Advanced Machining Processes
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Week - 06
Lecture - 15
Electro-stream drilling & EMM

Hello, and welcome to this lecture on Microsystems Fabrication by Advanced Manufacturing Processes. Just a 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 centre 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 in detail 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 an increasing, there is a tendency of the surface finish to be better. There would be lesser flow lines, because of increased in, increase in back pressure in the ECD process.

We also tried to empirically tried estimate 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 ablation. One of the reasons why ECD wheels are always higher life, and the process is an advantage over mechanical abrasion in the sense that there is a self-smoothing effect, because of the electrochemistry which is involved in dissoluting 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.

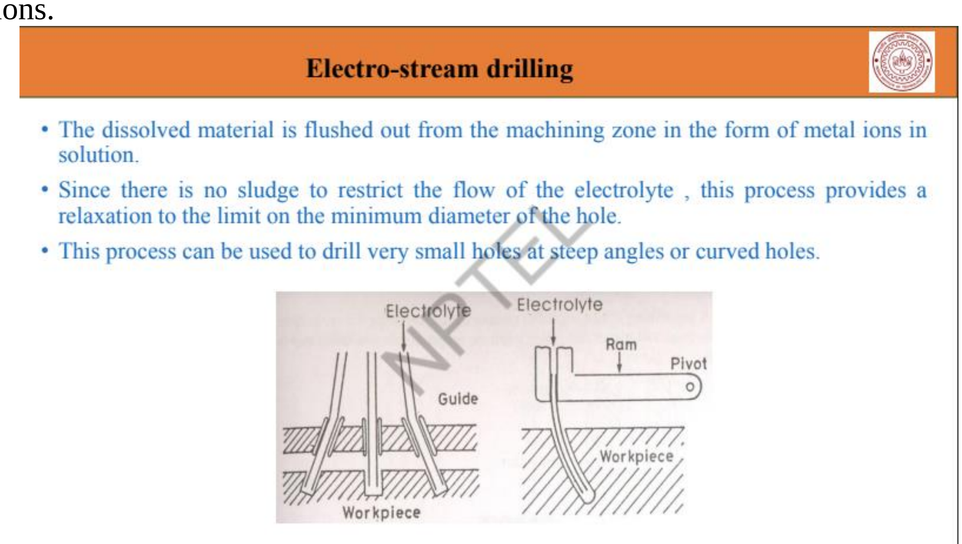
Today, we are going to do another associated process to begin with in electrochemical machining which is called electro stream drilling. Now, the standard electrochemical drilling process as you may recall, used the hollow metal tube as cathode through which the electrolyte was floated at a very high 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, that is the solution of material along the drilling phase and also along the drilling sides of such a tool which would result typically in 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.

Let us 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 the dissolution keeps on happening wherever there is metal, and the surface of this electrode is also a metal just as the end of the electrode is and therefore, there is a dissolution creating this oversize. So, in electrochemical drilling the, as we all know that the electrode, the tool electrode is made the cathode. So, it is negatively charged and typically the workpiece 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 and it is little different than 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. And 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, with both the electrodes and there is going to be a charge transport from one of the electrodes to the other. The tool made the cathode, the workpiece made the anode, and vice versa, and so on so forth. The only difference in electro stream drilling are two fold.

