion does; in terms of removal, where the activity can be prolonged over a higher amount of depth. So, that aspect ratio can increase accordingly. So, in 3D micro machining particularly when we are talking about large aspect ratio structure definitely the planetary EDM, micro EDM is a very good strategy to manufacture at this particular scale of the length.

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Let us look at some more examples and just because we are talking about aspect ratio, I would recall the Liga process which we had discussed earlier while doing the micro fabrication. And this Liga a process basically means, a lithography there is a detail step of a Liga process probably in next slide we will just recall some of that before going ahead. But this is a combination in this particular slide as proposed by takahata et al in 2000.

This is a case where micro EDM is being performed by combining it to the Liga process. So, as you can see here there are various steps. Just like lithography you have a PMM a layer; which is exposed to a x ray through a masking process and this ultimately we want to produce these features right here. So, these are sort of negatives of micro gearings which are produced in a high depth manner.

So, in the 1st step what happens is that this mask is realized using either leisure patterning or some other method with which this small structure here gear like structure can be made as openings typically, as openings. So, the mask has openings in the shape of micro internal gearings. These are internal gearings as can be illustrated now. If you look at the printing resolution of these gears, the internal gearings are of the diameter something as close to 200 microns.

There are distantly place this ways other by close to above 1 millimeters or... So, you take a resist PMM I m using X ray lithography a why we need using X ray lithography. Because, X rays are typically high energy radiations and they can go up to a larger depth within the PMM material. So, in this case it is needed that the depth up to which the internal gearing should go on that layer 300 microns or so... So that is why it is needed.

So, you take a mask and expose PMM selectively here. So, you are exposing up to you now height or depth of 300 microns of diameters of internal gearings which are only 200 microns in nature. So, it is the expect ratio 1.5 in this particular case. Now, the PMM a is changed as soon as it gets exposed certain region. So, suppose in if you want to expose this region; which now you can see now you can see converted as etched area the particular case.

The structures the property PMMA here's changed and you can develop. These PMMA exposed PMMA out very well using some kind of developing solution etcetera. And so therefore, there are these craterous which has formulated on the PMMA itself. So, you can actually do the electroplating of this cavities and then after electroplating and planerise and polish on both side. So, that your left with only those features.

Which are embedded in a PMMA as electroplated features and the electroplating is done using this substrate here which is a conducting substrate that is should always remember conducting substrate. And there is always, the deposition of platinum along the craterous as which have been created here 300 microns. So, it is all deposited along with this whole craterous as well as on the conducting substrate here.

The substrate is later on removed as in this particular case you can see the substrate actual has been removed a and the conducting substrate is gone from here. And you have now, cavities like illustrated here open on the both ends which can be used for further machining. So now, advantage of here that is cavities are already pre coded with platinum right.

So, they are pre coded platinum they are platonized and they are like metallic in nature. So, they can be made an electrode so typically in this case if you want to do EDM

operation this is made the cathode. And a the work pieces in this case, has a size which is close to this the hole that can be see here and work pieces the made the anode. So, this work pieces is positive and this is the cathode negative.

So, the work pieces which was otherwise cylinder is now cut into a gear which is same image which is show here. So, this is the micro EDM work pieces. The advantage in this case and finally, the cross sectional area of this electrode look as beautiful as this. Wherein showed the gap of 3 microns is always there between the electrode and the EDM gear. So, that is more about process setting and probably the monitoring of the gap current value with CNC control we could do that kind of a feed rate of a micro gearing in to this particular structures. So, this is about the capability of high aspect ratio of the micro structures in combination with various processes like, Liga etcetera.

