Advanced Machining Processes
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Week - 06
Lecture - 14
Electrochemical Drilling & Grinding

Hello, and welcome back to this course on Microsystems Fabrication by Advanced Manufacturing Processes. So, we will quickly recap what we tried to learn in last lecture. Here as you see we tried to plot the workpiece profile into the tool profile. So, that we can do it in a 2D, and a 3D say 2-dimensional and 3-dimensional basis. We saw that if we plot a curve on the with the certain fixed relationship parametric form between x and y, what would be the corresponding tool equation or vice versa, provided you have a certain gap equilibrium gap and uniform field. We also said that if a surface is made up of many topologies of different regular surfaces connected together, then it is a good idea to individually replicate the corresponding part of the tool piece surface based on whatever functional relationship exists into the part of the workpiece surface.

Assuming the constant field criteria and then integrating the overall surface to have the whole complex profile, where close form expression of electric fields are available, particularly for regular cases, there is no problem as such the whole surface can be taken into picture. We also learnt about electrolyte flow and the designing of these flows and in that context, I would like to mention that the most important part in an ECM is to see if the tool is designed for the flow to cover all the zone of between the workpiece and the tool surface. If there is some residual area which is left over from the flow field, there is a tendency of the machining to be uneven, non-uniform, and then the die-sinking process or basis of the ECM does not come into the picture. We also looked at some properties which are desirable in electrolytes.

For example, they should be as non-toxic as possible, they should be able to allow charge transport in a smooth manner thus precipitating whatever emanates from the anode the workpiece side. So, that it can be carried away as a debris material then should be amenable to slightly higher temperatures, and it should also be less viscous as less viscous as possible. So, that there are diffusion you know based flow of debris into the flowing fluid so on so forth. And a variety of other properties like thermal stability, electrochemical stability etcetera should be analysed when we talk about different properties. We also looked at some standard metals and the electrolytes which are used there in for the purpose of ECM and then we designed certain electrochemical machining plants looking into the very basic requirements of such ECM units.

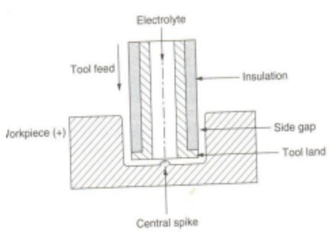
The basic requirement is a rigid stage and a rigid workpiece tool holder which is important because the gaps which are maintained while in equilibrium of an ECM process is typically of the order of a few microns, few tens of microns. And then it necessitates the surface properties become more prominent it necessitates the viscous forces over the inertial forces. So, there is a dominance, and therefore, because of the viscous forces there are large pressures which are felt, and the tool should be able to handle such pressures without getting warped or wobbled. And therefore, the stage needs to be very-very rigid while feeding the tool. We also learnt about the various aspects of the electrochemical machining system as such for example, you have to have a slurry tank, you have to have a process of filtration where the primary debris which comes out can be removed selectively.

And then you know the slurry can be re-circulated back into the system at a certain velocity. There should also be a bleeding mechanism where whatever slurry is going in the corresponding amount of air, which is closed in that enclosure, tank-like enclosure where ECM is carried out should be bleeded out. We also should try to avoid as far as possible metals in contact with the electrolyte other than the workpiece zone. So, everything whatever is holding the electrolyte should be properly coated. So, that there is no electrochemical machining action on the same although the most amenable to such actions is the tool holder.

And so therefore, proper coating of these tool holders are needed to prevent any stray machining to take place because of splashes, etc. as is the normal case with such electrolyte. So, wherever there is a field and wherever there is an electrolyte there is a possibility of machining which gets introduced. So, today we will be looking into slightly different aspect of ECM and the other corollary processes or associated processes like electro stream drilling, ESD, or electrochemical grinding ECG. And what are the basis, what are the basic mechanisms associated with material removal in such processes.

Electrochemical Drilling

- This process is shown in the figure below.
- A tubular electrode tool is used as the cathode.
- Electrolyte is pumped from the center of the tool and exists through the side machining gap, formed between the walls of the tool and the drilled hole.
- Machining occurs at high current densities in the frontal inter-electrode gap between the tool face and the work-piece.



- Side electrochemical dissolution acts laterally between the side walls of the tool and the component.
- The produced hole diameter is therefore greater than the tool by an overcut C_d.

