Microsystems Fabrication with Advanced manufacturing Techniques
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Lecture - 19

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Hello and welcome to this nineteenth lecture on Microsystems fabrication by advanced manufacturing processes.

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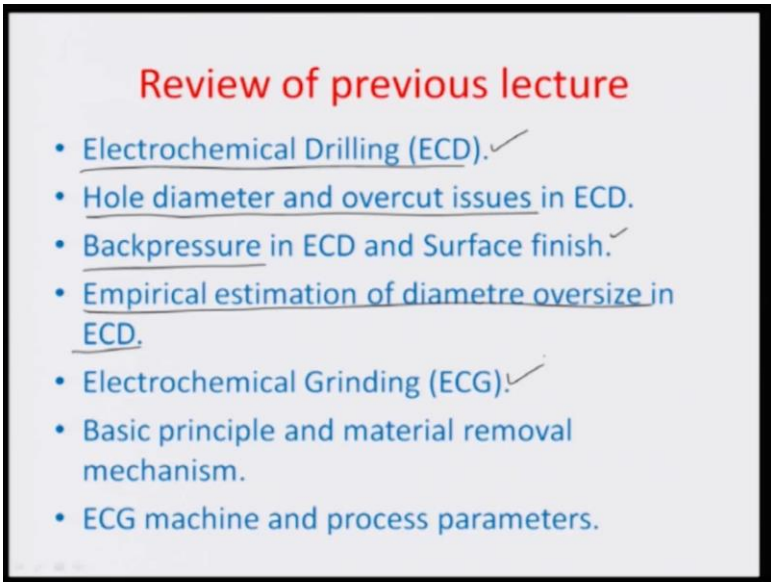

Just quick recap of what we tried to do last lecture. We talked about various electrochemical machining processes like; electrochemical drilling, where there was a concentric discharge of the electrolyte, from the center of the tool. And then we talked about various associated problems related to hole diameter and overcut size in the ECD process as it is commonly known. We also discussed about back pressure issues in ECD and the associated surface finish based on that; we had illustrated that as the back pressure increases, there is a increasing there is a tendency of the surface finish to be better. They would be lesser flow lines because of increased in increase in back pressure in the ECD process.

We also tried to empirically tried, estimating the diameter oversize in such ECD machining processes. Finally, did the other associated process; electrochemical grinding, where most of the material about 90 percent or so, was found to be removed by electrochemical dissolution and about 10 percent material would get removed by physical abrasion. 1 of the reasons why ECD wheels are always higher life and process is an advantage over mechanical abrasion in the sense that, there is a self smoothening effect because of the electrochemistry, which is involved in desolating the whatever layers are ablated from the surface.

We also talked about the basic principles of material removal and the mechanisms involved there in the ECG process and then tried to have a detailed overview of the ECG machine and different process parameters. Today we are going to do another associated process to begin with, in electrochemical machining which is called electro stream drilling.

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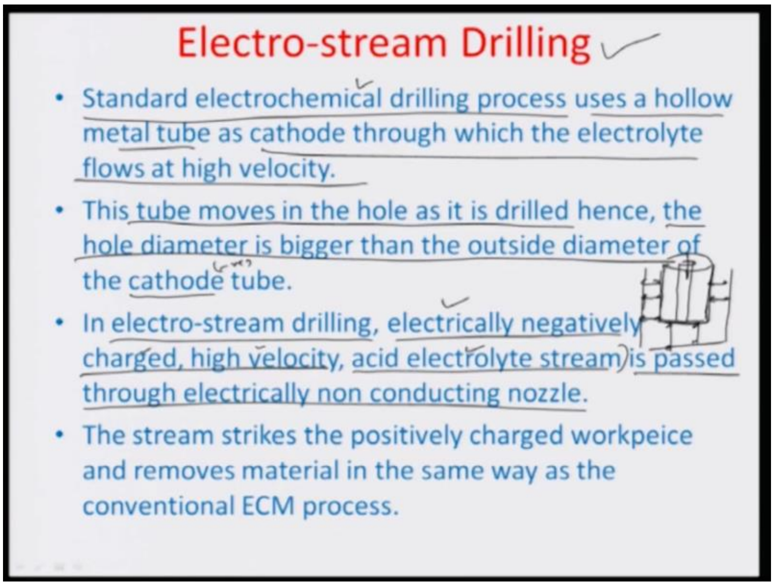

Now, the standard electrochemical drilling process as you may recall, use the hollow metal tube as cathode through which the electrolyte was flowed at a very high velocity and this tube moved into the hole as the drilling was being performed. And the hole diameter that came out, was kind of bigger than the outside diameter because of, the overcut issues associated with the cathode tube.

So, there is dissolution of material along the drilling face and also along the drilling sides of such a tool, which would result typically the oversize of the hole diameter, that it would be intending to formulate. So, there is going to be a flow of electrolyte across this central concentric tube. And the overcut that would be generated, would typically be in this area, just make it a little better looking.

So, the typical overcut would be in this area, in this particular gap on both sides. Because of obvious reasons, that dissolution keeps on happening wherever there is metal; on the surface of this electrode is also a metal just as the end of the electrode is and therefore, there is a dissolution creating the oversize. So, in electro electrochemical drilling, the electrode, the tool electrode is made the cathode; so it is negatively charged. And typically the work piece is made the anode. And the dissolution happens because of the potential difference between the cathode and the anode. And this we have I think quite well studied in the last few lectures about ECM.

The other important phenomena which I would like to sort of introduce, is the electro stream drilling. Its little different then the ECM process, in the sense that electrically negatively charged high velocity acid electrolyte stream is used for doing the machining operation in this particular case. So, therefore, even if the electrolyte is passed through a nozzle which is non conducting in nature, still there is going to be machining operation. In ECM you cannot afford to have that, because the electrolyte itself does not have any charge unless it is actually coming in contact with the both the electrodes and there is going to be charge transport from 1 of the electrode to other; the tool made the cathode, the work piece made the anode and vice versa and so on and so forth.

The only difference in electro stream drilling are twofold; 1 is that the tool electrode need not be conducting in nature and it is the electrolyte itself which is negatively charged and it sort of represents the action of the electrolyte itself of the electrode itself in e c m. So, it is a sort of liquid electrode, as you can probably envision the process to be.

So, the electrically negatively charged high velocity acid electrolyte is typically thrown, as a jet stream on to the surface that you want to machine. And the stream strikes the positively charged work piece and there is electrochemical dissolution because, there is always a potential difference between this negative acid electrolytes stream and the positively charged work piece. And machining takes place in the same manner as a conventional ECM process, although in this case it is between that liquid stream acting as an electrode instead of the tool itself.