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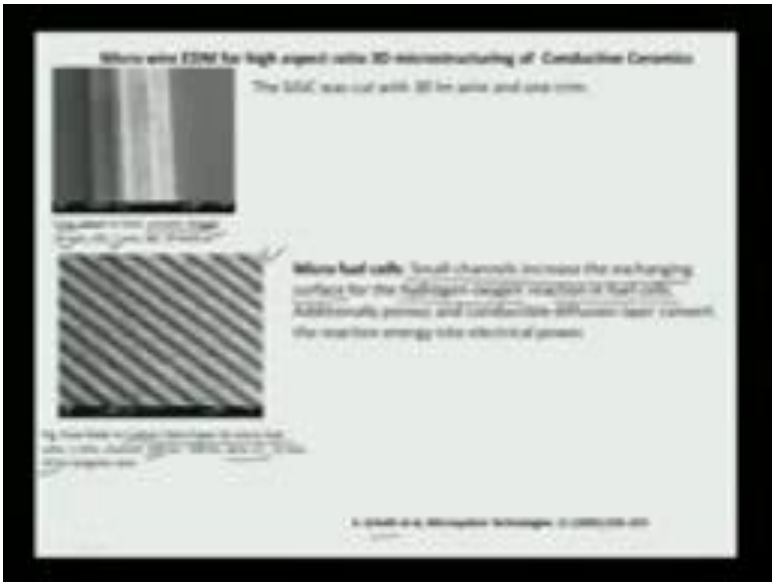

These are some other examples again you know you can see, how high aspect ratio as structures can be developed by micro wire EDM using the same concept of Liga plus EDM has been illustrated before. These are pillars is of dimensions 80 to 525 microns in in lengths scales. So, 80 microns the breathed of a thickness of the pillars and the 225 125 microns is the depth of the pillars.

These pillars are being printed of 400 and micron depth. So, they are very high aspect ratio structures which can only be you obtain through this specialized process. This again is a steel gear assembly. So, steel gear wheel cutter with the 20 microns tungsten wire and this is with 1 trim using the CNC wire cut process, EDM process as had been illustrated earlier.

The gear wheel has only an outer diameter of only about 500 microns. So, that how small this greater is and high of board 6 mm. So, you can think of the high aspect ratio that involved in this kind of a structure and you can see the number of teeth in this particular case is 8. So, there are both 8 teeth made in this gearing. So, such is the power of this 3D novel 3D micro structuring process.

Again another very good example of again a ceramic gear wheel. The height is 10 mm and the od's above 1 mm number of teeth are 8 in this particular case. Again, in for micro fuel cell applications schoth at al has shown a very small channels with increased with increased exchanging surface for a Hydrogen, Oxygen reaction to takes place in fuels cells. And so this illustrates carbon paper, fiber micro fuels cell and the channel sizes report close to 500 microns area is only 15 to 25 mm square the schoth wire this as this application is only above 500 mm the diameter.

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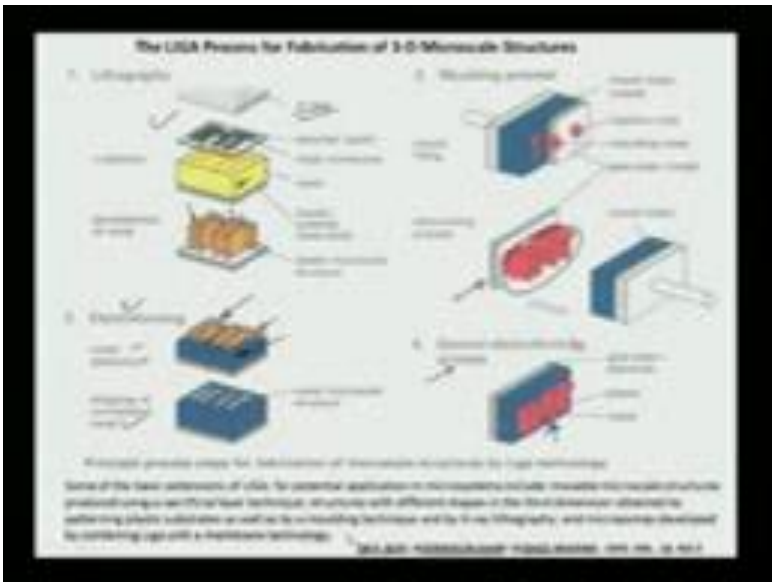

So, that is again another very good last illustration micro wire EDM can do. I will just briefly illustrate as I promised about the Liga process and because, you now it is important way of the Liga is combined with EDM to make many useful features. So, here for example: there are different steps in Liga. So, just like lithography irradiation resist here with the mask here the word IMT is written as a position, which are the black are position which are transplant. This typically means that, position which are black are a transparent are beam transparent and portions which are actual beam. So, there are stopping the x rays beams from going in to the resist. Wherever there is non-exposure, there is the retention of the resist to the IMT gets retained here. And then, you can actual electroform by deposition metal on this particular sort of words formulated.