Of course, the primary mechanism is electrochemical machining, but there are certain other important aspects which are coupled to the ECM process in order to formulate these new processes which exist. And for microsystems application these learning these nitty-gritty of the associated processes of the electrochemical machining is very important from a standpoint of manufacture. So, let us look at these processes, and to begin with we start with just electrochemical drilling operation. So, the fundamentally this process is illustrated here. So, you have a tubular electrode which is used as a cathode in this case which is also the tool.

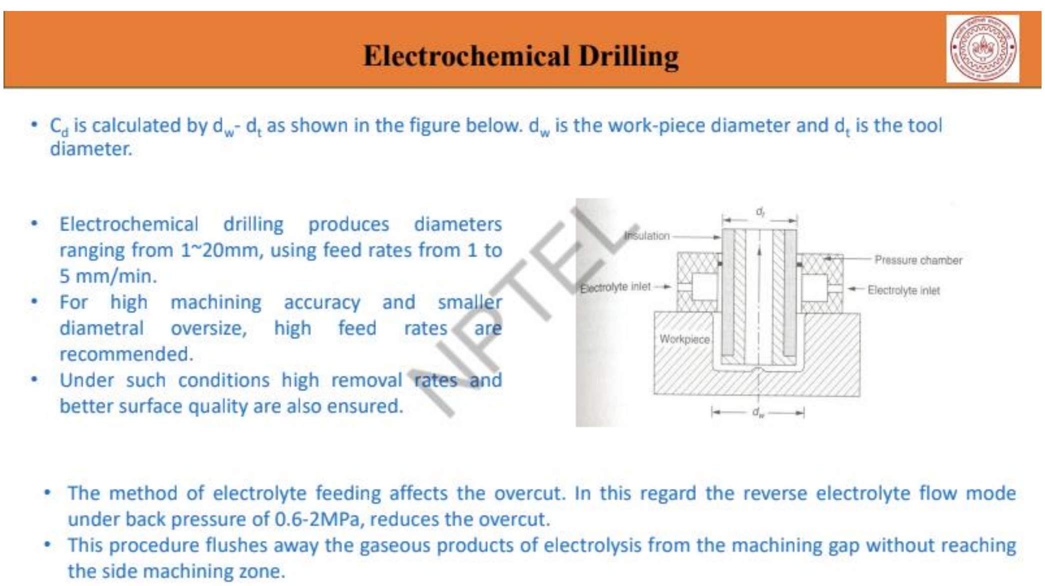
So, this is the tool side. The electrolyte is pumped from the centre of the tool and exist throughout the side machining gaps. So, therefore, the electrolyte is transported here in this axis of the tool, and it emanates sidewise. So, it goes between the workpiece and the tool gap and the machining gap which is formulated here. So, it basically also gives the question of how much protection you should give in terms of shielding the electric field which is between this electrode here and the tool surface.

So, you have to provide proper insulation in the sides. So, that there is no stray machining effect which happens because of sides of the electrode. Now, it is a drilling operation meaning thereby this hole that you want to drill is a through hole. So, definitely, it is a high aspect ratio structure that we are trying to fabricate in a bulk micromachining sense across the thickness of the material. The machining occurs at high current densities in the frontal interior electrode gap between the workpiece and the tool face this gap right here.

And of course, as you know here because of this presence of the flow dynamics across the emanating surface of the tool of the electrolyte there is a ridge which is automatically formulated. So, because this is a sort of place where the fields may not be that homogeneous or uniform. The fields may exist between, for example, these 2 sides. So, the electric fields and the current densities are highest here and the field reaching here because of these electrodes here may be smaller in value. And therefore, this region is depreciated of the overall electric field that it faces.

So, there is a tendency of this ridge to develop and that is only because of this coaxial portion done in the tool for the electrolyte flow. Side electrochemical dissolution acts laterally between the side walls of the tool and the component somewhere in these regions here. So, the side gaps on both sides which exist is where the side electrochemical dissolution would happen. And let us say if you want to produce a certain hole diameter Cd this overall machining dia which comes out would be definitely more than Cd. So, if this is the machining dia and the machining dia which comes out is greater than Cd in this particular case because of side machining.

