Advanced Machining Processes
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Week - 07
Lecture - 16
Applications of Machining

Hello, and welcome to this lecture on Microsystems Fabrication by Advanced Manufacturing Processes. A quick review of the previous lecture, we were discussing about electro-stream drilling in great details. I just like to recall that it is a process where there is 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 cathodic effect; a virtual cathodic effect and the workpiece made the anode dissolute and whatever ions come out of the workpiece are not precipitated or that they do not react with any other constituent in the acid electrolyte itself. And so, they are dissolved as ions and therefore, the process does not need any re-flushing because there is typically no nucleation or no particle growth based on electrochemical processes.

So, we looked at how ESD can be used to drill inclined and steep angular holes and cavities. We also talked about the 2 different variants that 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 feed towards the workpiece. 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 micromachining is an absolute need for the several applications in the industry and discussed some of these applications and some research in the area of ECMM or EMM.

Just to recap a little bit, we showed this particular illustration here where with various pulse durations in the nanosecond regime varying between 50 nanoseconds to 2 nanoseconds. We could see how the resolution changed and how the interpenetration distance also changed proportionately. So, in this particular illustration, we used a 0.2 molar HCl pulse amplitude and then we also considered a 2.2-volt voltage with a 10 per cent duty cycle.

And then we also the authors of this particular case tried to also measure the workpiece and the tool voltages, surface potentials and found out a machining speed of 2 millimeters per minute experimentally as well as through modelling approaches. So, what also is important is the spatial resolution and the width of the lateral gap between the tool and the workpiece obtained for different pulse durations that is the gap width is calibrated as a function of pulse duration. And you can see the gap width steadily increases with the pulse duration meaning thereby that more is the duty cycle of the pulse, or more is the duration during which the pulse remains on, the workpiece is subjected to more voltage for greater amount of time and dissolves more. ECMM is also applied in this particular case where ultra-short voltage pulses again are used for obtaining this copper tongue for example, this is an ECMM image of this copper tongue, and this has a thickness of close to about 2.5 microns.

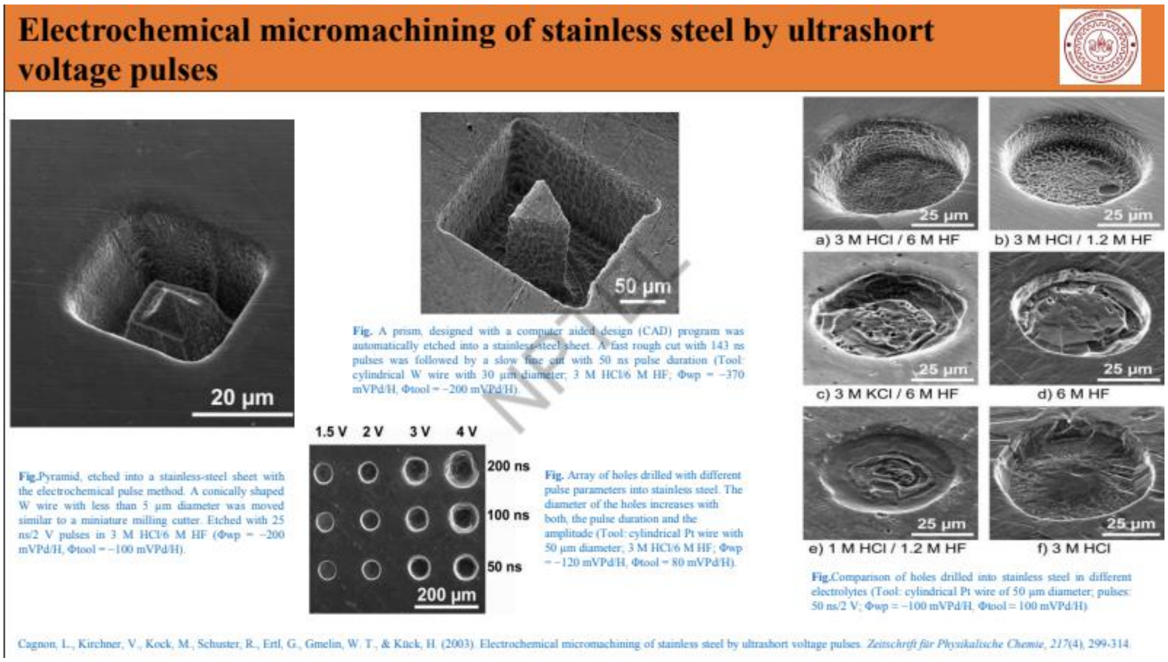
This is how small it is thickness-wise; it is etched by a 2-megahertz sequence of 50 nanosecond pulses of duration of magnitude 1.6 volts. The tool in this case is a 10-micrometer diameter mechanically flattened piece of platinum and it just you know very nicely compares to an ant leg. This here right here is an ant leg, and you can see the scale is almost comparable in the ECMM image which is above and below to each other which shows the typically the process capability of the system. This is a 50-micron scale, this is a 5-micron scale, so about the 10th that is about the comparison.

So, this particular machining process used an electrolyte which was 0.01 molar hydrochloric $HClO_4$ and 0.1 molar $CuSO_4$. The other illustration is given by an in-situ formation of a single hole on a gold substrate by using a voltage pulse of duration 50 nanoseconds again of a 2-volt magnitude. And this is utilizing 1 molar copper sulphate and 0.5 molar sulfuric acid solutions. The hole is formed in the location of the tip during the application of the pulse, and this is represented by the black arrow. The hole formation process, the initiation of the hole formation process has been shown in this particular schematic photograph. And you can see that there are about 3 single copper clusters on gold formed by three 50 nanoseconds and 3-volt 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 is the resolution here, this is being done at a resolution of 10 nanometers which is way beyond what you have seen so far. So, with ultra-short voltage pulses, you can actually write as well as develop tools or electrochemical machining at this particular scale of few tens of nanometers. Some other important features of this is the tunnelling voltage and current. Tunnelling voltage is in the range of minus 300 millivolts and the current is about 1 nanoampere in this particular case. So, that is about how small the ECM process can go and still have a resolution.

So, this resolves very well with one of some of the current high-energy beam processes like FIB, x-ray lithography so on so forth. So, this is another example borrowed from Zhu et al in 2009 where they are talking about a perforated cathode. So, this is a perforated cathode and the anode here is the workpiece 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 workpiece and owing to this particular arrangement the EMM or the electrochemical micromachining is able to drill holes with such fine resolution close to about probably 0.5 mm. Each of this hole must be in the range of few 100 microns I am sure, and this is a blown-up SEM image of the same hole array, and this right here illustrates the cross-sectional shape of a single hole. So, the work material in this case which is made the anode is workpiece which is a chromium alloy 1Cr18Ni9Ti. The thickness of the workpiece is about 0.3 millimeters that is about 300 microns and the cell voltage that you are applying to do this machining here is 18 volts. So, this gives you some feeling of the kind of voltages, resolutions and hole diameters that you can achieve with different workpieces.

Yet another example is borrowed from Laurent group as can be seen in this illustration here.



This was reported in 2003 and this talks about again electrochemical micromachining of stainless steels by ultra-short voltage pulses. The figure here is an SEM image of a pyramid which has been etched into a stainless-steel sheet and again with electrochemical pulse method. It is conically shaped you can see the conical shape right about here in the center and these 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 moving linearly on a surface in this case although it is not a metal-to-metal contact like a typical milling cutter would do with the surface in this case it is an electrochemical machining or electrochemical milling operation which does most of the material removal.