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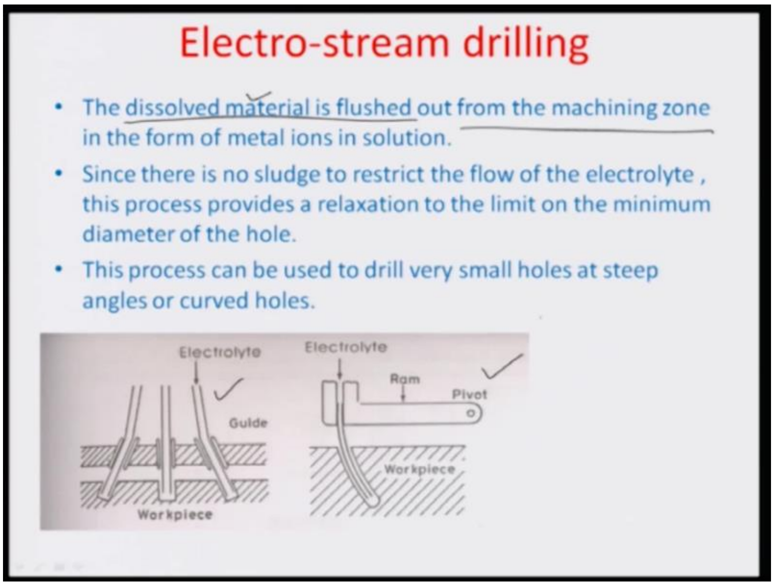

So, naturally the dissolved material is flushed out of the machining zone. You can see here are 2 illustrations where, there are steep or curved holes which are being made using the electro stream drilling. So, the dissolved material in this case is flushed out from the machining zone, by pushing it through other negatively charged stream of acid which is following.

One major difference in this particular ESD case of the ECM is that, in the ECM there was a requirement of generating a precipitate as the debri or the byproduct of the electrochemical reaction of the metal, which would caused or furnished metal removal. In this particular case; however, we do not need to make a precipitate, but we can afford to have the metal to be dissolved within the ionic stream as ions and because just because they are ions, there is no need of flushing.

The machining zone at least it is not that high as ECM process, because precipitates itself nucleate and they are not in the dissolved state and then there becomes a problem of clogging. And in this case, because it is ionic in nature, it is completely dissolved, there is no nucleation or growth or there is no as such particle, which is formulating that all ions dissolved in the solution itself. It is very easy to take out the residuals coming out of the machining process, by just keeping a positive pressure on the acid stream. There are no clogging cases or which happen in this ESD case as oppose to the ECM case.

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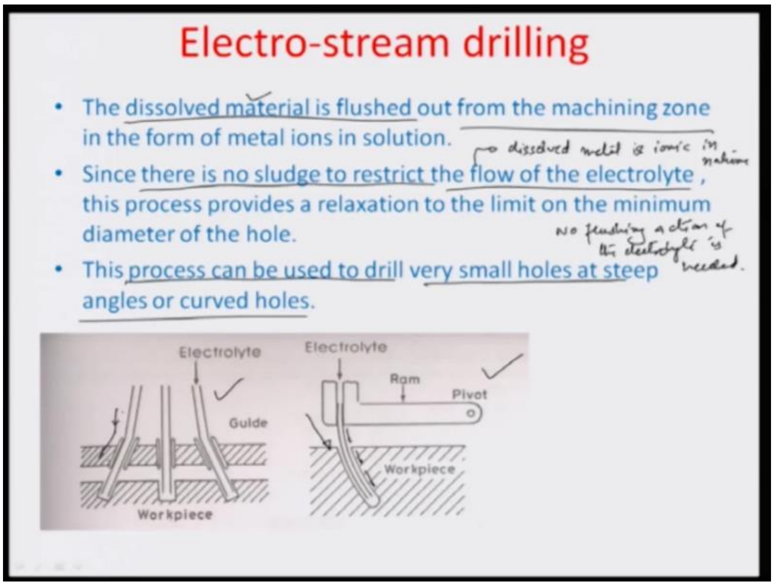

So, there is no sludge formation and there is no restriction of the flow of the electrolyte, because they dissolve material is in form ions. Just let us write this down here. Dissolved metal is ionic in nature. And that is one of the reasons why, no flushing action of the electrolyte is needed. So, the process can be used to drill very small holes at steep angles or even curved holes sometime. You can see this is a very difficult machining proposition, which cannot be done by any other technique, but by using a jet stream and directing the jet stream, using a non conducting nozzle in a certain manner, you can cut curved holes or steep holes at steep angles as you can see here, along the work piece very easily using the ESD process.

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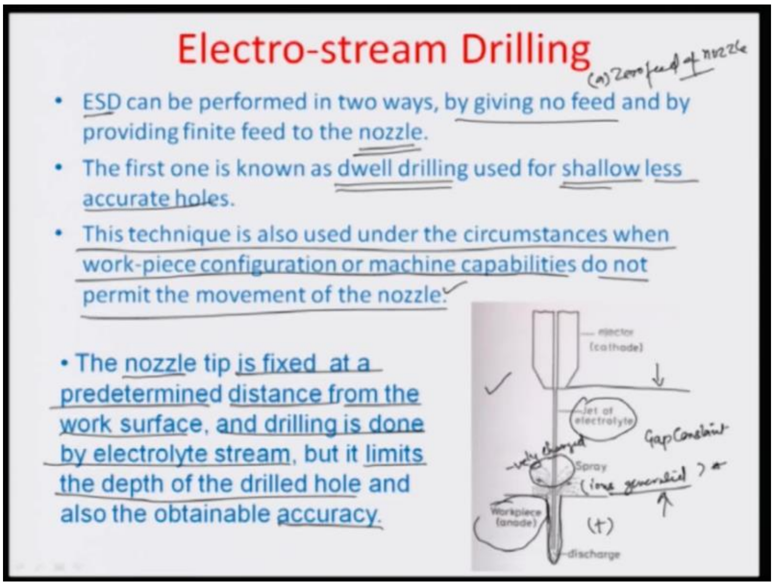

The ESD process further can be categorized into 2 different modes: 1 of the modes comes when you do not give any feed or do not provide any feed to the nozzle, which carries the acid stream of the electrolyte. So, there is 0 feed of nozzle. And typically this is also called as dwell drilling. The name dwell suggest that the electrode stationary. And these are normally used for shallow less accurate holes, sometimes confined to the surface machining operations. And this technique is also used under circumstances, when the work piece configuration or machine capabilities, do not permit the movement of the nozzles. They are many a times when you face the situation, were you cannot move the work piece or you cannot ensure relative motion between the tool head and the work piece.

So, the nozzle is fixed at a certain predetermined distance from the work surface and drilling is done by electrolyte stream, which hits as a jet typically. But of course, there are limitations on to the depth of the drilling hole or depth of the hole drill and also limitations related to the accuracy behind the process. It is shown here very beautifully in this nice schematic or the work piece is made the anode here and you can see a jet of the electrolyte being sprayed by a otherwise static electrode. So, this gap is constant, no feed whatsoever. And this jets the acid stream in form of a jet at a certain velocity. When it hits the work piece, it starts the drilling action, because of ECM dissolution

The acid mind you is negatively charged and the work piece is intentionally made positively charged. And whatever splashes come out of the region are good enough to carry the ions, which are generated in this process and there is no precipitate formulation as such or any debri issue which would need separate high pressure flushing. So, the streams velocity itself is a self flushing agent, for removal of all the ions which are dissolved in the solution from the work piece.