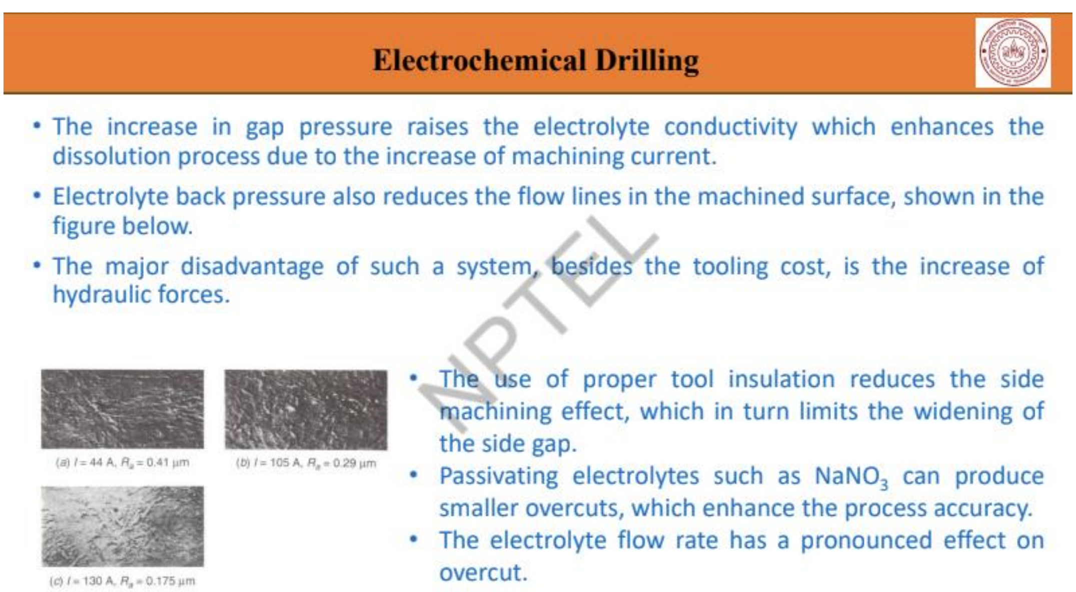
So, the Cd is calculated by the following manner. So, if supposing dw is the workpiece dia which eventually gets formulated and dT is the tool dia.



So, definitely, this Cd or the side machining gap happens because of the difference between dw and dt. So, dw minus dt is Cd. So, electrochemical drilling produces diameters ranging from about 1 to 20 millimetre and using feed rates from 1 to 5 millimetre per minute typically that is what the range is and for high machining accuracy and smaller diametral oversize high feed rates are recommended.

So, under such condition high removal rates and better surface quality are also ensured. So, the method in which you feed the electrolyte sometimes influences the overcut as such and the overcut is basically the amount of Cd which is basically the difference between the workpiece dia which gets finally formulated, and the tool dia that you are using. So, for example, in this regard, the reverse electrolyte flow mode under back pressure reduces the overcut. So, if instead of making the electrolyte flow in this direction you are trying to flow the electrolyte in a reverse direction entering from the side and going towards the axial centre will definitely have a smaller Cd or a smaller overcut of the hole that you want to produce. The only thing you have to ensure that there has to be a back pressure of about 0.6 to 2 mega Pascal for this. So, what it does is that it procedure flushes away the gaseous products of electrolysis for machining gap without reaching the side machining zone. And therefore, whatever conductivity changes locally would happen because of the dissolved gases those changes will not happen. And so, the machining will be more precise because of the back pressure it ensures that the gas kind of oozes out of the whole electro-electrolyte tank as such. So, that is 1 aspect of its electrochemical drilling.

Now, 1 thing which is important here to mention is that the increase in the gap pressure as you have seen before between the workpiece and the tool. So, this gap raises the electrolyte conductivity, and it enhances the dissolution process due to increase in machining current naturally because the gases are no longer getting trapped here. Because there is a back pressure, and the gas gets diffused away from the electrolytic system and you are assuming that you are flowing the electrolyte under the back pressure from the side to the centre. So, generally what people have found is that this electrolyte back pressure would reduce the flow lines which otherwise happens on a machine surface. For example, you can have a look at the surfaces here which are products of the electrochemical drilling.



And you can see that there are varied level of surface roughness's which are achieved because of different current values that you are using. So, if the value of current is 44 amps for example, the roughness is 0.41 microns, if it is 105 amps the roughness is about 0.29 microns and if it is 130 amps it is about 0.175 microns so on so forth. So, as you are seeing here that if the current density is more or the current per unit area is more that you are pumping in the roughness is overall reducing from 0.41 microns to about 0.175 microns. So, 1 aspect is, of course, electrolyte back pressure of reduction on the roughness as I have already told. The other aspect is the amount of current that is being used for the purpose of the electrochemical machining.