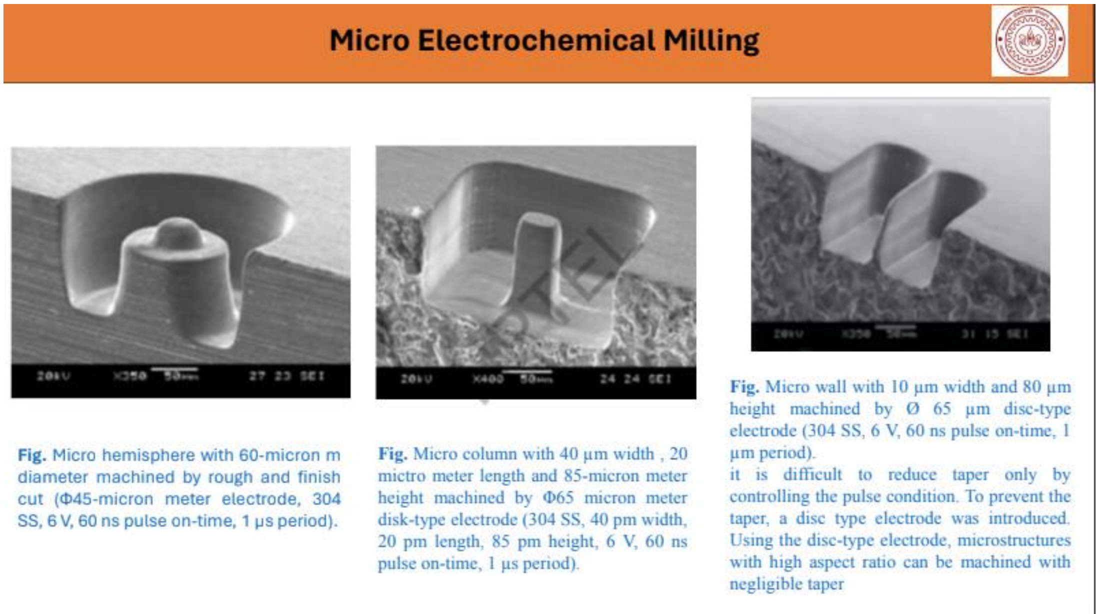
So, it is a dissoluting the material away by a circular tool. So, this moves although it is itself about 0.5 microns it moves along a path here which gives you an illustration of how this cavity was made or realized in a stainless-steel sheet. There was a pulse duration of 25 nanoseconds that this group 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 independent workpiece and tool potentials were measured as minus 200 and minus 100 millivolts respectively with respect to a standard hydrogen electrode.

This again is another illustration of what is the process capability related to ECMM. You can see for a pulse durations varying from 50 nanoseconds to 200 nanoseconds there are different hole diameters of the range of close to about 30 to 50 microns which are obtained at different pulse magnitudes. So, this is an array 4 volts 200 nanoseconds, 3 volts 200 nanoseconds these are the different hole diameters being made the different voltage nanosecond combinations. In this case, the tool was a cylindrical platinum wire and that had a diameter tip diameter of 50 microns and reported values here indicate what kind of electrolyte was used is again HCl hydrofluoric acid combination and the workpiece potential and the tool potential are rated as minus 120 and 80 millivolts with respect to a standard hydrogen electrode. There are 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 molarities of the hydrofluoric acid with respect to the HCl and you can see various surface topologies being generated based on the different electrolytes. So, by large, this happens to be the best combination to do ECMM. So, a process balancing like this has to be made for good machining to happen. Here again, is a very beautiful SEM picture of a prism and this has been designed with a computer-aided program and it was etched in stainless steel, and this was actually done with the faster rough cut of 143 nanosecond pulse duration using ECMM and then there was a slow fine cut of 50 nanosecond pulse duration used in this particular case. The tool in this was again a cylindrical tungsten wire with 30 micrometers diameter.

So, typically the movement here is in a similar manner as happens in most of the computer-driven tools where there is a path geometry which is provided in terms of a CAD file and the XYZ stage is set in a manner. So, that it goes between different coordinate values in a manner that CNC also happens. So, it is a sort of computer numeric control which is, which directs the tool to 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 thereby that this one side alone is close to about 50 microns and the whole depth or the whole width here is about 100 by 100 microns and the depth also it cannot be figured out here in the SEM, but it is actually about 100 microns or so.

So, getting such a feature using non-lithography, non-energy beam techniques is highly cumbersome unless you go for electrochemical micromachining. So, there is some beautiful illustrations of milling, electrochemical milling here. You can see this is borrowed by Kim et al's work published in 2005 where he talks about the fabrication of a micro hemisphere with about 60 micrometer diameter machined by a rough as well as finish cuts. The electrode used here is about 45-micron diameter electrode, it is a wire and the material that you are using of the electrode is stainless steel 304 and basically using a 6-volt 60 nanosecond pulse on time duration for a 1-microsecond period to achieve this particular feature right here. Beautiful again micro feature illustrated on stainless steel.



Similarly, this again is another example where a microcolumn has been with the width of 40 microns and 20-micron length and 85-micron height. So, very high aspect ratio has been machined by again a 65-micrometre disc-type electrode and this is again an example of milling where the electrode is rotated because of which there is machining taking place at this nanometric level. So, use a 304 SS stainless steel electrode in this case with 60-volt 60 nanosecond pulse on time duration and for a 1-microsecond period. This another is an illustration of a micro wall with 10-micron width. So, this is about close to 10 microns and 80 micron height which is this height right here machined by a 65 micrometer diameter disc type electrode again using the same material 304 stainless steel with 6 volt 60 nanosecond pulse on time duration for a 1 microsecond period.

So, one aspect which is a learning experience from this particular work is that it is very difficult to reduce the taper only by controlling the pulse condition and because electrochemical machining as I think I have illustrated many times earlier is a self-tapering process. And so, typically a better idea would be to use a disc type of electrode which in this case they have used Kim et al has used. And you can actually have high aspect ratio of your microstructures if the milling tool is disc shaped. So, again some very nice illustrations of ECM. So, let us now look at a little bit different process EDM and 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 modelling and the process details later.

But in from an application standpoint, ECM is combined with this EDM process to formulate a hybrid-making machining strategy which is called ECDM that is electrochemical discharge machining. So, you must understand the basic principles etcetera here and some application standpoint what EDM does and how ECDM would be different from ECM or ECDM EDM. So, that is the reason for using this right here. So, just a brief summary of what this process is about. So, there is an electrode which is mobile in nature, and it is basically the cathode and the workpiece is made the anode here and instead of putting an electrochemical or instead of putting an electrolyte here or an electrochemical agent here, you put an insulating dielectric fluid.

Electrical-Discharge Machining

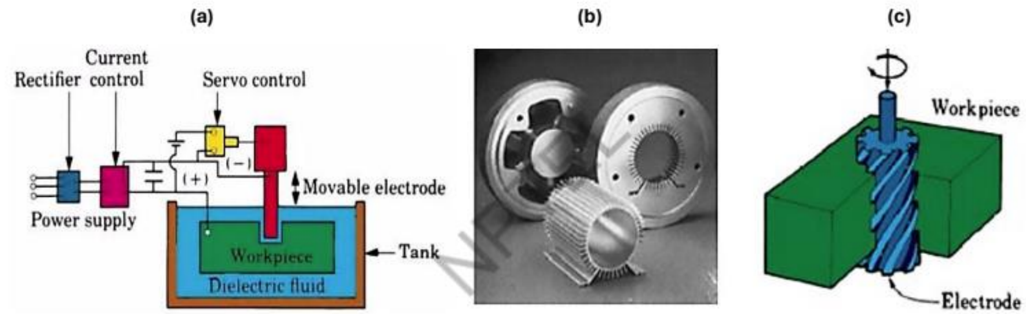


Fig. (a) Schematic illustration of the electrical-discharge machining process. This is one of the most widely used machining processes, particularly for die-sinking operations. (b) Examples of cavities produced by the electrical-discharge machining process, using shaped electrodes. Two round parts (rear) are the set of dies for extruding the aluminum the aluminum piece shown in front. (c) A spiral cavity produced by ECM using a slowly rotating electrode, similar to a screw thread.