The micron scale and you can strip off the irradiated resist a and because of that the portions of the resist un irradiated; which is actually here a this is made on the that resist by the by. So, when this gets remove then, you can actually have this IMT structures our features coming out. In this demoulding process and then, you can do secondary the electroforming process also to make a plastic or metal sheet out of it.

So, that is why it is called galvanic that is the forming, which is involved that is the galvanic coating of the material involved using a metal substrate in this case this substrate here actual metal for doing this coating. And then, there is also lithography involved by using high energy x rays beams. So, a this the very good process illustrated by Bleu et al in science reviews some time back this slide was borrowed from this paper actually.

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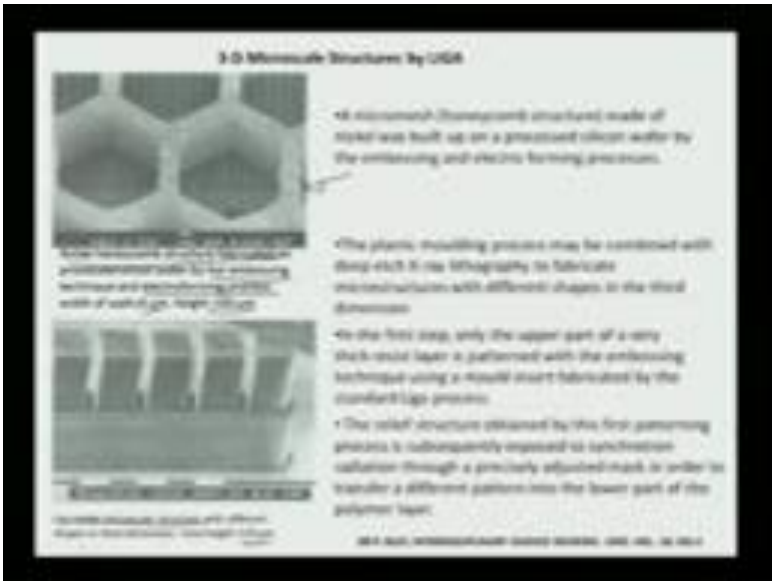

There are lot of application that Liga has to offer is nickel honey comb structures. For example: fabricated on process or Silicon wafer and this has been obtained by the Liga process. Where the initial process of hot embossing, but then nickel electroforming used and the width of walls in this case is about this micro height is above 100 microns. Similarly, these are Liga made nickel microns structures shapes the third dimension. The total height is above close to 520 micros.

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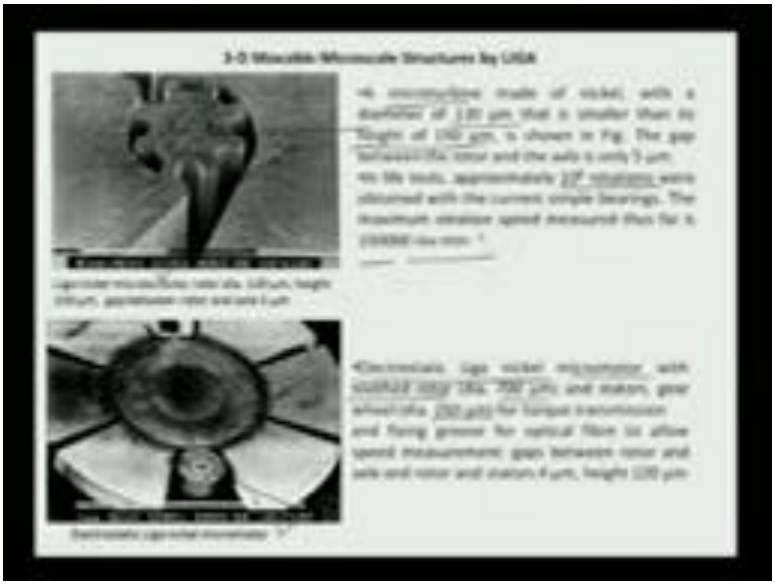

Similarly, a there has been reports made by all about different electro statically made Liga nickel micro motors or micro turbines as can be seen in very clearly in this particularly figures. Where the diameter micro turbine in this case only about 130 micro and the height 150 mm higher than the diameter. So, it is the last then the diameter high aspect ratio structures. If you now if really tests this a turbines it can generate about 10 to the power of 8 rotations.