And 1 again disadvantage, a major disadvantage of such a system is that beside the tooling cost the overall system dynamics if the hydraulic forces are more would go up. So, the cost of the system also for designing an electrochemical system which can handle increased hydraulic forces, increased pressures would be very high. Remember that rigidity aspect of the tool holder etc., which we discussed while designing the electrochemical machining process. Of course, you need to use or properly insulate the sides of the drill, the electrochemical machining has the same parameters as any other ECM process.

So, if side insulation is not happening then there is a huge amount of Cd which is created because of additional electrochemical transport between the side and the tool face itself. And therefore, we can say that use of proper tool insulation would reduce side machining effect and this in turn would limit the widening of the side gap. So, you can have more accurate processes if insulation is proper. So, 1 important aspect which we have actually studied also while doing this theorizing of electrochemical machining and ion transport as we have seen before is that there are certain passivating agents which you would use from time to time in electrolytic solutions. So, that you can get a better surface finish.

For example, it has been seen that if NaNO3 sodium nitrate solution is used along with salt water there is an action which creates a smoothing, a self-smoothing effect of the surfaces that are produced. And also, it can remove process inaccuracies. So, you can have exact size of the Cd, the overcut, very small amount of overcut, and all those processes related to the accuracy of the tool. And the reason why that is so is that the passivating electrolyte is creating generally an ion atmosphere which shields which is maybe a non-participating ion in the whole process. NaNO3 for example, is a non-participating ion when the electrolyte is NaCl and water normally salt water which is used for the machining of iron workpieces Fe.

So, if it is non-participating the goal that that particular solution, passivating solution would have is it would produce a high-density field as such where the ion of interest that is being machined would easily get emanated out. And there may not be a problem about getting influenced by the fields that are emanated from the workpiece or the tool as such. So, you are creating a situation which is free for the ion of interest to move freely. That means it comes out into the solution does the precipitation everything free of the fields that are imposed to this ion by either the tool or the workpiece. So, that kind of a goal is being achieved by a passivating electrolyte and the purpose of it is also to create a large background field in the solution itself.

So, that the effects of the tool and the workpiece gets minimised that way. So, as we know that as we have seen that electrolyte flow definitely in this particular case in drilling particularly has a huge impact on the process overcut. So, if the flow rates are slightly higher the velocity is higher, and the overcut may be more if the velocity is an optimum best the overcut may be lesser so on so forth. So, there are certain other aspects of this machining, for example, the machining current increases proportionately to the tool feed rate. If the tool approaches the workpiece at a higher speed and the machining current would be more because you can obviously, think of it because the amount of field which is created is also inversely proportional to the tool electrode gap, and as this gap is reducing in a faster manner thereby meaning the tool is approaching faster to the workpiece.

Electrochemical Drilling

- The machining current increases proportionally to the tool feed rate.
- Sparking takes place when the tool advance rate towards the work-piece is greater than the anodic dissolution rate.
- Under such circumstances the frontal gap decreases to a critical value at which sparking occurs, causing damage to both the tool and work-piece.
- An empirical relationship has been derived between the diametral oversize 'C_d', the gap voltage 'V' and the tool feed rate 'a'.

  $C_d = 0.225\ V^{0.74-0.056a}$

The amount of increase in the electric field because of that approach also is more and subsequently field and current density are connected by an equation J equals field times of K where K is the conductivity. If the conductivity is assumed to be the same in that situation, we can say that the current density or ion transport would be more if the field is more. So, the rate of approach with the reduction of distance between the workpiece and the tool thereby increasing the electric field ensures greater current densities which would then machine at a higher machining rate or material removal rate. So, there are certain ill effects which take place, particularly in electrochemical drilling process. For example, one such undesirable effect is sparking, and sparking typically takes place when the tool advance rate towards the workpiece is greater than the anodic resolution rate.