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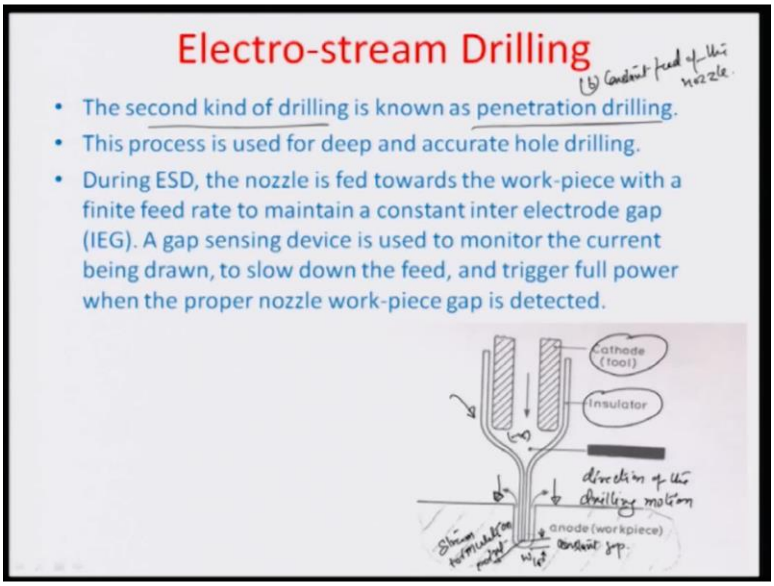

The other case in electro stream drilling is known as a penetration drilling case. As the name here suggests, this is a case where you have constant feed of the nozzle. So, in this particular case you have to ensure that, the guiding nozzle which is otherwise insulating in nature and which does contain a cathode tool which provides this negative charge to the electrolyte, is moved along the drilling motion. This is the direction of the drilling motion. And you basically move the nozzle along with the acid is stream, last keeping the gap between the work piece and the point where this stream gets generated.

So, we call it stream formulation point. The gap between the work piece and this stream formulation point is more or less made constant. And this would typically happen, when the dissolution rate of the work piece is similar to the constant gap. We have in fact done a lot of modeling related to the equilibrium gap, in earlier illustrations along this lecture. Similar manner you have to ensure that, the feed motion in this particular case of the insulating nozzle, is similar to the rate of dissolution of the work piece.

So, the process of course is used in deep and accurate hole drilling. And during ESD, as I told you earlier the nozzle is fed forward towards the work piece, with a finite feed rate. And it maintains a constant inter electrode gap. In fact, just similar to the ECM, in this particular machine also, a gap sensing device is used, typically to monitor the current that is being drawn. And similarly, you know it a feedback closely feedback control which monitors the feed; makes it slow or go higher depending on dissolution rate of the material. And the current of course, is a function of the gap as you know from earlier calculations.

So, probably triggers full power when proper nozzle work piece gap is detected. And this gives you a very good drilling operation on the work piece. So, having said that, I think we have come to the end of all the associated electrochemical machining processes. Just a quick recall; we studied in details about the modeling issues and about the fundamentals involved in the ECM process. We also did all the associated processes including, electrochemical drilling ECD, ECG electrochemical grinding and now finally, electro stream drilling.

So, this gives us a sort of bases to start our next process; which is about understanding the applications of particularly, the micro machining area where ECM can be used heavily.

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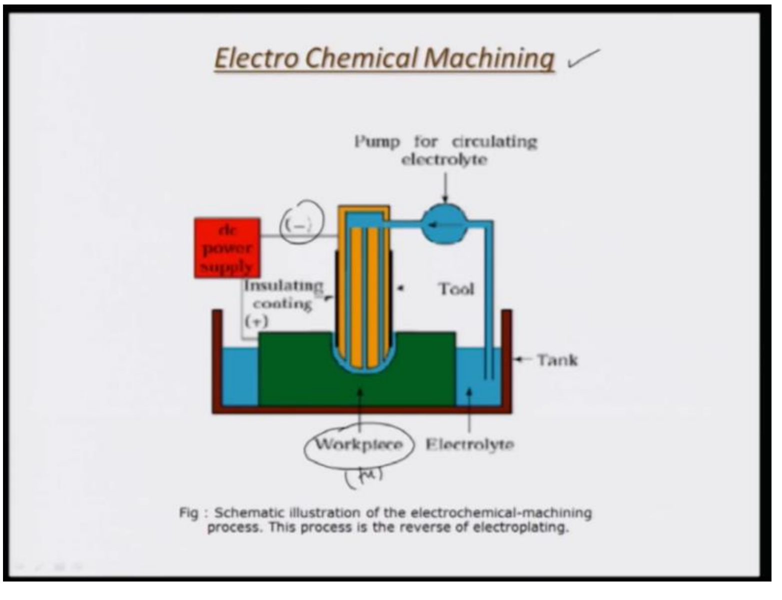

So, let us look at some potential applications and just to illustrate once more, the ECM process is about the electrochemical transport, of material from a positively charged work piece made the anode and a negatively charged tool center, in the presence of an electrolyte.

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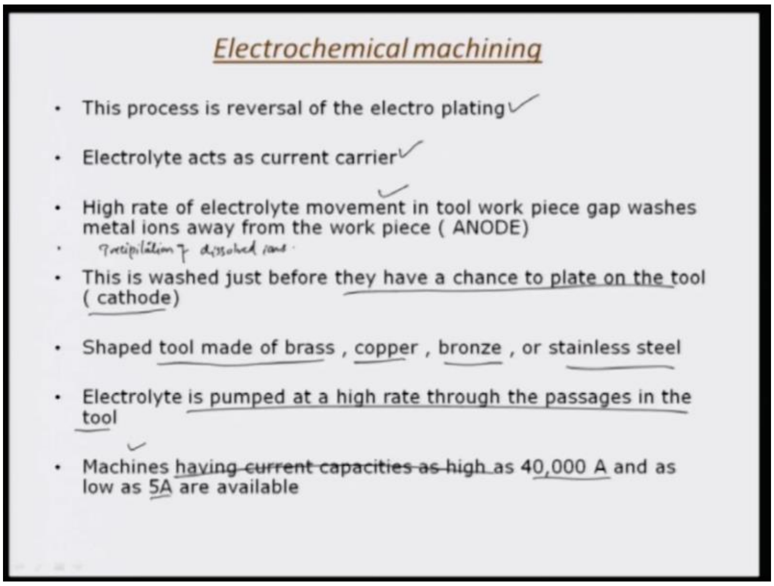

This is a sort of schematic or a cartoon which generates the ECM process. And the process typically is a reverse of electro plating; the electrolyte access a current carrier and there is a high rate of electrolyte movement in tool work piece gap, which washes away the metal ions which have been formulated as precipitates. And this is washed just before they have a chance to plate on the tool cathode. In fact, there is another step in between, where there is a precipitation of dissolved ions.