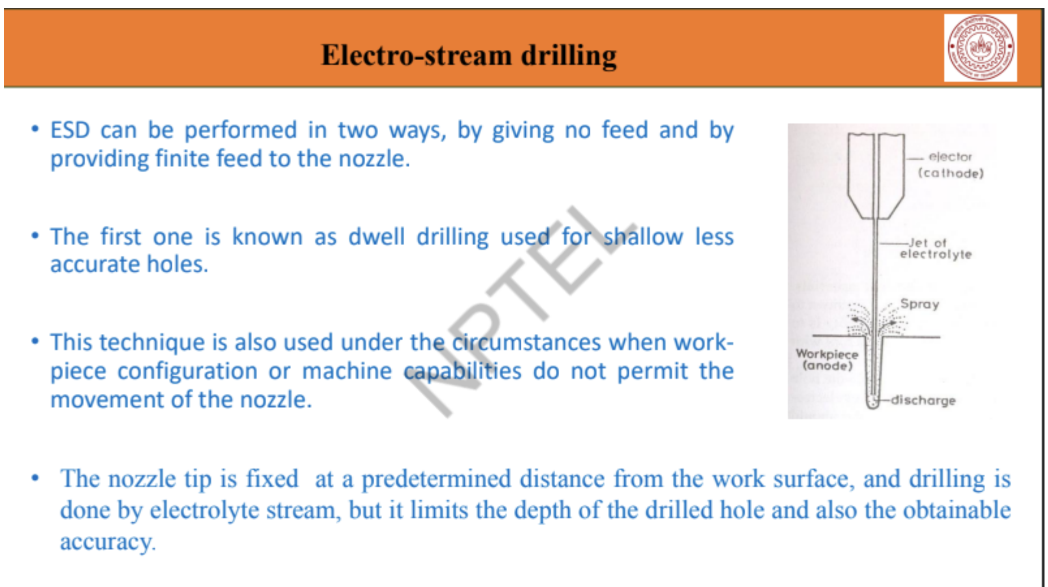
One is that the tool electrode need not be conducting in nature, and it is the electrolyte itself, which is negatively charged, and it sort of represents the action of the electrolyte itself, of the electrode itself in ECM. So, it is sort of liquid electrode as you can probably envision the process to be. So, the electrically negatively charged high-velocity acid electrolyte is typically thrown as a jet stream onto the surface that you want to machine. And the stream strikes the positively charged workpiece and there is electrochemical dissolution, because there is always a potential difference between this negative acid electrolyte stream and the positively charged workpiece. 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.

So, naturally, the dissolved material is flushed out of the machining zone. You can see here are two 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. And one major difference in this particular ESD case from the ECM is that in the ECM there was a requirement of generating a precipitate as the debris or the byproduct of the electrochemical reaction of the metal which would cause or furnish 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 the 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 there are 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 occlusions which happen in this ESD case as opposed to the ECM case. So, there is no sludge formation and there is no restriction of the flow of the electrolyte because the dissolved material is in form of 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 sometimes 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 workpiece very easily using the ESD process. Further can be categorized into two different modes. One 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.

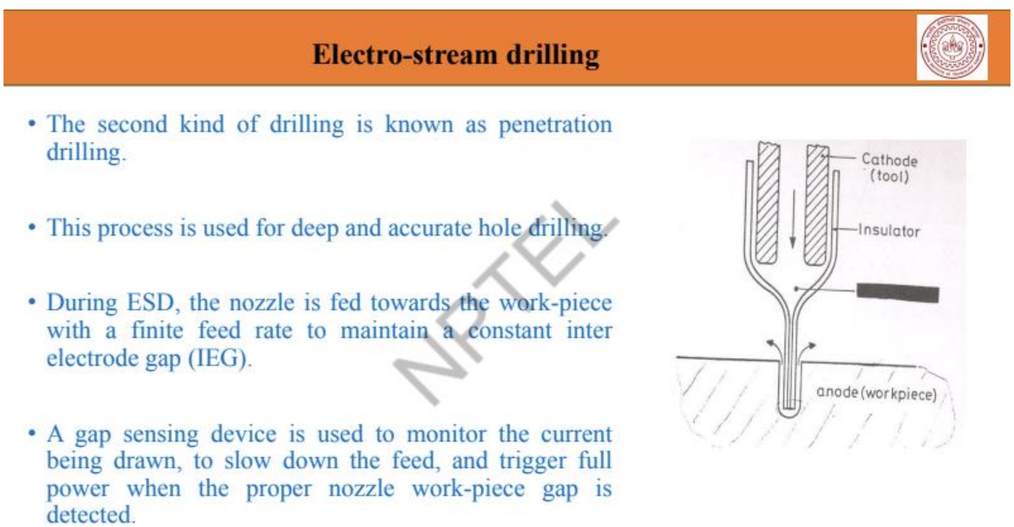


So, there is zero feed of nozzle and typically this is also called as dwell drilling and the name dwell suggest that the electrode is stationary. And these are normally used for shallow less accurate holes sometimes confined to the surface machining operations. And this technique is also used under circumstances when the workpiece configuration or machine capabilities do not permit the movement of the nozzles. There are many a times when you are faced with the situation where you cannot move the workpiece, or you cannot ensure relative motion between the tool head and the workpiece. So, the nozzle is fixed at a certain pre-determined 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 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. The workpiece is made the anode here and you can see a jet of the electrolyte being sprayed by 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 and when it hits the workpiece it starts the drilling action because of ECM dissolution the acid mind you are negatively charged.