So, you already know from the electrochemical machining theory that if the tool is approaching the workpiece there is one aspect of the tool getting dissolved. So, that the surface the workpiece getting dissolved that the surface of the workpiece recedes away from the tool and then there is the other aspect of the tool getting fed in and the overall equilibrium happens when the amount of or the rate of at which the workpiece surface is dissolving is the linear rate at least is same as the feed rate that is how you calculate. So, if there is a difference as such because of a fastly approaching tool or a rapidly approaching tool if there is a difference in this rate of dissolution then there would be a tendency of the 2 surfaces to touch each other, and even when it comes to just about touching there is this sparking phenomena which is essentially a discharge an ionic discharge which would happen because of the very small hills and valleys produced on both the surfaces that is the tool and the workpiece surfaces and they getting in very close proximity to each other. So, the field is so high that it boils off the electrons from the small hills and valleys and that results in a sparkling. So, you have a tendency of sparking particularly at a higher advance rate tool advance rate where this rate is much more than the dissolution rate of the workpiece and we should not go towards the higher tool advance rate by the way because the process is disturbing and there is a huge amount of impact on the power source because of this sparking and we should, by and large, avoid that in case of electrochemical machine.

So, it can cause damage, particularly to the tool and the workpiece. So, of whatever has been experimentally determined there exists this empirical relationship between the diameter over size Cd which is actually equal to this workpiece dia minus tool dia. We have just seen it in the last example, the last schematic, and the gap voltage between the frontal end of the tool and the workpiece surface as such this is V. Particularly for a particular feed rate let us say if a is the feed rate in that case empirically it has been determined by experimental observation that the Cd what happens is proportional to the power of voltage to the power 0.74 minus 0.056 a. So, this a is basically in millimetres per minute. So, that is about what we have for electrochemical drilling process. The next example that I would like to consider is another corollary or an extension of the electrochemical machining and it is called ECG or electrochemical grinding.

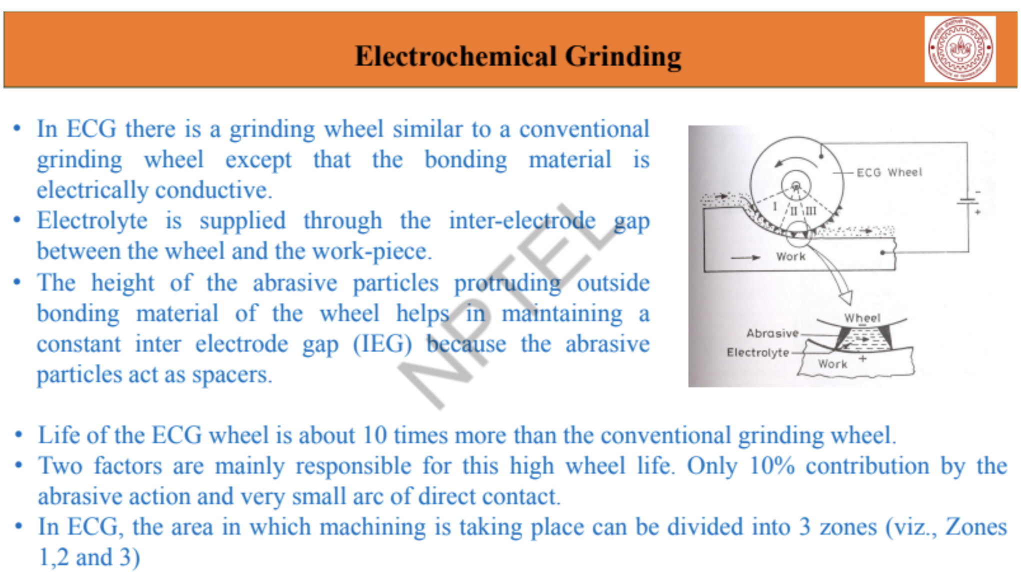
And let me just recall a little bit about what conventional grinding typically does. So, conventional grinding is a very fine machining process which in general produces a superior surface finish of the components. And the conventional grinding is typically used as a finishing operation on most of the components that are sent for grinding because they are dimensional tolerance as such is low. But the dimensional tolerance gets significantly affected with associated problems like burr, burrs or comparatively large heat-affected zone, or thermal residual stresses which would create a sort of breakdown of the surface structure right. Because grinding is a multiple-cutting tool with lot of abrasive particles which are embedded into a matrix which rotates with respect to a workpiece. And there is a heavy amount of deformation on the surface, plastic deformation on the surface which happens because of the small abrasive grains continually hitting the surface at a very small depth of cut. So, in fact, the grinding is an operation where you get mostly splinters coming out which means that the metal which is emanating is so small that it gets oxidized and burnt away as it goes out of the surface.