The tools are typically made up of conducting materials: brass, copper, bronze, stainless steel. And electrolyte is pumped at a high rate through passages in the tool and machining having current capabilities of as high as 40 kilo amperes to about 5 amperes are available. So, in summarily looking at e c m this is the process.

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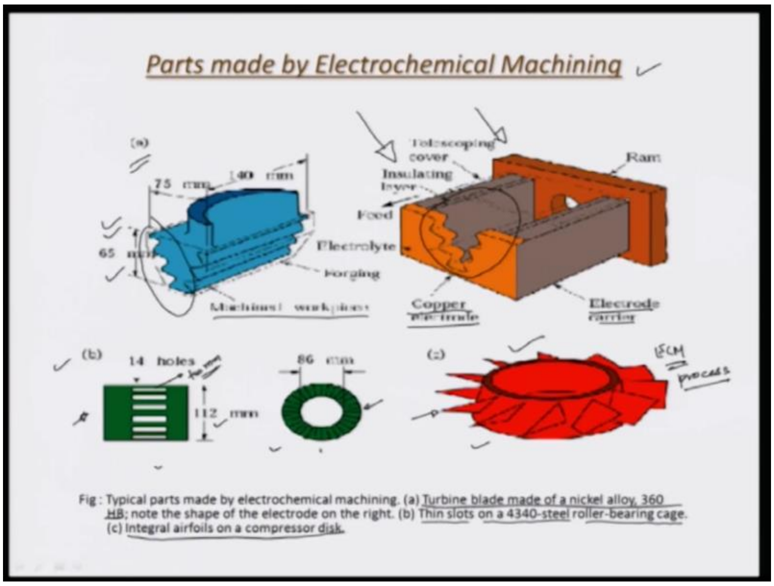

There are extreme complex shapes and features, which can be generated by designing a proper or appropriate tool using ECM machining processes. This particular slide mentions, you know figure a right here is the example of a turbine blade, which is made of a nickel alloy 360 h b. The corresponding tool which is used to make this complex shape is given on the right side here. You can see the complexity, particularly in this particular region, which is really the negative map or an inverse map of the feature that, you would like to obtain on the work piece surface.

So, a copper electrode of the exact negative replica is created and which would eventually result in a complex machine work piece surface, like this; using the processes that we have illustrated before. Figure b right here, shows thin slots and this is made on a 4 3 4 0 steel roller bearing cage. And you can actually see that, if you look at this scale here, this is about 112 millimeter. So, each of the slot is close to about a few millimeters.

So, is very easy for a the ECM process to have a different scale expect in the machining. You can go to macro level machining and you can also go to very low size micro level machining. And figure c indicates; integral air foils on a compressor disc, which again has been made using the ECM process.

So, you just need to sort of map the tool surface, in a methodology which has been illustrated to you earlier; by looking at a final part design or a drawing. And you can go to these complexity levels as such been illustrated here. This is a micro gearing for example.

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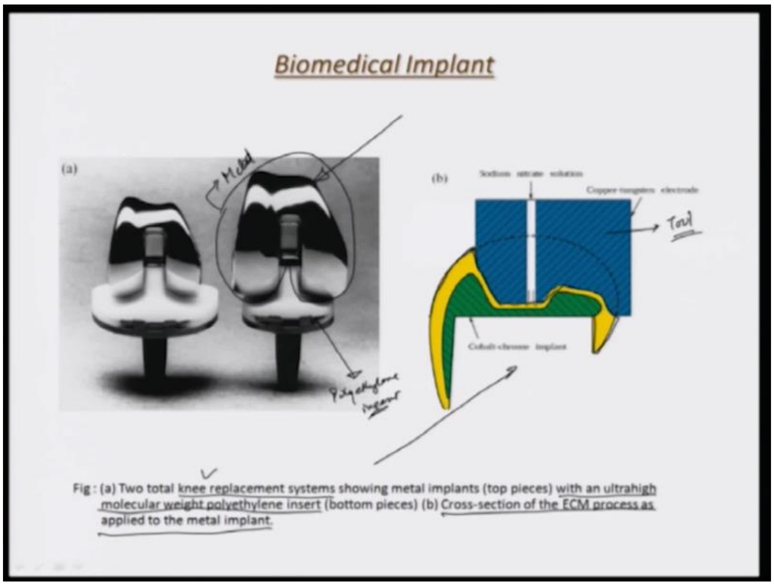

Now, this for example, is a biomedical implant. So, an extremely complex topology, which otherwise may not be machineable with the conventional machining process. So, this implant is basically a knee replacement system. And they made with an ultra high molecular weight polyethylene insert; the bottom piece here is that insert, polyethylene insert. And this portion here is the metal; the top portion is the metal. And you can think of the kind of complexity is that, ECM process can handle if it can do proper finish machined surfaces in case of knee replacement like this.

This of actually shows the cross section of the ECM process as applied to the metal implant. You can look at the complexity of this machined surface, necessitating this blue region which is the tool. So, this is the cathode tungsten electrode or tool which would do the machining operation. On the machined surface final machined surface is a cavity shown by this yellow region. So, its otherwise very hard and difficult to obtain such a structure, using conventional micro machining. Therefore, ECM is very well suited for such applications.

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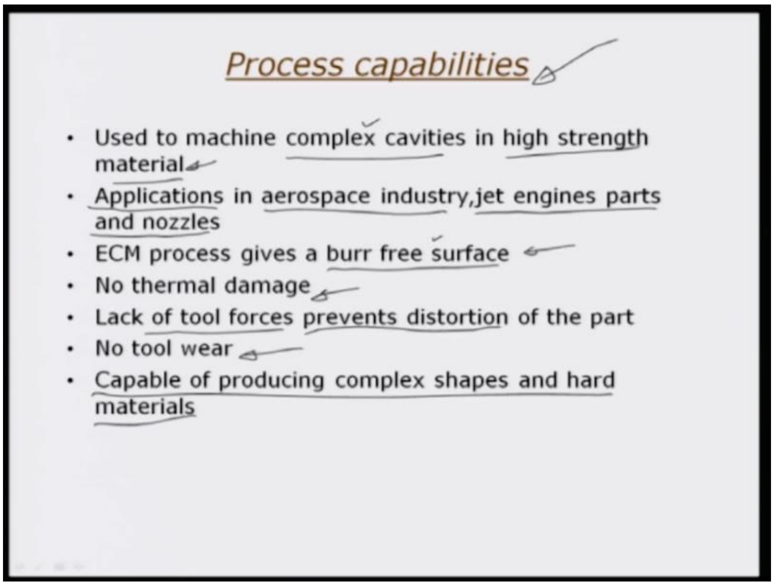

So, in if you look at the process capabilities of ECM, you can use this to complex, to machine complex cavities, particularly with high strength materials, composites or domains in that region. It finds wide applications in aerospace industry, jet, engine parts extremely complex and needing high strength and dynamic in nature, and nozzles. And the process gives a burr free surface in all such applications, not only it can handle complex ships and cavities, but it can do a good finish on the machining aspect.