And the workpiece 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 debris issue which would need separate high-pressure flushing. So, the stream's velocity itself is a self-flushing agent for removal of all the ions which are dissolved in the solution from the workpiece. The other case in electro stream drilling is known as a penetration drilling case. And 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 stream thus keeping the gap between the workpiece and the point where the stream gets generated. So, we call it stream formulation point. The gap between the workpiece and the stream formulation point is more or less made constant.



And this would typically happen when the dissolution rate of the workpiece is similar to the constant gap. We have in fact done a lot of modelling related to the equilibrium gap in earlier illustrations along this lecture. In a 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 workpiece. 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 workpiece 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 is a feedback closed-loop feedback control which kind of monitors the feed makes it slow or go higher depending on the 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 workpiece gap is detected.

And this gives you a very good drilling operation on the workpiece. 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 detail about the modelling 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 basis to start our next step process which is about understanding the applications of particularly the micromachining area where ECM can be used heavily.

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 workpiece made the anode and a negatively charged tool centre in the presence of an electrolyte. This is a sort of schematic or a cartoon which generates the ECM process, and the process typically is a reverse of electroplating. The electrolyte acts as a current carrier and there is a high rate of electrolyte movement in tool workpiece gap which washes away the metal ions which have been formulated as precipitates. And this is washed just before you have a chance to plate on the tool cathode. And in fact, there is another step in between where there is a precipitation of dissolved ions.

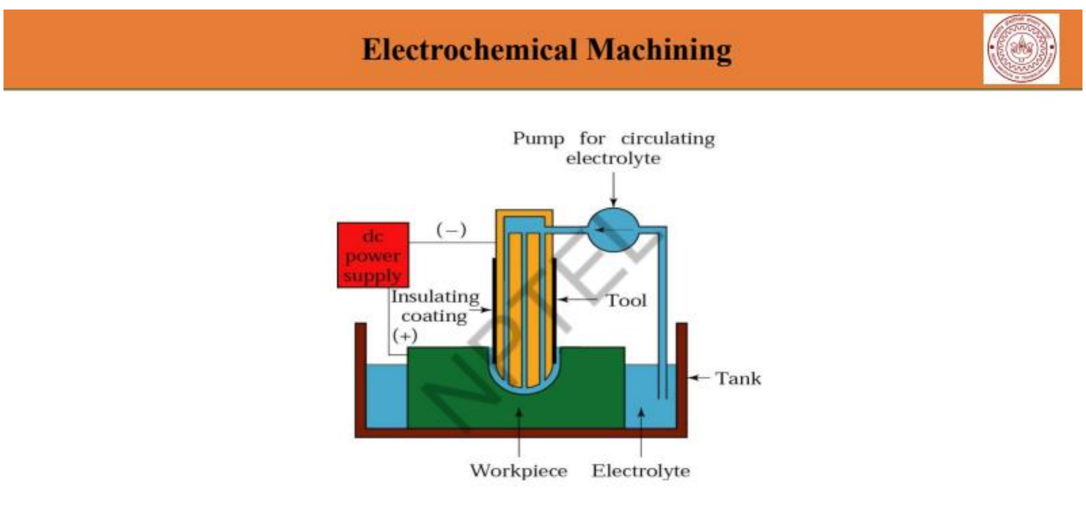
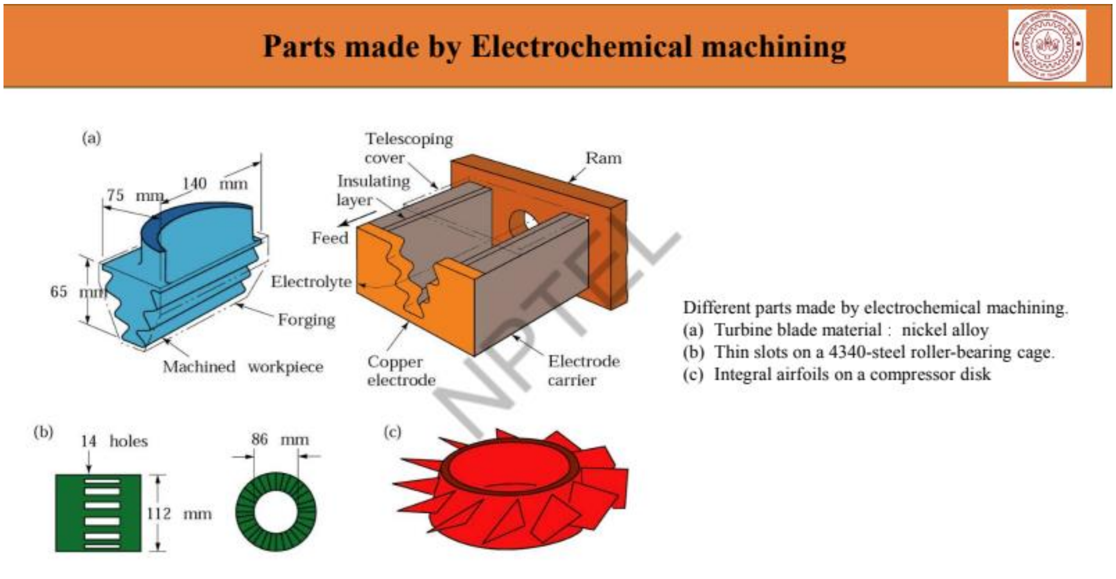