That is how above the life time this turbines and then, the rotation we can go to very height of the rage of 150000 RPM. So, such is the beauty about this micro machine, micro scale process a with the electrostatic Liga aging you have made the people are reported this micro motor which is made with toothed rotor diameter 700 microns toothed this is the toothed part of a with wheeled I have transmission 250 micro per transmission.

Then, you can actually get the power of the, this motor the this small pioneer wheel and this can rotate very, very higher RPM and this scales on the few microns. So, you can imagine the kind of power RPM ratios that can be obtained at these particular scales.

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Again another very important example Liga has to offer you can make micro channel array to the high aspect ratio of close to 12 a here. These are 3 dimensional micro structures again micro column well array is micro groups with curvatures a some of these microstructures with high aspect ratio of about 30 or more. And then, these are the micro lens array all made with Liga process as report by when at all 2001.

Liga is the really power full tool. So, I am going to now illustrate little bit about a the ECDM process. Because actually, we have talked about high aspect ratio by combining Liga with the EDM and a you now these hybrid process always seen to work better than the normal routine process. And ECDM such process, where the power of both the EDM and ECM are combined 1 go together.

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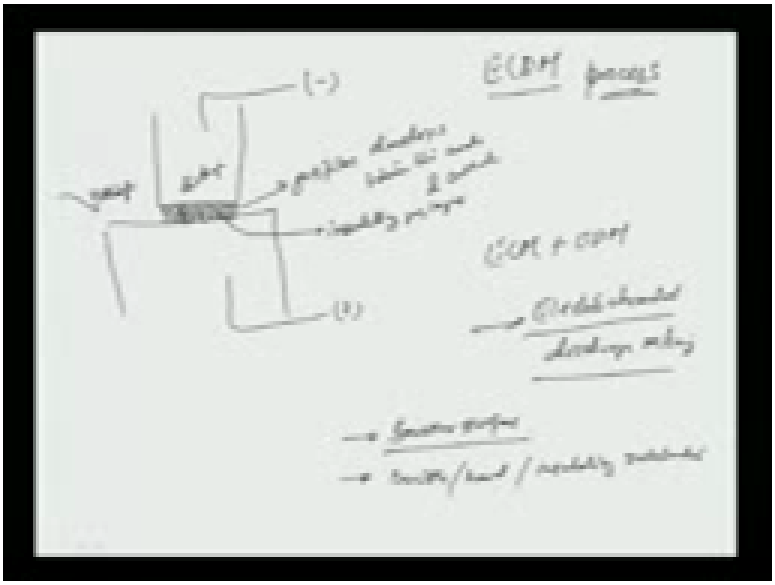

And for that I would like to just illustrate that a you, if this the electrode suppose in ECM operation and there is the work is here close to it. The electrode has you now made the a cathode and the work is piece has made the anode. Suppose, in there is the electrolyte it instead of a dielectric fluid which come into the region which starts the gasification process. So, there is some gas bubbles which are generated close to both the work piece as the result which there is the gas film which develops between the anode and the cathode.

So, this leads to a the formulation of a insulating gas layer I would say and again the concepts of the discharge may come in here as was a illustrated in case of EDM before. So, this where is the discharge which happened because, the breakdown of the you know the electrical breakdown in the gas like EDM. And the film actually gives way to the path of electrons to the current by making the path of electrons a by making the path to the flowing electrons to flow between the cathode and the anode.

Then, it is by thermal ablation that eventually the bulk material is removed, and then if ECM is tell going on in same region there is going to be self leveling activity done by ECM after the EDM operation is done. So, it is the combination of ECM and EDM which is the actually known as electro chemical discharge machine. And this machining

has been able to demonstrate much smoother surface than the EDM our ECM stand alone, not only that done on brittle on hard and insulting substrates also. So, this is the beauty of this ECDM process and I am going to just give a few example were ECM and EDM are combined together.