There is no thermal damage, which otherwise would happen if there is a metal to metal shearing action, which would create such a shape or tool as is done normally in CNC or other kind of machines. There is a lack of tool forces and therefore, is passive non contact and it leads to the prevention of all sort of distortions, which otherwise would happen if you had a contact machining, kind of a situation. There is very less tool wear, which I think I had illustrated earlier was, mainly due to the small gap and the high pressure of the electrolyte.

There is always a viscous track associated with such a flow, which would create some kind of a war page or a detoration on the tool surface. And the process is capable of producing complex shapes on hard materials, that is what the buying point of this process e c m processes.

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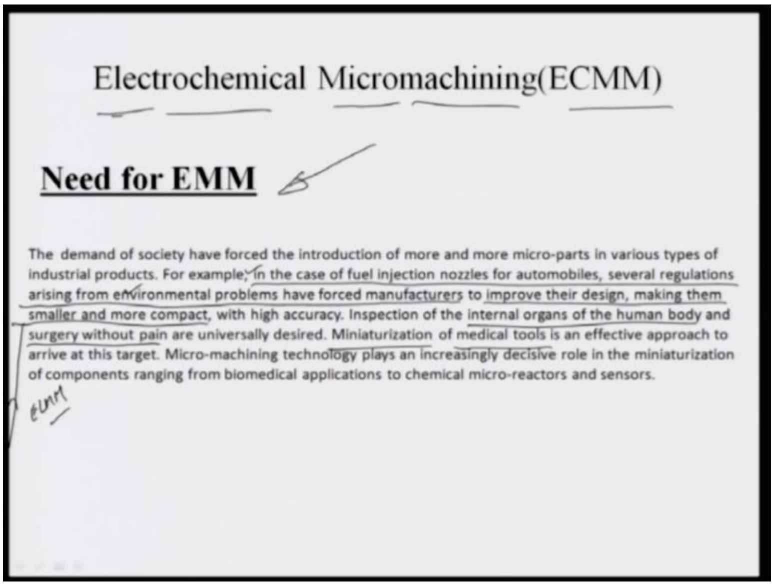

So, that is how the process capability is of this ECM processes detailed. And because of such capabilities, there is a huge need for the electrochemical processes; particularly at the micro domain. We call this electrochemical micro machining ECMM. So, the machining activities have to the micro domain, as detailed by me earlier in my earlier lectures; because of the requirements of various industries like; aerospace or automotives. And there is always small venturies which etcetera which are used in nozzles for fuel injection purposes. And that is one of the best utilizations of this complex micro machining processes, which are repeatable in nature, which have direct impact on the society.

So, in case of let say, fuel injection nozzles for automotives, several regulations arising from environmental problems, have forced manufacturers to improve their design; making them smaller and more compact. So, this need can be addressed by the ECMM or electrochemical micro machining. Other aspect that is involved in, you know direct with the direct application of the ECMM can be felt as in the biomedical domain, particularly in the surgery domain were there are small or small instruments like; grippers etcetera, which would be used in a very small section of the tissue, with very less or minimal damage to the surrounding tissues.

Therefore, painless surgery, surgery without pain, particularly of the internal organs of the human body also necessitates certain medical tools, which have to be miniaturized to an effect where, there is very less issue about the surface finish and very highly high accuracy in the overall dimensions which are needed. So, therefore ECMM plays a major role in some of these applications and its widely accepted industry process.

So, what I am going to do is; to sort of scan through a list of different applications now, borrowed from the literature, where ECMM has been directly used for getting complex shapes and features. They are with you, acknowledgements to the concerned groups which have worked in this area.

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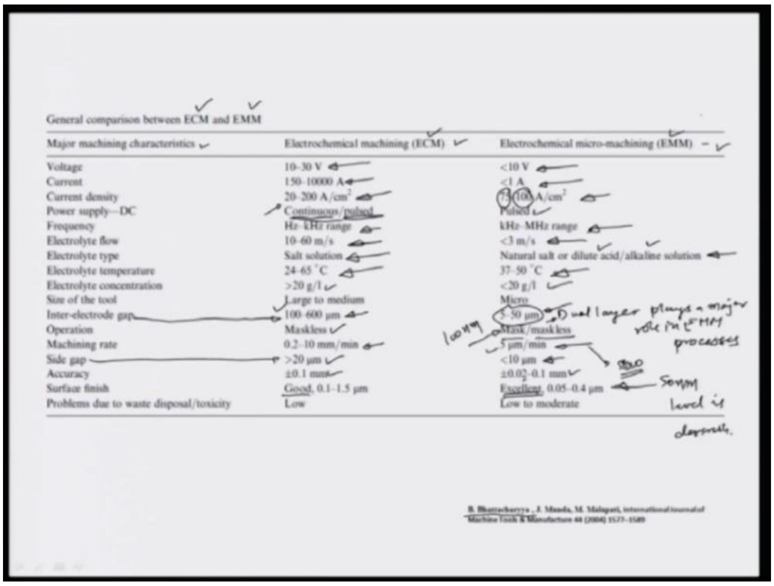

General comparison between ECM and EMM

Major machining characteristics	Electrochemical machining (ECM)	Electrochemical micro-machining (EMM)
Voltage	10–30 V	<10 V
Current	150–10000 A	<1 A
Current density	20–200 A/cm²	75–100 A/cm²
Power supply—DC	Continuous/pulsed	Pulsed
Frequency	Hz–kHz range	kHz–MHz range
Electrolyte flow	10–60 m/s	<3 m/s
Electrolyte type	Salt solution	Natural salt or dilute acid/alkaline solution
Electrolyte temperature	24–65 °C	37–50 °C
Electrolyte concentration	>20 g/l	<20 g/l
Size of the tool	Large to medium	Micro
Inter-electrode gap	100–600 μm	5–50 μm
Operation	Maskless	Mask/maskless
Machining rate	0.2–10 mm/min	5 μm/min
Side gap	>20 μm	<10 μm
Accuracy	±0.1 mm	±0.02–0.1 mm
Surface finish	Good, 0.1–1.5 μm	Excellent, 0.05–0.4 μm
Problems due to waste disposal/toxicity	Low	Low to moderate

B. Bhattacharyya, J. Munda, M. Malapati, International Journal of Machine Tools & Manufacture 44 (2004) 1577–1589

So, the first comparison that I would like to draw between ECM or ECEMM or a EWCMM process, that is, electrochemical micro machining or electrochemical machining process, is given in this table very nicely by Bhattacharya at all in 2004. And here, let us look at some of the differences in terms of the major machining characteristics, in both these processes ECM and EMM or ECEMM.