And the advantage of a dielectric fluid is that it provides a path between the tool and the workpiece right about in this particular gap which is non-conducting in nature. So, as this path is non-conducting and you keep on charging this potential to a higher negative potential, there is a tendency that the medium which is very small in this case which is an insulating medium breaks down and there is a discharge which happens because of the charge difference from the cathode in this particular case. So, a discharge is typically a momentary stream of electrons which is released by the cathode, and they are driven by the field and the positive potential of the anode, and they are accelerated and then in this condition they hit upon the workpiece which leads to the discharge of the it leads to a situation where this discharge creates an ablation or a thermally ablated zone with a melt pool. And as the electron pressure reduces on the surface there is a tendency of cavitation to happen because the medium itself is not so fast as the electron velocity and it has high inertia and so it takes some time for the medium to come back into that portion. And so, for a momentary instant, there is a creation of a low-pressure zone which creates the pull 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 electrochemical machining. I am going to give this details of the modelling process etcetera in later on lectures. But here from a standpoint of what EDM can do you can look at some of the components high aspect ratio systems you know examples here are for example, you can have these 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 the set of dies for extruding the aluminum the aluminum piece is shown in the front. So, this is the piece, and this is the die these are the dyes which are used for extruding this particular piece.

So, such examples are very commonplace where EDM is used for these applications. This for example, is another illustration where there is a workpiece made the anode and the electrode made the cathode and there is a spiral cavity being produced by either ECM or EDM type of operations. So, having said that a slight variant of this process is found in very commonplace 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.

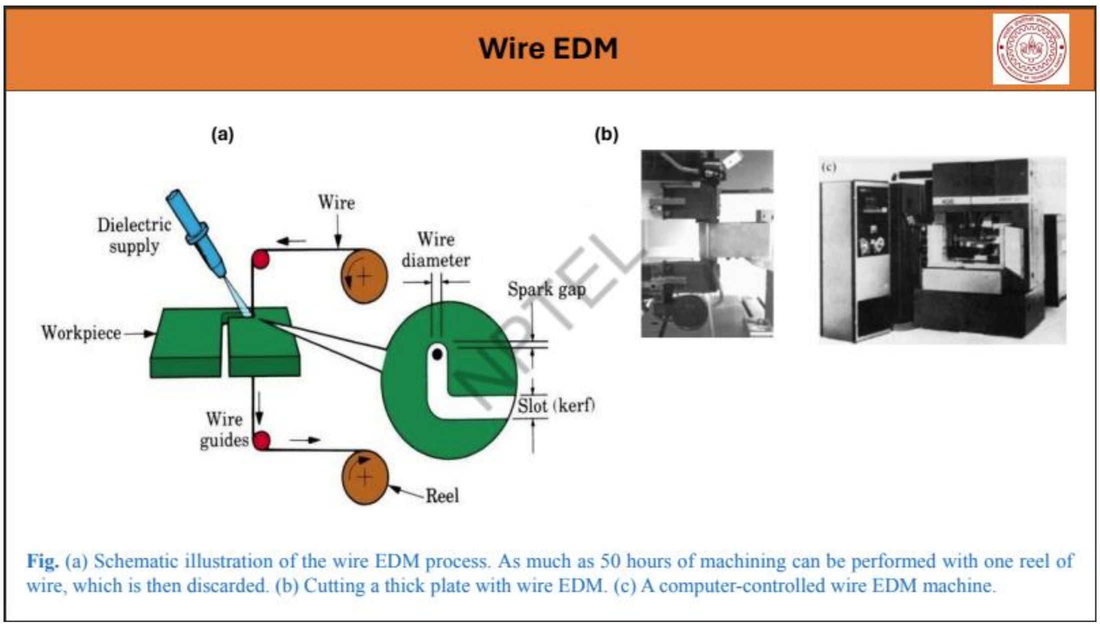
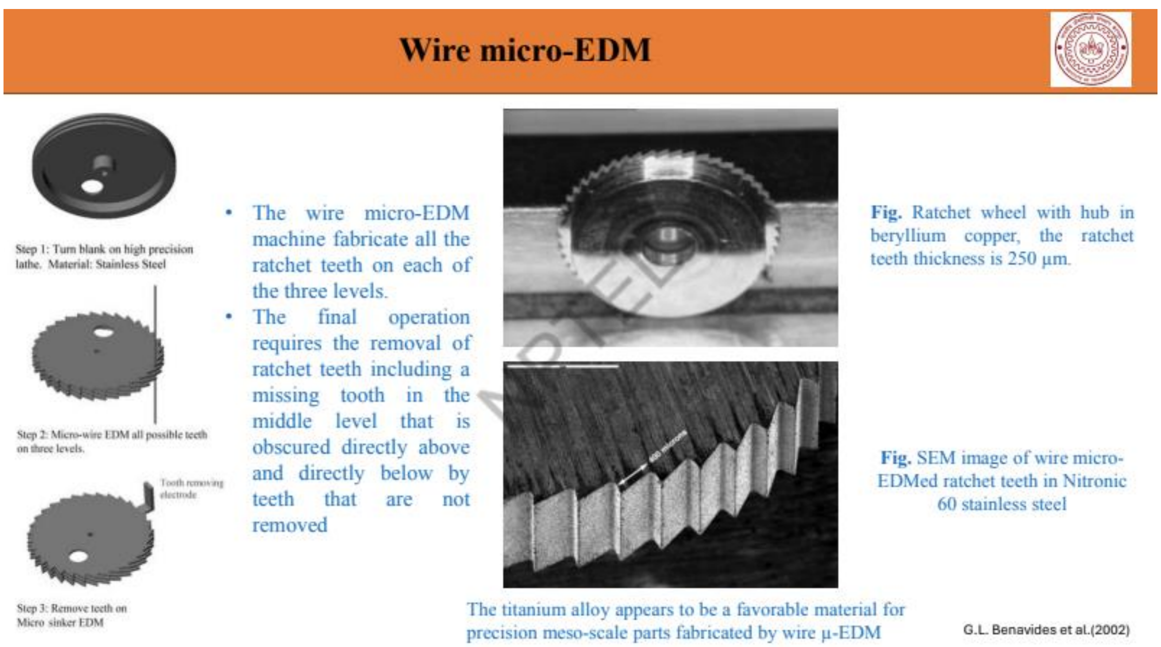


Fig. (a) Schematic illustration of the wire EDM process. As much as 50 hours of machining can be performed with one reel of wire, which is then discarded. (b) Cutting a thick plate with wire EDM. (c) A computer-controlled wire EDM machine.

So, essentially what it means is that you have a coordinate layout which is there and then between the coordinates, there is movement of the particular tool and that creates its machining effect on the workpiece. In this particular case, there is a workpiece which is made the anode. So, the workpiece is made the anode and there is a supply dielectric supply, supply of dielectric fluid insulating fluid in the work zone and there is a wire, and this wire is normally made the cathode. So, the wire actually is fed from a roll you can see between this roll here and this roll here the wire is being fed and as the wire slowly emanates out it there is a discharge which happens between the wire the cathode and the workpiece anode and wherever the wire moves. So, this slot right here is an L slot which is otherwise seen in the top view.