Fig. Schematic illustration of the electrochemical-machining (ECM) process.

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 ECM this is the process. And there are extremely 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



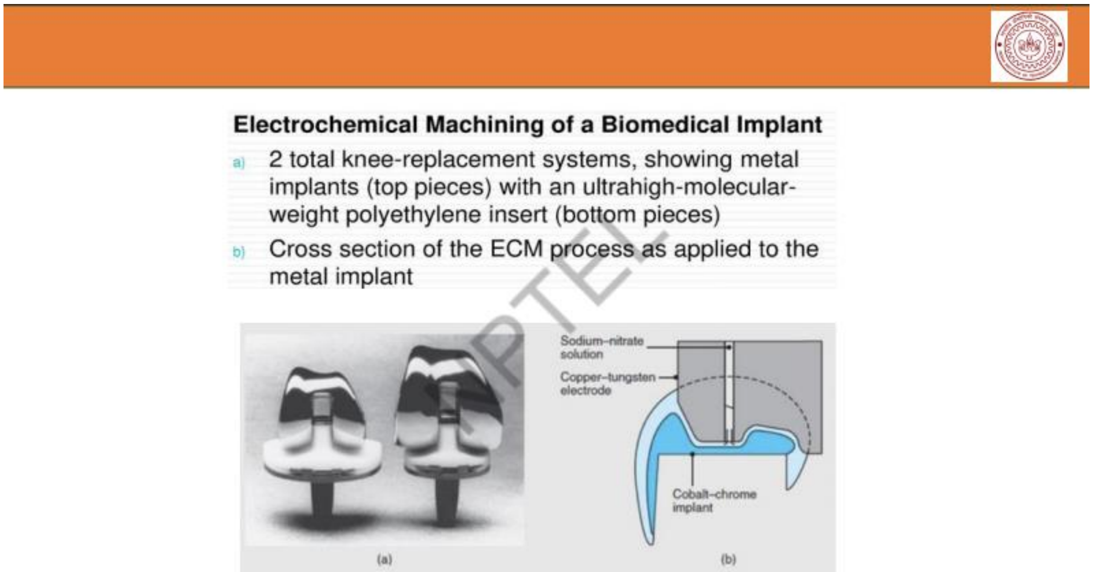
made of a nickel alloy 360 HB. And the corresponding tool which is used to make this complex shape is given on the right side here.

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 workpiece surface. So, a copper electrode of the exact negative replica is created, and which would eventually result in a complex machined workpiece surface like this using the processes that we have illustrated before. Figure b right here shows thin slots and this is made on a 4340 steel roller bearing cage. And you can actually see that if you look at this scale here this is about 112 millimetres. So, each of the slot is close to about few millimetres.