So, the voltages which are used mostly in the ECM process, is in the range of 10 to 30 volts whereas, in the EMM or a ECMM process the micro machining, the voltages are very often less than 10 of volts. And the current used in ECM is as high as 10 kilo amps; vary all the way to 100 and 50 amperes. But, we want to keep the current in the micro machining domain as possible; so typically it is less than 1 ampere.

Similarly the current density in the ECM is quite high; 20 to 200 ampere per centimeter square. But it when we look at the corresponding EMM processes, they range between 100 and 75. So, you cannot go above 100. And it is not the wise idea to even go as low as 20, because in this case the current density is responsible for all the material transport, as I think I had modeled earlier and told earlier. And here the idea is to be able to, as quickly as possible remove, what about small material you want to remove in the micro machining domain.

So, the power supplies which are used for both operations are quite variant. In case of ECM, mostly continuous power supplies are used, continuous dc. And sometimes there are pulsed dc which is used because, of the dual layer and other models which we had illustrated earlier in our previous lectures. Whereas, in the ECMM case you only use pulsed dc signals as the major machining signals. Or the frequency of the pulsed signals, are typically in this case of ECM hertz to Kilo hertz range. But you know in the EMM it has to be very high so that, you have very less scope of redeposition. The frequency is in the mm domain is typically Kilo hertz to Mega hertz range.

Similarly, the electrolyte flow is restricted to a lower value, in case of EMM less than 3 meters per second. Whereas, you can go all the way to about 10 to 60 meters per second in case of normal ECM. The electrolyte types are different; they are salt solutions when you talk about ECM. But when you talking about EMM, they can be dilute acids or alkaline solutions or even natural salt solutions of lower concentration or lower order. Electrolyte temperatures are kept typically in the range of 24 to 65 degree Celsius in the ECM. And in the ECMM or the micro machining case, the temperature ranges quite moderate, varying between 37 to 50 degree Celsius.

The electrolyte concentration as I told you earlier, is kept quite high in case of ECM, but is reduced in case of electrochemical micro machining. And if we talk about the gaps or the magnitudes of the various electrode gaps, you can see the difference almost immediately and therefore, the dual layer plays a major influential role in EMM processes. The inter electrode gap is between 100 and 600 micrometers in ECM, but it changes to 5 to 50 micrometers in EMM.

So, dual layer also is quite commensurate with a few 10s of nanometers and therefore, the dual layer plays a very critical role, when the gaps of the EMM's are reduced to the level indicated. Typically the ECM operations are mask less in nature, but you need sometimes usage of masks in case of EMM operations. Sometimes it can be mask less, but if you had to selectively introduce small features sizes in maybe 100s of nanometers regions.

So, in that case, you probably need a mask to do the ECM process at the micron scale. Machining rates very visible is commensurate with the current data and also the current density data. In this particular case, the machining rate and the micro machining is almost of the level of micrometers per minute whereas, in case of normal ECM process it is about 10s of millimeters per minute.

So, there is a huge difference in the way at the material removal is taking place, EEMM the material removal is quite slow by an order of magnitude almost. The side gaps in this case come to be about greater than 20 micrometers, particularly the oversize of the drills etcetera that we are considering. This case it has to be maintained to less than 10 microns. And of course, the accuracy of the processes you can look you know, it can go out to the micron domain about close to 0.0 to millimeters or about 20 microns in case of EMM, whereas, in case of ECM it goes to all the way to 100 microns.

So, definitely a EMM is a much more surface oriented surface topology oriented process. The surface finishes pretty good in ECM, but if you talk about EMM, it has to be really excellent and as low as 50 microns of 50 nanometers level is desirable. So, that is in a nutshell; what the parametric differences are between the ECM and the EMM process.

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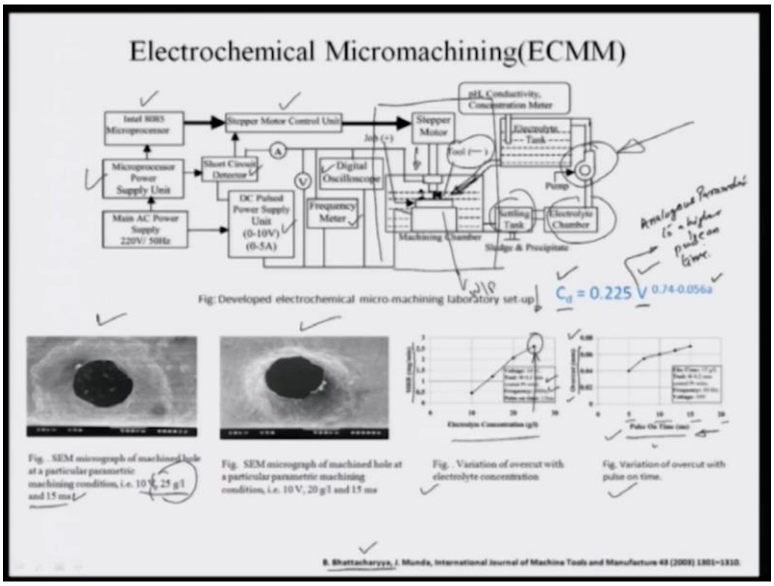

Let us look at some of the work done by many groups earlier. This shows how the ECMM unit is more controlled process than the ECM unit. Here, this region is really the region which is the machining center, you have a work piece here, and you have a tool region. Again tool is negative, work piece is positive as any other ECM process. There is a electrolyte which is being pumped through this nozzle right here, into the work piece zone. And of course, there is a flow handling system.

So, you have a settling time for the sludge to get settle down; there is a filtration system, there is a pump, there is a electrolyte chamber; so which causes the electrolyte to re-circulate. There are different controllers here; there is a Intel 8085 micro processor, which this group is using for setting up such a system. There is a stepper control motor, which gives drive to the tool. And this ensures the quick start and stoppage of the lead screw drive, which would actually feed the tool towards the wok piece. There is a short circuit detective, there is a dc pulse power supply and there is a measurement frequency meter, which monitors what is a frequency at which the pulsing is happening.

So, digital monitor the signal as well. And then there is of course, a microprocessor power supplying unit, which controls based on the gap current; the distances between the tools and the tool and the electrode. So, these are 2 nice SEM illustrations, of their scaling electron micrographs of machined holes, at a particular parametric machining condition. The machining condition used at 10 bolts dc pulse supply, 25 gram per liter of electrolytic concentration and a machining time of about 15 milliseconds.