So, therefore, in a normal mechanical grinding as such you can say that although it is a high tolerance, high you know super finish. So, basically, lower tolerances can be achieved using that grinding. But then this dimension, dimensional tolerances are significantly associated with these different problems, burrs, heat affected zone of the workpiece or residual stresses which is there. So, the surface gets modified because of these problems. Now, in order to take care of such problems in a conventional grinding people have switched on to electrochemical grinding or ECG which is actually a process where at least a part of the material removal which takes place is by electrochemical dissolution.

And as such the surface finish would be much more in case of ECG than in case of a conventional grinding system, mechanical grinding system. So, we can say that electrochemical grinding process has mostly these defects taken care of, and you can get anodic workpieces which are mostly free of burrs because of the ECG process. So, during electrochemical grinding, the material is removed by mostly as I told you electrochemical dissolution, which is about 90 percent of the overall material, and then a little bit by mechanical abrasive action which is about only 10 percent of the material removal. So, one has to design the tool system in a manner so that the dissolution is at such a rate that it removes 90 percent of the material work material at a very high rate. And by the time some abrasive action mechanical abrasion action starts taking place already a lot of material has been dissolved away.

So, that is how you have to design the ECG or the electrochemical grinding process. So, one very important and significant aspect of ECG that is that the workpiece and the grinding tool both have to be conductive in nature because it is an electron flow process. So, you cannot have one of the components non-conductive or insulating in nature both of them have to be essentially metallic as far as the surfaces go. And therefore, the ECG tools so created are having this component ensured that they have overall a high conductivity on the surface not all grinding tools are conductive in nature, but at least the electrochemical grinding tool is designed in a manner so that it has high conductivity on the surface. So, the electrolyte is circulated in a ECG process and there should have there have to have so it has to have an effective recirculation system which includes a flow supply of the electrolyte and also a flow filtration system where whatever residue of the process comes out as dissolved electrolyte and the precipitate which is coming out for precipitate of machining that has to be somehow taken away from the electrolyte for recirculating it back into the process.

And we have seen that this sodium chloride and a passive wetting agent sodium nitrate $NaNO_3$ is typically used most of the time for ECM processes. So, we can say that in this ECG process also a similar composition can be given. As I already illustrated earlier the role of a passive wetting electrolyte is to create a high field. So, that as such the ions which come out do not get influenced by the workpiece in the tool surface. So, if we look at the basic process mechanics in an electrochemical grinding operation it is represented in the schematic here.



So, you have a grinding wheel which is almost similar to a conventional grinding system and here as I already illustrated the bonding material is not any epoxy or any non-conducting system it has to be essentially electrically conductive binding material to make the ECG wheel.

So, the electrolyte is supplied through the IEG or the inter-electrode gap here in this particular case this gap right here is the IEG or the inter-electrode gap and that happens between the wheel and the workpiece. So, the gap here is basically between this wheel ECG wheel and the workpiece. So, 1 more aspect is the height of these abrasive particles which are bonded onto the metallic wheel. The height sticks out to just about an extent where it is equal to the inter-electrode gap.

So, for 1 instance of operation, there is a cell which is formulated between let us say the 2 abrasive grains which are there on the surface the workpiece and the matrix the conducting matrix binding the grains on the wheel side. So, there is a small electrochemical cell a local electrochemical cell which is created in this manner between the ECG wheel and the workpiece. So, you have to ensure that the height of the abrasive particles protruding outside the bonding material would be kind of all similar in shape or constant in size, and therefore, it has to help in maintaining this inter-electrode gap because of the abrasive particles which act as spacers in turn and then it tries to create a compartment holding an electrolyte for high rate of dissolution on a local area between the wheel and the surface in question. So, some facts and figures about this ECG process a conventional you know grinding wheel if you look at the lifetime and then you compare it with the ECG wheel it is about 10 times more if you consider an electrochemical grinding wheel. So, the surface the overall the effective lifetime of such an ECG wheel is much more than a conventional grinding wheel here because you are not doing any mechanical abrasive action.