And so, it is very easy for the ECM process to have a different scale aspect 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 has been illustrated here.
This is a micro gearing for example. Now, this, for example, is a biomedical implant. It is an extremely complex topology which otherwise may not be machinable with the conventional machining process. So, this implant is basically a knee replacement system. And they are 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 complexities that ECM process can handle if it can do proper finish machined surfaces in case of knee replacement like this. This actually shows the cross-section of the ECM processes applied to the metal impact. 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. And the machined surface, final machined surface is a cavity shown by this yellow region. So, it is otherwise very hard and difficult to obtain such a structure using conventional micromachining. And therefore, ECM is very well suited for such applications. So, in a nutshell, 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. So, not only it can handle complex shapes 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, it is passive non-contact, and it leads to the prevention of all sorts 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 warpage or a deterioration 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 ECM processes. So, that is how the process capabilities of this ECM process is detailed. And because of such capabilities, there is a huge need for the electrochemical processes, particularly at the microdomain and we call this electrochemical micromachining ECM.

So, the machining activities have translated to the microdomain 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 venturi, small orifices which etcetera which are used in nozzles for fuel injection purposes. And that is one of the best utilizations of this complex micromachining processes which are repeatable in nature which have direct impact on the society. So, in case of let us 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 micromachining.

Other aspect that is involved in you know directly with the direct application of the ECMM can be felt is in the biomedical domain, particularly in the surgery domain where there are small catheters 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. And 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 it is a 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. And they are with due acknowledgments to the concerned groups which have worked in this area.

So, the first comparison that I would like to draw between ECM or ECEMM, or ECMM process that is electrochemical micromachining or electrochemical machining process is given in this table very nicely by Bhattacharya et al. in 2004. And here, so let us look at some of the differences in terms of the major machining characteristics in both these processes ECM and EMM or ECMM. 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 ECMM process the micromachining the voltages are very often less than 10s of volts. And the current used in ECM is as high as 10 kilo amps varies all the way to 150 amperes, but we want to keep the current in the micromachining domain as minimalistic as possible.

So, typically it is less than 1 amperes. Similarly, the current density in the ECM is quite high 20 into 200 ampere per centimetre 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 a 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 modelled earlier and told earlier. And here the idea is to be able to as quickly as possible remove whatever small material you want to remove in the micromachining 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.

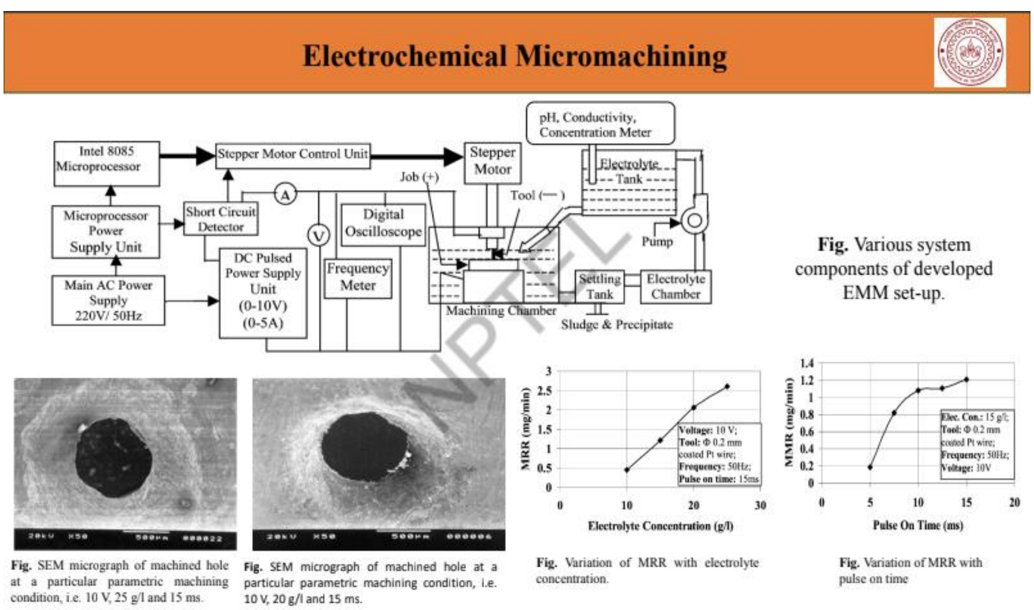
Whereas, in the EMM case you only use pulsed DC signals as the major machining signals, or the frequency of the pulsed signals are typically in this case of ECM hertz to kilohertz range. But you know in the EMM it has to be very high. So, that you have very less scope of a redeposition and the frequencies in the EMM domain is typically kilohertz to megahertz range. Similarly, the electrolyte flow is restricted to a lower value in case of EMM less than 3 meters per second. Whereas it 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 are 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 ECM or the micromachining case. The temperature range is quite moderate varying between 37 to 50 degrees Celsius. The electrolyte concentration as I told you earlier is kept quite high in case of ECM but is reduced in case of electrochemical micromachining. And if we talk about the gaps or the model the magnitude 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 micrometres in ECM, but it changes to 5 to 50 micrometres in EMM. So, dual layer also is quite commensurate with a few tons of nanometres 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 maskless in nature, but you need sometimes usage of masks in case of EMM operations. Sometimes it can be maskless, but if you had to selectively introduce small feature sizes in maybe hundreds of nanometres regions.