So, there is also a variation of overcut with respect to the electrolytic concentration and also with respect to the pulse on time that has been illustrated by this group. And what they show is that, there is an increased MRR of the material in terms of milligrams per minute, with respect to various electrolytic concentrations. The whole picture here is corresponding to about 25 gram per liter, which is somewhere around this region.

So, this is the value that has been illustrated, where machining has been carried out. Some other parameters related to this process are, that the is a tool which is about 200 microns diameter coated platinum wire and the pulse frequency in this case about 50 hertz and they using 15 milliseconds time. The effect of the overcut on the pulse on time illustrates, that as the number of pulses have increased, the overcut has more, which is obvious from an illustration given earlier in ECM that; as can be seen in this formulation here where cd is the diametric oversize, v is the voltage and A is 38 tool feed rate.

So, if the feed rate is higher, the cd goes down; that means, you have lesser time, relaxation time given to the system by having a increase or enhanced feed of the work piece towards the tool towards the work piece. So, just because we are talking about pulse on time, this voltage here in this equation, is analogous to a higher pulse on time. So, you can think of it as if, the electrodes are facing the voltage for a higher duration if the pulse on time is more in comparison to the pulse of time.

If, the electrodes are facing a voltage for a higher duration, the diametral oversize is going to get increased, because of that voltage. So, therefore, intuitively also the overcut relationship with pulse on time, happens to be quite well.

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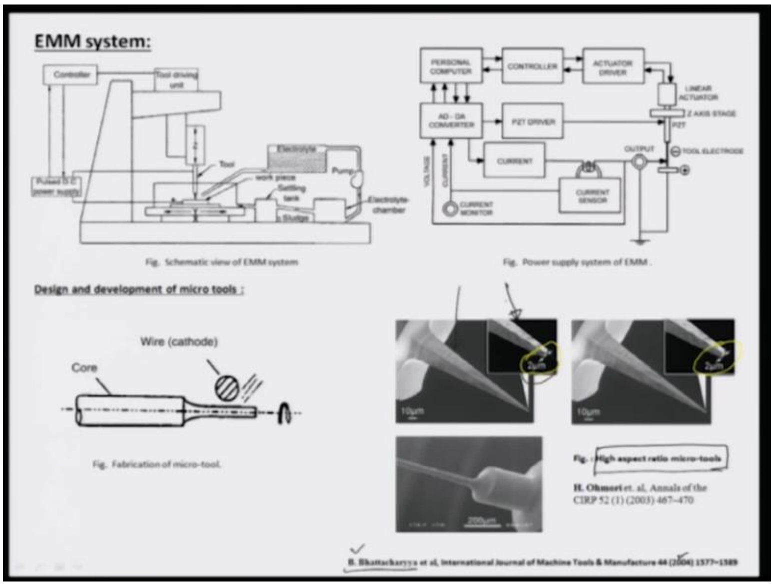

The other example that borrowed from the same group again in 2004, they have reported a formulation of a high aspect ratio micro tool, as you can see in this particular case here. The tips high is of 2 microns as shown in this SEM, has very nicely been illustrated, which otherwise is not very doable in terms of manufacturing, unless you talk about something like a glass pulling process, which breaks the glass into a almost the size of a 2 micron tip by a virtue of shear, at a certain higher temperature; whether glass achieves slow ability. So, but they have successfully done this 2 microns on metal using again the ECM process using a wire cathode, as can be seen here.

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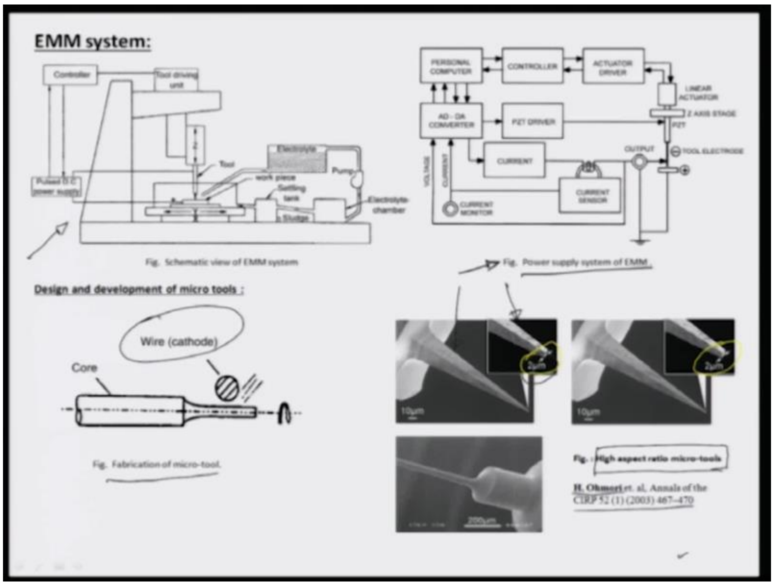

The work piece has been given small rotations and the wire cathode has been able to generate this kind of a very pin pointed shape. The EMM system that they use in this particular case, is illustrated in this figure right here, shows the power supply system for such an EMM process.

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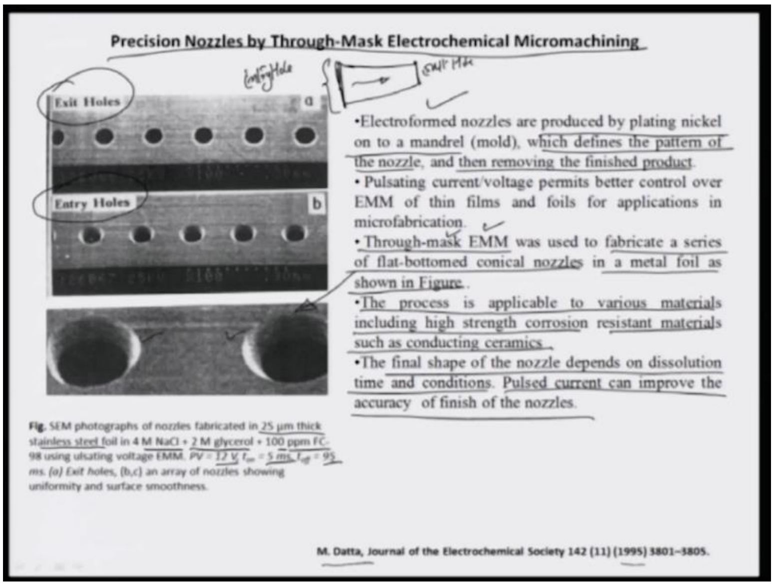

Let us look at the few more examples of what EMM electrochemical machining can do micro machining. This for example, is again borrowed from this group at all in 1995. And they talk about the fabrication of precision nozzles through a mask approach. So, they use, they develop this electroformed nozzles and they produce it by plating nickel on to a mandrel mold which defines the pattern of the nozzle and then removes remove the finish product from in.