So, the wire actually the motion of the wire path would be first in this direction and then in this direction. So, the wire comes all the way into this and then goes like this and wherever the wire proceeds there is a arcing because of which is this complex L slot depending on the path of the guide of the wire would formulate on the workpiece. So, this is a very interesting high-capability process which is used in the domain of advanced manufacturing processes for doing extremely complex shapes and features. And I just like to 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 the 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 precision motions of the stage itself.

So, the stage needs to be very fine-tuned. So, this is how a wire cut EDM system looks like in the laboratory. This right here is that wire and it is passed between the rolls, 1 roll can be seen here the other roll is probably out of the picture. And there is a way to mount the workpiece in this particular case which gives the basis of EDM. So, let us now look at some of the micro structuring being done by wire micro EDM operations. So, some very nice illustrations by Benavides group in 2002 where he talks about the creation of a small ratchet wheel with diameter of with the teeth thickness of about close to 250 microns in beryllium copper.



So, the way to make it is that they take a blank and then turn the 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 operations like drilling etcetera, these mounting holes or the center mounting of these blank is being formulated. Once this is formulated, they use a wire here, this right here is a wire between the 2 tick marks, and they perform a micro wire EDM on of all possible teeth at the 3 levels of this blank. The blanks are cut into 3 different levels as can be illustrated here. And 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 of cleaves it diametrically. So, the electrode goes all the way to the other side here and cleaves it diametrically. So, that 3 pieces can be realized which are independent discs with micro gearing cut on each of them. So, the wire micro EDM machine fabricates all the ratchet teeth on each of the 3 levels and the final operation requires the removal of the ratchet teeth including a missing tooth in the middle level that is obscured directly above and directly below by teeth that are not removed.

So, this right here shows a detailed view, a same image of the wire micro EDM ratchet teeth structure, and this is in Nitronic 60 stainless steel. And they have also done it for titanium alloys, and they have seen that the process is quite favorable for titanium, machining titanium alloys also by micro wire EDM. So, this is a very highly capable process now for doing this micro features and structures. So, you can imagine the ratchet teeth thickness of 250 means, this one section here is only 250 micrometer thick and there are 3 such sections and different levels of this particular mechanism. So, this is one very fine example of what CNC wire cut EDM can do apart from that there are many other applications of the micro EDM process.

One 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 being made by the whole machining is being made by a micro EDM operation, use a radius of this cylindrical cavity of the extent of about 200 microns and the depth of this cavity is about 100 microns. So, and if you look at the pyramid structure, the pyramid is about 120 micron tall, and it is a square pyramid. So, each side of the square is about 60 microns, 60 microns. So, this comments highly about the way that EDM or the capability process capability of EDM to do 3D micro-structured architectures or parts.

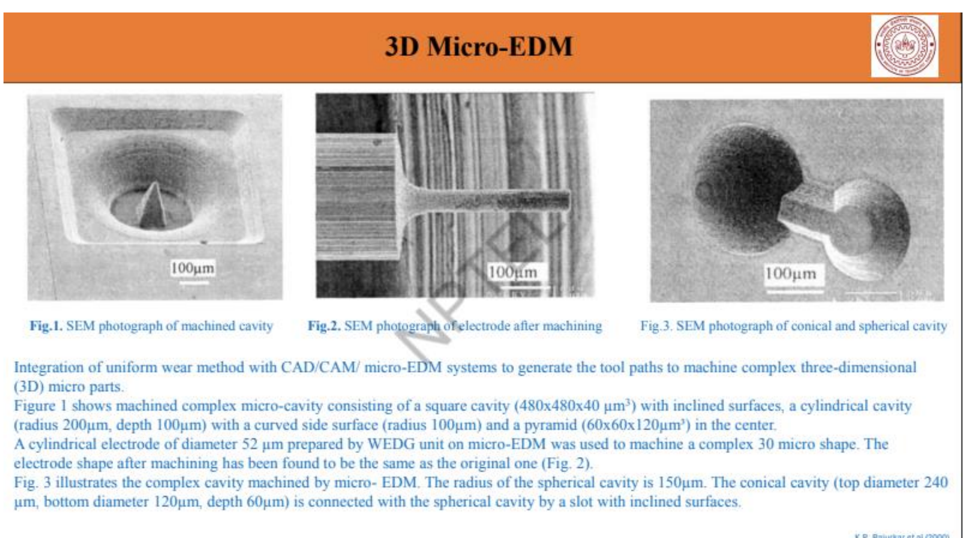
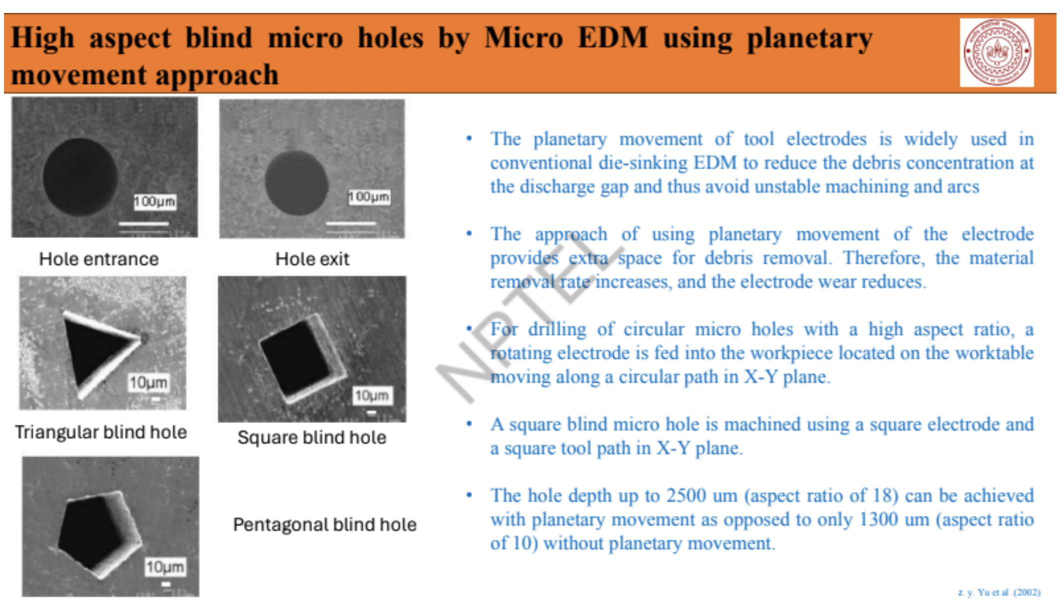


Figure 2 again is an electrode, a circular electrode, the same image of a circular electrode and this tip size here must be close to about probably 10 of, 10 of microns. So, this is doable again using a micro EDM process. This cylindrical electrode was prepared by you know a wire-assisted electro-discharge grinding unit, the electro-discharge machining process. And I think I had illustrated further earlier that with another kind of an identical wire-assisted ECM process, we had produced about 2 microns of tip size. In this particular case, although the tip size is slightly higher it is about 5.2 micrometer, but it still is a very high improvement over the other machining processes which exist. Figure 3 here illustrates a complex cavity machined by again a micro EDM tool, the radius of the spherical cavity in this particular region is about 150 micrometer. The conical cavity is 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 one case probably this part is through a die sinking operation where the tool is a negative replica of this or it is a cavity.