So, in that case, you probably need a mask to do the ECM process at the micron scale. Machining rates is very visible is commensurate with the current data and also the current density data. In this particular case the machining rate, the micro machining is almost of the level of micrometres per minute. Whereas, in case of normal ECM processes it is about tons of millimetres per minute. So, there is a huge difference in the way that the material removal is taking place.

EMM the material removal is quite slow by an order of magnitude almost. The side gaps in this case comes to be about greater than 20 micrometres particularly the oversize of the drills etc. 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 up to the micron domain about close to 0.02 millimetres or about 20 microns in case of EMM. Whereas, in case of ECM it goes to all the way to 100 microns. So, definitely, the EMM is a much more surface-oriented, surface topology-oriented process. The surface finish is pretty good in ECM, but if you talk about EMM it has to be really excellent. And as low as 50 microns of 50 nanometres level is desirable. So, that is in a nutshell what the parametric differences are between the ECM and the EMM process.

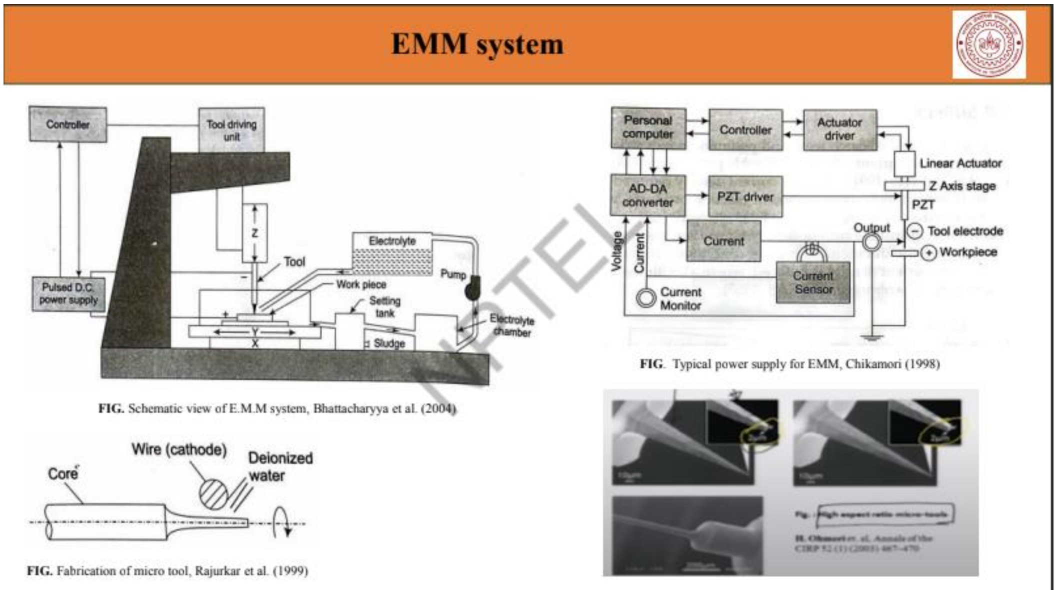


Let us look at some of the work done by many groups earlier. This shows how the ECM unit is more controlled process than the ECM unit. Here this region is really the region which is the machining centre you have a workpiece.
Here you have a tool region again tool is negative workpiece is positive as any other ECM process. There is an electrolyte which is being pumped through this nozzle right here into the workpiece zone.
And of course, there is a flow handling system. So, you have a settling tank for the sludge to get settle down there is a filtration system there is a pump there is an electrolyte chamber. So, which causes the electrolyte to recirculate. There are different controllers here there is an Intel 8085 microprocessor which this group is using for setting up such a system. There is a stepper-controlled 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 workpiece. There is a short circuit detector there is a DC pulse power supply and there is a measurement frequency meter which monitors what is the frequency at which the pulsating is happening.