So, what they do essentially is that, it is like a through mask EMM process that they are using. They develop a mask and selectively try to take out or dissolve out the material electrochemically. And such EMM is used to fabricate this trough mask EMM with this through mask. And using the EMM process fabricating, a series of flat bottomed conical nozzles in metal foils as shown in this figures. These are the nozzles, these are the nozzles and they are flat bottomed.

So, this shows the exit hole size and exit hole size you can see is smaller in comparison to the entry hole sizes, which makes it like a nozzle right. And nozzle is typically, where the this is the entry hole size and this is the exit hole size. The direction of the fluid is from the greater cross sectional area to a lesser cross sectional area. So, the process of course is applicable to various materials, including high strength corrosion resistant materials, such as conducting ceramics. And the final shape of the nozzle, depends on dissolution time and conditions of course, pulsed current has been seen to improve the accuracy of the finish of the nozzles.

So, this another illustration where, almost nozzle diameter close to the range of about 10s of microns have been fabricated in a 25 micrometer thick stainless steel foil, by using mask EMM. So, you have a mask being fabricated, so that, there is selective dissolution along certain regions, shielding of the other regions. The electrolyte they use in this cases about 4 molar N a C l and combination of tool or glycerol and about 100 ppm fc 98. And they use a pulse rating bolt age, here in this case of 12 volts, with the on cycle time of 5 milliseconds in a off cycle time of ninety 5 millisecond.

So, you are using mostly 5 percent of the total vaulted cycle. So, you can see the uniformity and the smoothness with which these nozzles have been produced using mask electrochemical micromachining.

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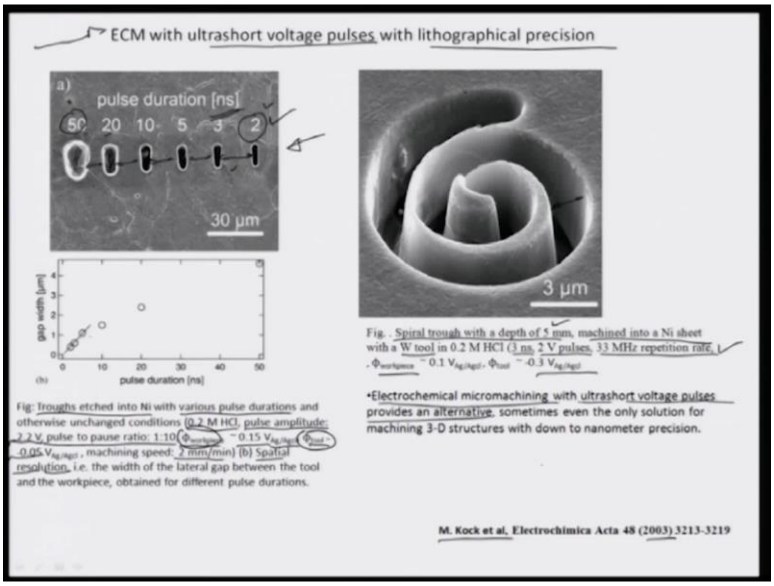

The other example that I have borrowed is from, kock at all is group which they reported in 2003, where they talk about the fabrication of various ultra short small miniaturized structures, with using ultra short voltage pulses. And they have almost claimed that, they get lithographical precision by using these ultra short voltage pulses, when they do ECM electrochemical machining. Here you can see that, there are certain troughs which have been etched in nickel shown in this SEM schematic here. And they have been machined with various pulse durations, which are also indicated, varying between 50 to 2 nanoseconds that are how small the pulse duration is. That is why they call it ultra short pulse duration.

The other conditions which are specified in this particular set up, is corresponding to 0.2 molar h c l as the electrolyte. There is a pulse amplitude their using of 2.2 volts and then there is a almost 1 is to 10 that is 0.1 or 1 percent. So, 10 percent duty cycle that there using of this particular pause. So, also that, the potential that they are using on the work piece is close to 0.15 volts as measured with respect to agacl electrode silver silver chloride electrode and that on the tool is measured as minus 0.05 volts again, as calibrated with respect to the silver silver chloride electrode.

So electrochemically, they have very nicely been able to establish; what is the independent or individual potentials on both the cathode as well as the anode. They obtain a machining speed of close to 2 millimeters per minute and they are getting a the special resolution, almost you can see of the size of close to 25 microns. And you can actually also see that, this gap or the special resolution is sort of reduce, as you are increasing the pulse duration from 2 nanosecond to 50 nanosecond.

So, at about 2 nanoseconds resolution, the gap is about close to 25 microns whereas, if you look at between 50 and 20 nanosecond resolution, the gap has now closed on to almost half that value about, probably 50s 15 microns 10 to 15 microns. So, they do fine that, there is a resolution aspect in printing while talking about different pulses and the shorter is the pulse duration the better control the process has, what they are illustrating here.

Similarly in another work they have shown, by producing a spiral trough with a depth of about 5 mm machined in a nickel sheet again. In this case, they have a tungsten tool that is being used for doing this small duration. You can see, the width of a spiral is close to about 1 micron or 1.5 microns probably and the depth is 5 millimeters which is a very high aspect ratio in terms of all machining which has been demonstrated so far.

So, they use a 3 nanosecond 2 volt pulse and they are repetition rate or the pulse pulsing frequency is close to 33 mega hertz. So, they are for the first time, introducing a high voltage pulsation to see what is the finishing aspect associated with such a high voltage pulsation. So, the work piece potential in this case is 0.1 volts with respect to a agacl electrode and the tool potential is calibrated as minus 0.3 volts with respect to a agacl electrode.

So, these 2 illustrations definitely give us an inside that, this electrochemical micromachining particularly with ultra short voltage pulses provides, an alternative solution to almost nanometric level precision which is otherwise brought in by lithography or processes like etcetera. And then this can provide 1 of the very important solutions for particularly 3D structure or 3d micromachining, 3D structure fabrication.

The other all option is of course, is which lithography galvan affirming process is. I think, I had illustrated little bit and I am going to do some more examples later on for lega. But the high aspect ratio structure, can be very in a very nice manner in a very simplistic manner be produced by electrochemical micromachining, which can very well with some of the precisions given by the lega process.

So, this kind of brings us to an end of today's lecture on the what ECM can do with different illustrations. We have given some, we have described some nice examples of the capabilities of the ECM. I would in the next lecture, start focusing on some of the variants of ECM, which would have and for that we need to illustrate another process called EDM. So, although I will not do the modeling of EDM at this stage, I will just show you some applications related to EDM which is electrode discharge machining. And then, there is a hybrid process between ECM and EDM which is of paramount importance to the micromachining industry called ECDM which is called electrochemical discharge machining.

So, my objective here would be finally, in the next lecture to give you some process applications related to that variant of the ECM which is called ECDM. And although we are going to learn about EDM process in subsequent lectures in great details, but I am going to sort of switch gears a little bit and try to give you an introduction into the EDM with some applications. So, that you can better understand that, how this ECDM variant of the electrochemical machining, is utilized in the micromachining industries.

Thank you.