And in this particular case, the tool is a projection coming out of the tool surface they can be done parallelly on a surface. So, that is the capability of producing a 3 dimensional structured, highly structured surface of at the microscopic length scale. And such kind of operations demonstrate the capability of the micro EDM process, micro electro-discharge machining process. Another you know aspect of EDM reported by Yu et al. in 2002 which talks about a high aspect ratio blind micro hole kind of structures.

These are the micro hole structures, and the holes can be either triangular holes or square holes or even pentagonal holes depending on the electrode that is being used. And this is using planetary movement approach of the tool.



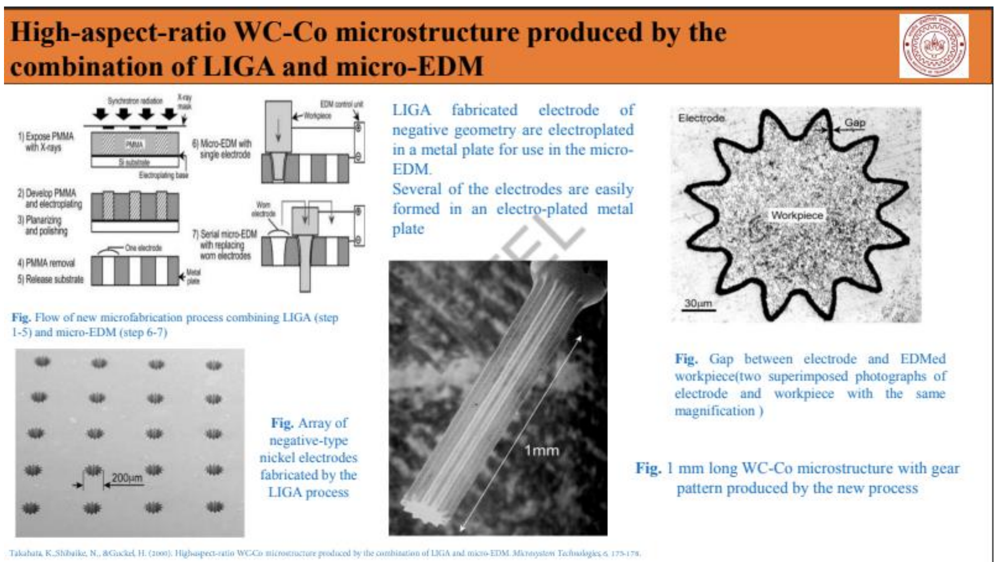
So, the planetary movement is in this case basically smaller electrode moving or following across the hole the internal contour of the hole. So, the planetary movement of the tool electrode is widely used in this conventional die sinking EDM process. And one of the reasons why that is used is to give a sufficient gap for debris removal would take place. And so, the machining is always stable because of non-accumulation of the debris at 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 of a rotating electrode is put inside the tool. So, a similar kind of machining cannot be done if the holes concerned have non-circular cross-sections. For example, in this case, it is a triangular hole or a square hole, but in that event, a square blind micro hole can be machined by using a square electrode.

So, you just develop an electrode which is very close to this. And maybe 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 tool which was following a circular path and even you could have rotated the tool while following it. The square tool can also follow a square path and that would give you a very good machining operation. 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 are different strategies that now people use for doing this micro idiom with planetary movement or planetary motion. In fact, all these holes are to the depth of about 2500 micrometers. And in fact, if you look at one of these edges here or for example, this particular edge they must be close to if this is 10 microns this must be close to about 130 or 140 microns. So, having said that a very good aspect ratio of the order of about close to 18 or so is generated using this kind of a process. So, it is actually a very good and capable process for doing high aspect ratio structures at the micron scale.

So, if you had no planetary movement for example, if this same process would have been produced by a normal electrode of the same size as the hole etcetera. The aspect ratio would then come to about close to 10. So, in a way, it illustrates what the planetary motion does in terms of debris removal where the activity can be prolonged over a higher amount of depth. So, that the actual ratio can increase accordingly. So, in 3D micromachining particularly when we are talking about large aspect ratio structures definitely the planetary idiom, micro idiom is a very good strategy to manufacture at this particular scale of the length.

So, let us look at some more examples and when just because we are talking about aspect ratio, I would recall the LIGA process which we had discussed earlier while doing the microfabrication. And this LIGA process basically means lithography, galvanofurmung, abformung. And there is a detailed step of the LIGA process probably in the 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 idiom is being performed by combining it with the LIGA process. So, as you can see here there are various steps just like lithography you have a PMMA layer which is exposed to 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 first step what happens is that this mask is realized using either laser patterning or some other method with which this is 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 something like close to 200 microns. And they are distantly placed away from each other by close to about 1 millimeters or so. So, you take a resist PMMA and using X-ray lithography why we need X-ray lithography is because X-rays are typically high-energy radiations, and they can go up to a larger depth within the PMMA material. So, in this case, it is needed that the depth up to which the internal gearing should go on that layer is about 300 microns or so.

So, that is why it is needed. So, you take a mask and expose the PMMA selectively. So, you are exposing the PMMA selectively here and you are exposing up to you know a height or a depth of about 300 microns of diameters of internal gearings which are only 200 microns in nature. So, it is the aspect ratio is about 1.5 in this particular case.

Now, the PMMA is changed as soon as it gets exposed to certain regions. So, supposing if you were to expose this region which now you can see converted as this hatched area in this particular case, the structure, the properties of PMMA here has changed. And you can develop these PMMA, exposed PMMA out very well using some kind of a developing solution etc. And so, therefore, there are these crevices which has formulated on the PMMA itself. So, you can actually do electroplating of this cavities and then after electroplating you can planarize and polish on both sides. So, you are left with only those features which have been embedded inside the PMMA as electroplated features.

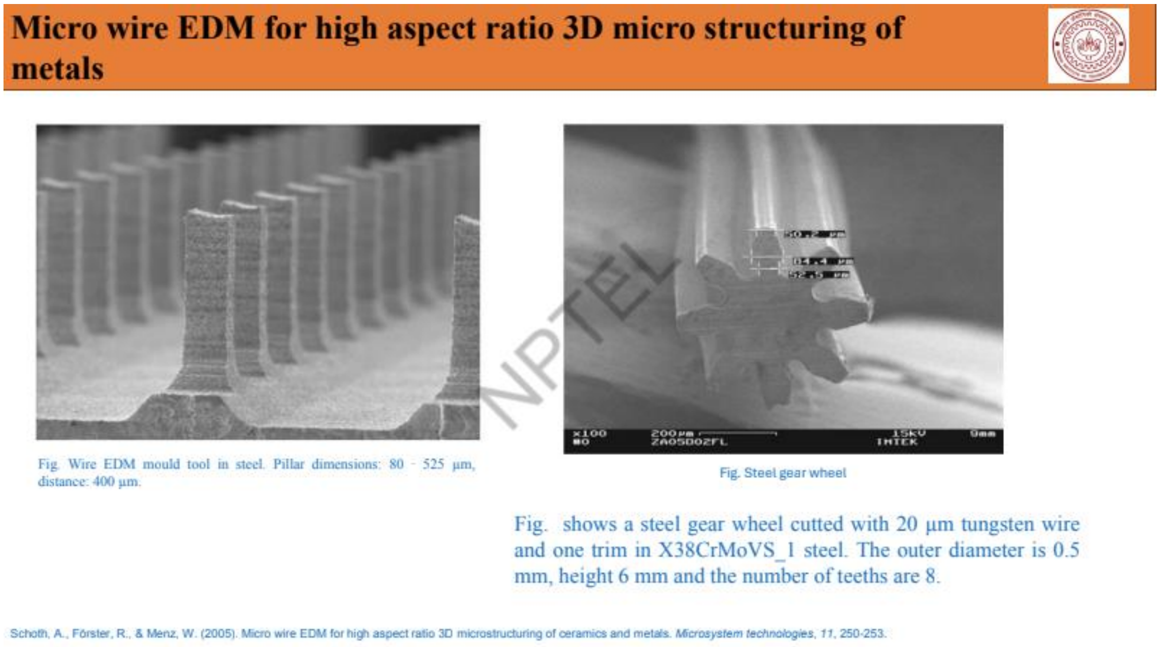
And the electroplating is done using this substrate here which is a conducting substrate that you should always remember conducting substrate. And there is always a deposition of platinum along the crevice which has been created here of 300 microns. So, it is all deposited along this whole crevice as well as on the conducting substrate here. The substrate is later on removed as in this particular case you can see the substrate is actually has been removed and the conducting substrate is gone from here. And you have now cavities like illustrated here open on both ends which can be used for further machining.