The digital oscilloscope to monitor the signal as well. And then there is of course, a microprocessor power supply 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 the scaling electron micrographs of machined holes at a particular parametric machining condition. Machining conditions use at 10 volts DC pulse supply 25 gram per litre 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.

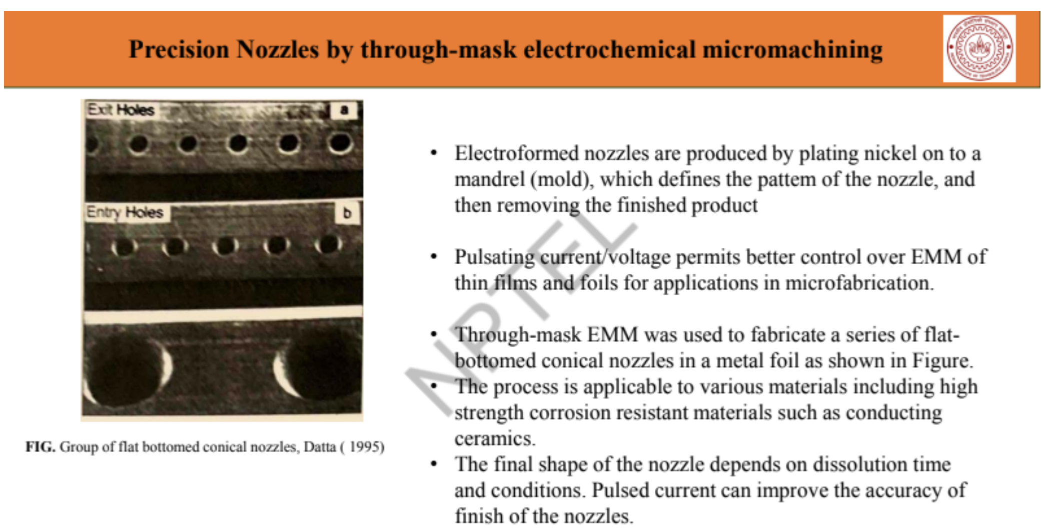
The whole picture here is corresponding to about 25 gram per litre which is somewhere around this region. So, this is the value that has been illustrated where machining has been carried out. Some other parameters related to this process are that they use a tool which is about 200 microns diameter coated platinum wire and the pulsating frequency in this case about 50 hertz and 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 is more which is obvious from an illustration given earlier in ECM that as can be seen in this formulation here where Cd is the diameter oversize, V is the voltage and a is the 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 an increased or enhanced feed of the workpiece towards the tool towards the workpiece.

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 on time, and if the electrodes are facing voltage for a higher duration the diameter 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. The other example that I 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 tip size 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 an almost a size of a 2-micron tip by virtue of shear at a certain higher temperature where the glass achieves flowability.



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. The workpiece has been given small rotations and the wire cathode has been able to generate this kind of a very pinpointed 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. Let us look at a few more examples of what EMM electrochemical machining can do, micromachining.