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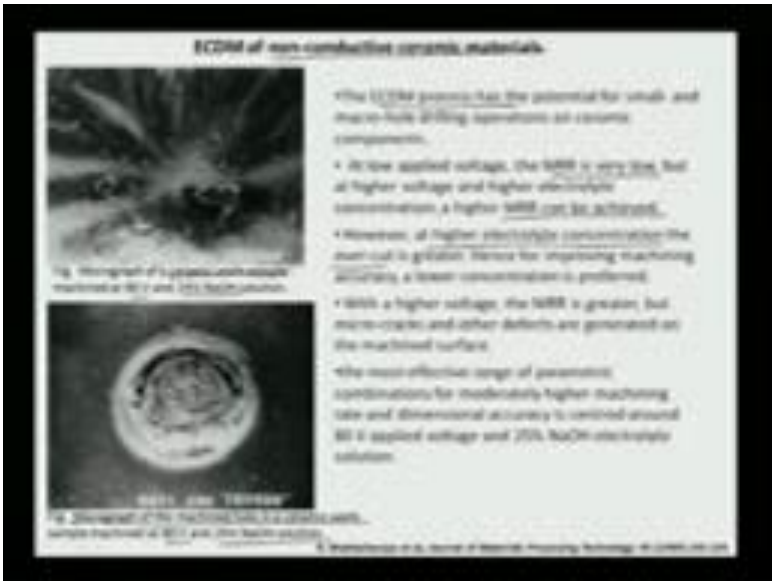

For giving certain you now machining certain non-conducting ceramic materials. For example: in this particular case you can see the ECDM process which has been able to carve out a small complex features in ceramic work sample. And this typically machined that 90 volts a with the solution of Sodium Hydroxide 25 percent. And the although, the MRR is very low high voltage and high electrolyte concentration;

The MRR something which can be achieved probably varying the arrays concentration voltage values and the thing which is important for me to tell here that it the higher electrolyte concentration. There is the increasing over cut in the machine and the accuracy of the machine to surface varies, higher concentration typically, people prefer either medium over concentration of electrolyte in this ECDM case. This again Illustration of is the micrograph of machined hole in ceramic work sample machined at 80 holed 25 percent in a which electro light.

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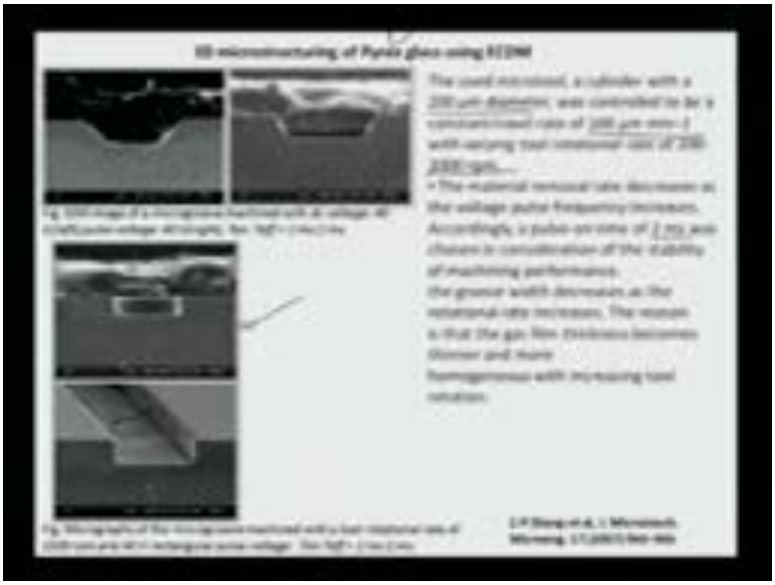

There are some other examples are like of ECDM process where in Pyrex glass people have used ECDM micro milling. So, there is a disc type motion here of a tool which is actually rotated at a very high RPM 200 RPM so. And which actually creates this is discharge machining the chemical, electro chemical discharge machining happed between the substrate and the tool and in this particular illustration you can see some beautiful images of channels being produced of at the CMM images of a channels being produced at a all sometime of roughly about 2 milliseconds.

The tool travels in this case at a constant travel rate of 100 micro meters per minute. So, process is little slow in terms of the ma the machining removal rate etcetera. And the tool diameter in the case of which has been used as the cylinder of about 200 micro meter diameter.

So, I think I am towards the end this lecture and the we have covered more or less is the applications related to ECM, EDM and a combination high break process of a Liga and EDM, as well as ECM, EDM called ECDM. So, in the next module we are going to work more on the process details related to the electro discharge machining operation and try to model the process from a physics point of view.

Thank you.