So, now the advantage here is that these cavities are already pre-coated with platinum. So, they are pre-coated with platinum, they are platinized, and they are like metallic in nature. So, they can be made in an electrode. So, typically in this case if you want to do EDM operation this is made the cathode. And the workpiece in this case has a size which is close to the hole that can be seen here and the workpiece is made the anode.

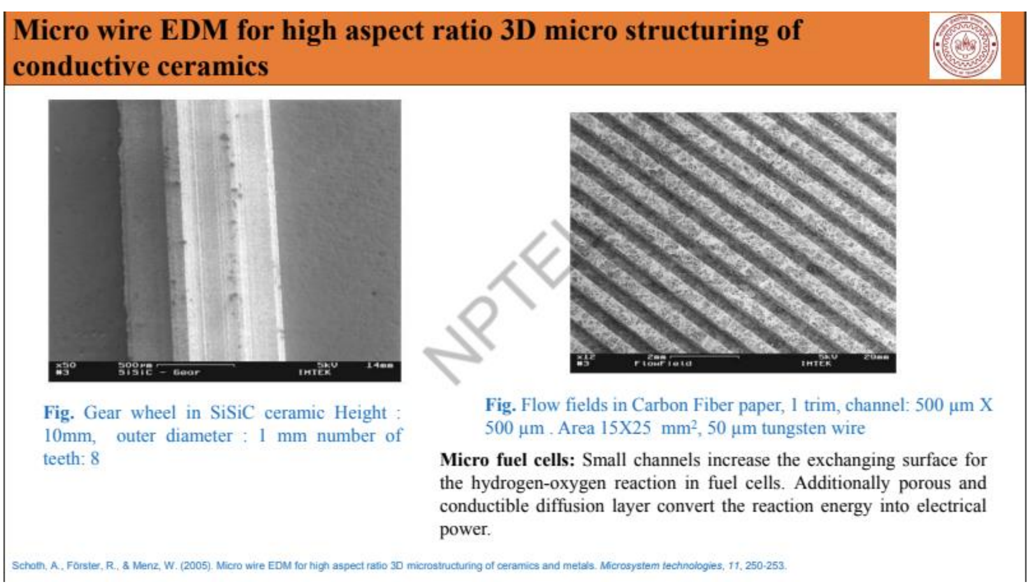
So, this workpiece is positive and this is the cathode negative. And so, the workpiece which was otherwise the cylinder is now cut into a gear which is SEM image of which is shown here. So, this is the micro EDM workpiece. The advantage in this case and finally, the cross-sectional area of this electrode looks as beautiful as this where you have to ensure that a gap of about 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. So, with the CNC control, you can do that kind of a feed rate of this micro gearing into this particular structure.

So, this is about the capability of high aspect ratio microstructures in combination with various processes like LIGA etc. These are some other examples again you know you can see how high aspect ratio structures can be developed by micro wire EDM using the same concept of LIGA plus EDM as has been illustrated before. These are pillars of dimensions 80 to 525 microns in length scale. So, 80 microns is the breadth, or the thickness of the pillars and the 525 microns is the depth of the pillars, and these pillars are being printed at 400-micron depth. So, they are very high aspect ratio structures which can only be obtained through this specialized process.

This again is a steel gear assembly. It is a steel gear wheel cut with 20-micron tungsten wire and this is with 1 trim using the CNC wire cut process EDM process as had been illustrated earlier. And the gear wheel has only an outer diameter of only about 500 microns. So, that is how small this gear is and a height of about 6 mm. So, you can think of the high aspect ratio that is involved in this kind of a structure and you can see the number of teeth in this particular case is 8.

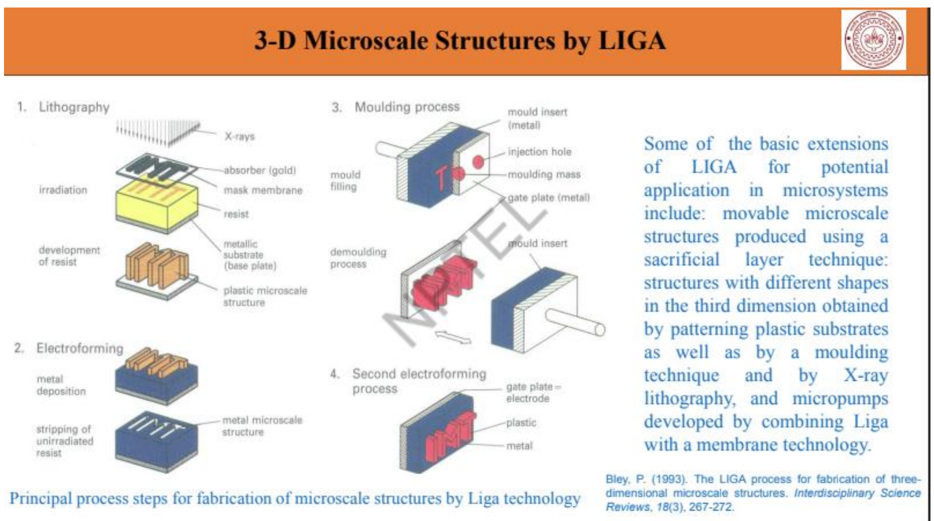


So, there are about 8 teeth made in this gearing. So, such is the power of this 3D, novel 3D micro structuring process. Again, another very good example of again a ceramic gear wheel. The height is 10 mm, and the OD is about 1 mm. Number of teeth are 8 in this particular case. Again, in for micro fuel cell applications, Schoth et al. has shown very small channels with increased exchanging surface for hydrogen-oxygen reaction to take place in fuel cells.



And so, this illustrates a carbon paper fiber micro fuel cell, and the channel sizes are about close to 500 microns, area is only 15 to 25 mm square. The tungsten wire that is used in this application is only about 500 micrometers diameter. So, that is again another very good illustration of what micro-wire EDM can do. I will just briefly illustrate as I promised the LIGA process and because you know it is important in a way that LIGA is combined with EDM to make many useful features.