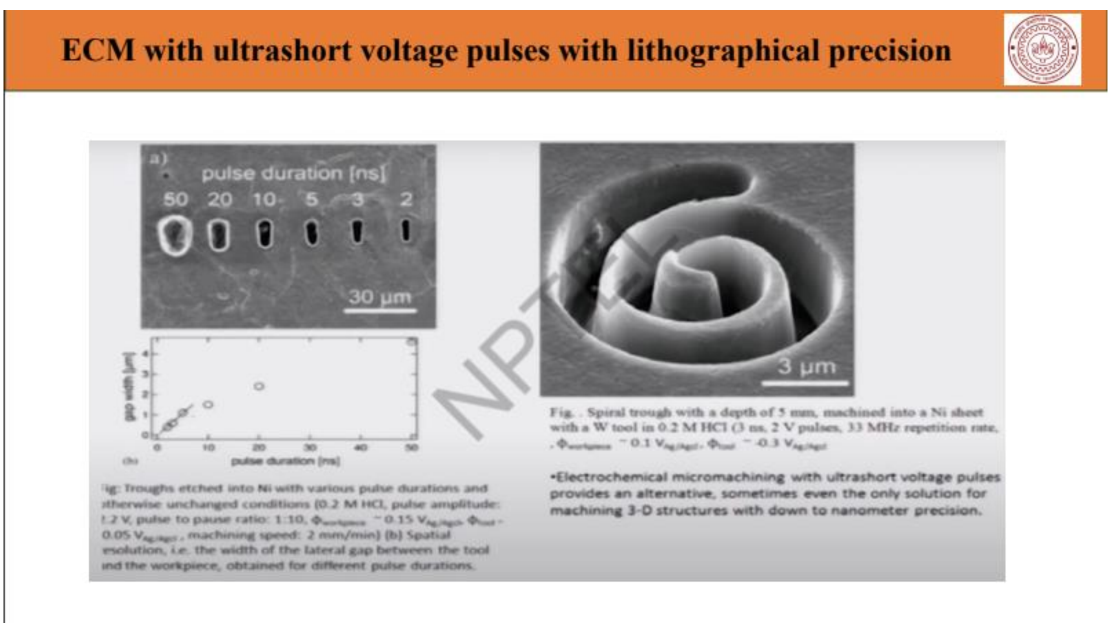
This, for example, is again borrowed from this group Dutta et al. in 1995 and they talk about the fabrication of precision nozzles through a mask approach.



So, they use, they develop this electroformed nozzles and they are produced by plating nickel onto a mandrel Mold which defines the pattern of the nozzle and then removes, remove the finished product from it. 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 through mask EMM with this through mask this and using the EMM process you are fabricating a series of flat bottom conical nozzles in metal foils as shown in these 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. A 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, pulse current has been seen to improve the accuracy of the finish of the nozzles.

So, this is another illustration where almost nozzle diameter close to the range of about 10s of microns have been fabricated in a 25 micrometre 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 case is about 4 molar NaCl and combination of 2 molar glycerol and about 100 ppm FC98 and they use a pulsating voltage here in this case of 12 volts with a on cycle time of 5 milliseconds and a off cycle time of 95 milliseconds. So, you are using mostly 5 percent of the total voltage cycle. So, you can see the uniformity and the smoothness with which these nozzles have been produced using mask electrochemical micromachining.



The other example that I have borrowed is from Kock et al's group which they reported in 2003 where they talk about the fabrication of various ultra-short or 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 is how small the pulse duration is that is why they call it ultra-short pulse duration. And the other conditions which are specified in this particular setup is corresponding to 0.2 molar HCl as the electrolyte. There is a pulse amplitude they are 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 they are using of this particular pause. So, also that the potential that they are using on the workpiece is close to 0.15 volts as measured with respect to Ag-AgCl 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, actually, 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 millimetres per minute and they are getting a 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 reducing as you are increasing the pulse duration from 2 nanoseconds to 50 nanoseconds.

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 15 microns 10 to 15 microns. So, they do find 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 the 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 millimetres which is a very high aspect ratio in terms of all the machining which has been demonstrated so far. So, they use a 3 nanosecond 2-volt pulse, and their repetition rate or the pulsing frequency is close to 33 megahertz. 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 workpiece potential in this case is 0.1 volts with respect to an Ag-AgCl electrode and the tool potential is calibrated as minus 0.3 volts with respect to Ag-AgCl electrode. So, these 2 illustrations definitely give us an insight 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 LIGA, etc. And then this can provide a one of the very important solutions for particularly 3D structures or 3D micromachining or 3D structure fabrication. The other option is, of course, LIGA which is lithography Galvano-firming process.

I think I had illustrated little bit, and I am going to do some more examples later on for LIGA. 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 rhyme very well with some of the precisions given by the LIGA process. So, this kind of brings us to an end of today's lecture on 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 modelling of EDM at this stage, I will just show you some applications related to EDM which is electro-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. And 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.