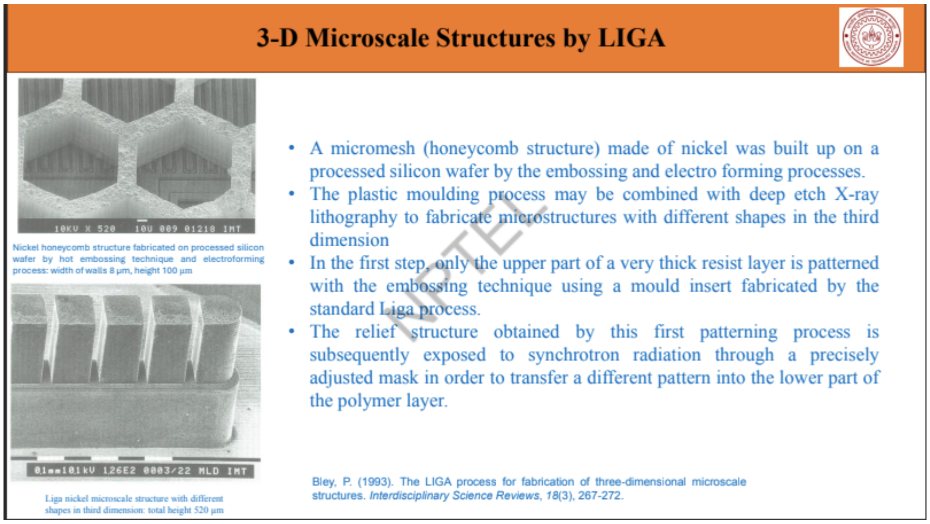
So, here, for example, there are different steps in a LIGA. So, just like lithography, you irradiate the resist here with the mask here the word IMT is written as portions which are black and portions which are transparent. This typically means that the portions which are blank are or transparent are beam transparent and the portions which are indicated as black are actually beam opaque. So, they are stopping the X-ray beams from going into the resist. So, wherever there is non-exposure there is a retention of the resist. So, the IMT gets retained here and then you can actually electroform by depositing metal on this particular set of words formulated at the micron scale.



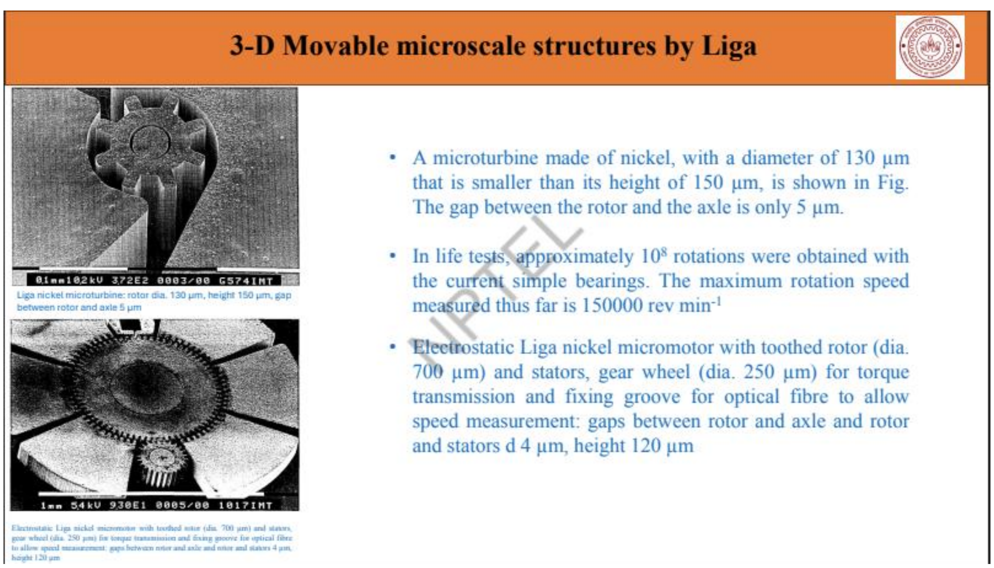
And then you can strip off the unirradiated resist and because of that the portion of the resist which has not been irradiated which is actually here this is made on that resist by the by. So, when this gets removed then you can actually have these IMT structures or features coming out in this demolding process. And then you can do a secondary electroforming process also to make plastic or metal sheets out of it. So, that is why it is called galvanoformung, abformung. So, there is a forming which is involved, there is a galvanic coating of the material which is involved using a metal substrate.

In this case, this substrate here is actually metal for doing this coating and then there is also lithography involved by using high-energy X-ray beams. So, this is a very good process illustrated by Bley et al in-science reviews some time back. This slide has been borrowed from his paper actually. And there are lot of applications that LIGA has to offer. This is a nickel honeycomb structure for example, fabricated on processed silicon wafer and this has been obtained by again LIGA process where the initial process was hot embossing driven, but then later on electroforming was used.

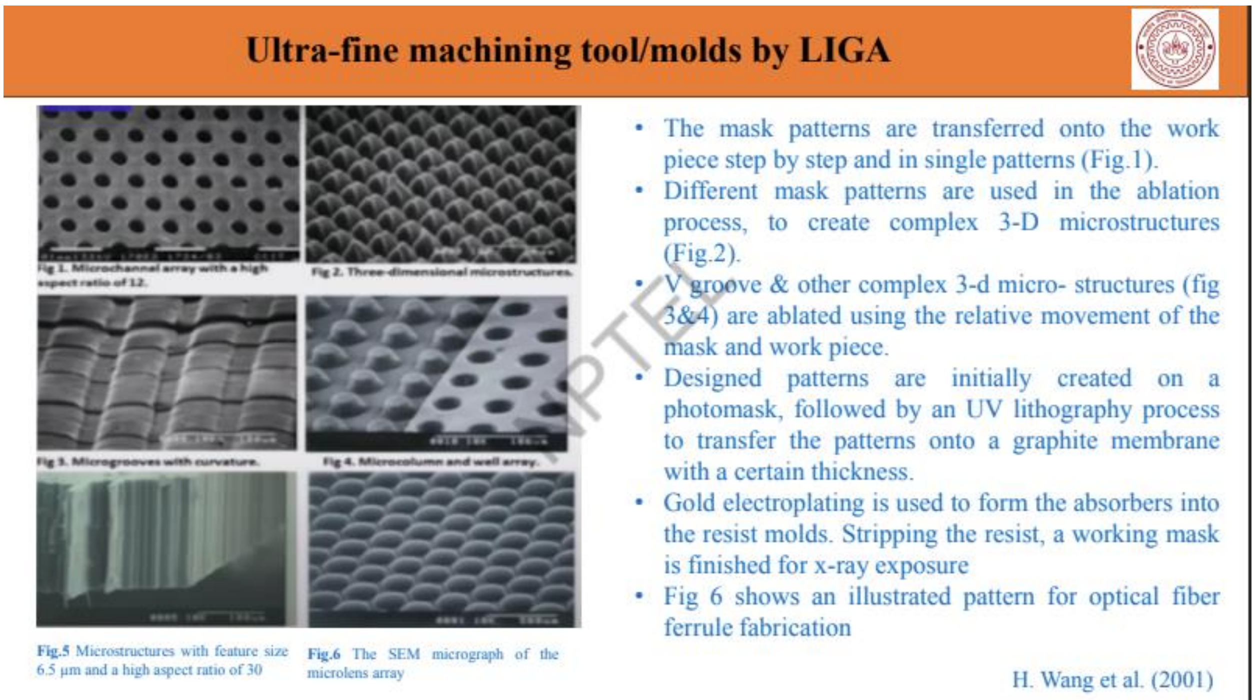
And the width of the walls in this case are about 8 microns, height is about 100 microns. Similarly, these are LIGA-made nickel microscale structures with different shapes in the third dimension, the total height is about close to 520 microns.



Similarly, there has been reports made by Bley et al about different electrostatically made LIGA nickel micro motors or microturbines as can be seen very clearly in these particular figures where the diameter of the microturbine, in this case, is only about 130 microns and the height is about 150 microns higher than the diameter. So, it is a large diameter high aspect ratio structure. And you know if you really test this turbine it can generate about 10 to the power of 8 rotations. So, how about the lifetime is of this turbine and the revolution that it can go up to is very high of the range of about 150,000 rpm.



So, such is the beauty about these micromachined micro-scale processes. With electrostatic LIGA again you have made the people have reported this micro motor which is made with a 2-3rd rotor of diameter 700 microns and stators this is the stator part with the wheel dia of approximately 250 microns for torque transmission. And you can actually get the power of this motor through this small pinion wheel, and this can rotate at a very-very high rpm and the scale only is few microns. So, you can imagine the kind of power rpm ratios that can be obtained at this particular scale. So, another very important example that LIGA has to offer you can make microchannel arrays with a high aspect ratio of close to 12. Here there is these are 3-dimensional microstructures again micro column array and well arrays microgrooves with curvatures some of these microstructures with high aspect ratios of about 30 or more and then these are the microlens arrays all made with LIGA processes as reported by Wang et al in 2001.



So, LIGA really is a very powerful tool. So, I am going to now illustrate a little bit about the ECDM process because naturally we have talked about high aspect ratio by combining LIGA with EDM and you know these hybrid processes always seem to work better than the normal routine processes and ECDM is such a process where the power of both the EDM and ECM are combined in one go together and for that, I would like to just illustrate that you know if this is the electrode supposing in a ECM operation and there is a workpiece here close to it and the electrode as you know is made the cathode and the workpiece is made the anode and supposing there is an electrolyte instead of a dielectric fluid which comes into this region which starts the gasification process. So, there is some gas bubbles which are generated close to both the workpieces as a result of which there is a gas film which develops between the anode and the cathode. So, this leads to the formulation of a insulating gas layer I would say and again the concept of discharge may come in here as was illustrated in case of EDM before. So, there is a discharge which happens because the breakdown of the you know the electrical breakdown of the gas like medium and the film actually gives way to a path of an electrons to the current by making a path of electrons by making a path to the flowing electrons to flow between the cathode and the anode and it is by thermal ablation that eventually the bulk material is removed and then if ECM is still going on in the same region there is going to be a self-levelling activity done by ECM after the EDM operation is done. So, it is a combination of ECM and EDM which is actually known as electrochemical discharge machining and this machining has been able to demonstrate a much smoother surface than normally the EDM or ECM stand alone and not only that this can be done on brittle and hard and insulating substrates also.

ECDM of non-conductive ceramic materials

Fig. Micrograph of a ceramic work sample machined at 90 V and 25% NaOH solution.

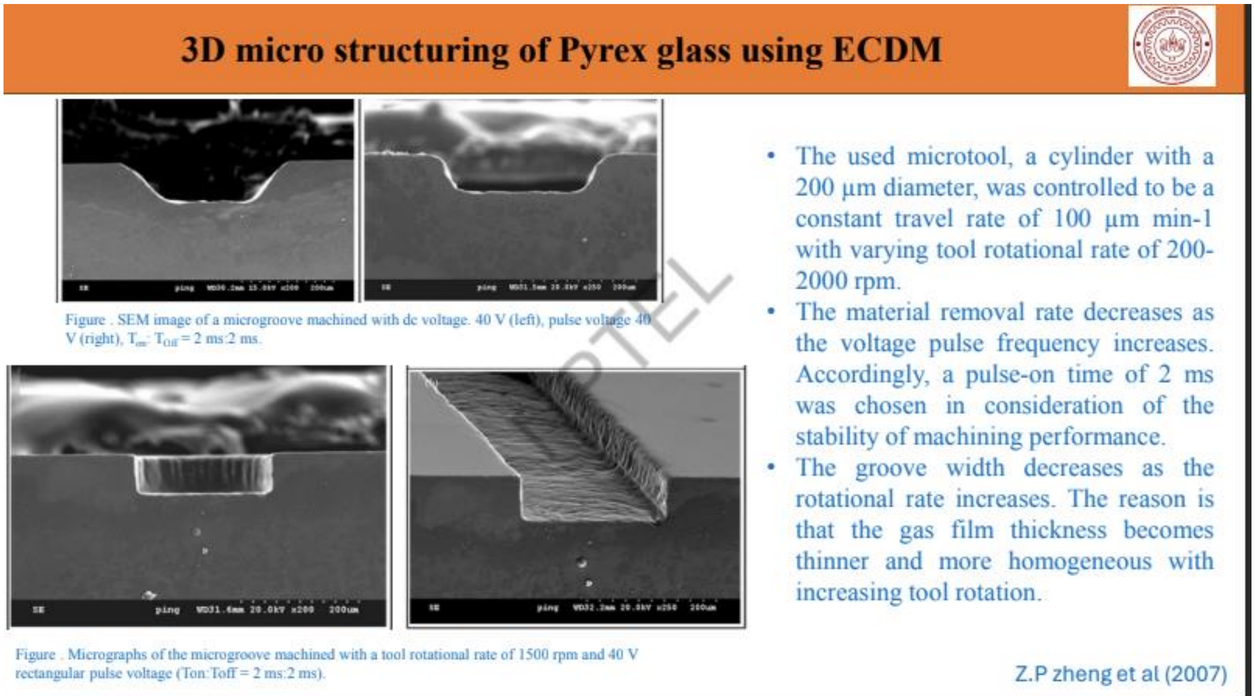
Fig. Micrograph of the machined hole in a ceramic work sample machined at 80 V and 25% NaOH solution

- The ECDM process has the potential for small- and macro-hole drilling operations on ceramic components.
- At low applied voltage, the MRR is very low, but at higher voltage and higher electrolyte concentration, a higher MRR can be achieved.
- However, at higher electrolyte concentration the over-cut is greater. Hence for improving machining accuracy, a lower concentration is preferred.
- With a higher voltage, the MRR is greater, but micro-cracks and other defects are generated on the machined surface.
- The most effective range of parametric combinations for moderately higher machining rate and dimensional accuracy is centred around 80 V applied voltage and 25% NaOH electrolyte solution.

Bhattacharyya, B., Doloi, B. N., & Sorkhel, S. K. (1999). Experimental investigations into electrochemical discharge machining (ECDM) of non-conductive ceramic materials. *Journal of Materials Processing Technology*, 95(1-3), 145-154

So, this is the beauty of this ECDM process, and I am going to just give a few examples where ECM and EDM are combined together for giving certain you know machining certain non-conducting ceramic materials. For example, in this particular case, you can see there is a ECDM process which has been able to carve out a small complex feature in a ceramic work sample and this typically is machined at 90 volts with a solution of sodium hydroxide 25 percent and although the MRR is very low at high voltage and high electrolyte concentration MRR is something which can be achieved probably by varying the various concentration voltage values. And the thing which is important for me to tell here is that at a higher electrolyte concentration, there is an increasing overcut in the machine and the accuracy of the machined surface varies at a higher concentration. So, typically people prefer either medium or lower concentrations of electrolytes in this ECDM case. This again is an illustration of it is a micrograph of a machined hole in a ceramic work sample machined at 80 volts 25 percent NaOH electrolyte.

There are some other examples alike of ECDM processes 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 or so and which actually creates this discharge machining the chemical electrochemical discharge machining happen between the substrate and the tool. And in this particular illustration, you can see some beautiful images of channels being produced of at the SEM images of channels being produced at a pulse on time of roughly about 2 milliseconds. And the tool travels in this case at a constant travel rate of 100 micrometers per minute.



So, the process is little slow in terms of the yield of the machining removal rate etcetera. And the tool diameter in this case which has been used is a cylinder of about 200 micrometer diameter. So, I think I am towards the end of this lecture, and we have covered more or less the applications related to ECM, EDM and a combination hybrid process of a ligand 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.