In fact, in conventional grinding, you have to do an operation of dressing where after every grinding process you have to redress the tool in order to start up an issue and one of the reasons is that most mechanical abrasions result in clogging of the gap between the abrasive particles on the surface of the wheel. In this particular case that is not the case because you are also carrying away the precipitate which is coming out of the material in the electrochemical machining aspect of the ECG and the tendency or the chances of the pockets to get redeposited with the debris is miniscule because you have designed the electrolyte in a manner in that manner. So, that whatever comes out goes as a precipitate and not as a deposit. So, therefore, ECG wheels automatically are about 10 times more in terms of their life than the conventional grinding system. So, the effective area in which machining is taking place can be divided into 3 zones and you can see them marked here as zone 1, 2, and 3 respectively.

Let us see individually what happens in all these 3 different zones in the ECG process. So, as I already illustrated before the electrochemical grinding is a combination of electrochemical dissolution as well as mechanical abrasion or removal of material mechanically. There is a 90-10 combination. So, 90 percent of the material gets removed by ECM process and 10 percent gets removed by mechanical abrasion process. So, there has to be some parity between these zones so called zone 1, 2, 3, and these different aspects of the ECM, and we will just see that zone by zone.

So, in zone 1 the material removal is purely due to electrochemical dissolution because you can see here that the abrasives are hardly in touch or hardly in contact with the workpiece. So, there is no mechanical abrasion as such which happens in this particular zone, zone 1. So, it is only whatever ion transport is taking place between the work piece surface as such this surface and the tool surface, which is a conducting matrix with particles, abrasive particles. So, rotation of this ECG wheel, of course, helps in drawing the electrolyte into the IEG.

So, it is a self-priming process. So, even if electrolyte is in the near vicinity and you are moving the grinding heel in a certain direction it is obvious to assume that whatever small fragments are coming out or sticking out as abrasive particles on the wheel they would pedal the electrolyte. So, it is a self-paddling action which would happen of the electrolyte, which is around here, and it gets pushed into the IEG or the inter-electrode gap. So, as a result of this whatever machining you are having in zone 1 and whatever reactions electrochemical reactions in zone 1 the products which are coming out of this zone as such start contaminating the electrolyte. So, in zone 2 and 3 whatever is the available conductivity of the electrolyte which is available here this conductivity is decreased because of whatever byproducts like debris and hydrogen gas is packed in zone 1 because of electrochemical dissolution.

So, in fact, there is a counter-effect. So, if the sludge is present or the debris is present the conductivity goes up and if gas products are present or gaseous products of the reactions are present the conductivity goes down. So, 1 is exactly counter to the other. So, if sludge is more than the conductivity is higher if gases are more the conductivity is lower. So, the net result is that there is a overall decrease in the value of conductivity of the electrolyte because gases are emanated and dissolved into the electrolyte system much faster in comparison to the dissolution of the debris which is solid and which is limited by diffusion kinetics.

And therefore, it yields a lower value of equilibrium gap. Equilibrium gap as such if you may decipher from your previous analysis on ECM is really determined by this lambda by f. So, that is what the equilibrium gap is and lambda is dependent on the conductivity. So, if conductivity is low then the equilibrium gap also automatically falls down. So, the IEG decreases because of a decrease in conductivity. So now, although the conductivity is lower and there is a certain smaller dissolution rate in zone 2, but as you can see here that between 1 and 2 there is a automatic transition which happens right and the particles here start to be in direct contact with the workpiece.

So, the transition between 1 and 2 zones brings in the additional contact of the abrasive particles with the workpiece. So, there is certain one-to-one contact between the particles on the wheel and the workpiece surface which happens on the transition between zone 1 and 2. And therefore, a small part of the material that is removed is in forms of chips as well. The moment it enters into zone 2 as you can very well see here by this blown-up schematic or portion of this 2 here, because of the direct contact of the abrasive particles with respect to the workpiece there is a formation of the small localized electrochemical cells, and these cells are formulated throughout the width of the grinding wheel because there are many such particles which are there. And in fact, we are talking about a very thin film of electrolyte and this thin film is more amenable to surface effects, because the gap is very small, and it prefers to stick to the surface because forces of adhesion are more to the surface than the forces of cohesion.

It is a very-very small thin film. So, it basically tries to contain itself in that small gap along with the tool and the workpiece and formulates a small electrochemical cell. So, there are several such cells across the width of the grinding wheel between the workpiece and the grinding surfaces which are formulated in this machining zone 2. So, therefore, in zone 2 the electrolyte is being forced into the equilibrium gap by the rotational motion of the wheel, and therefore, because of these formations of electrochemical etcetera the local electrolyte pressure increases in this part of the IEG. So, the pressure is very high and of course, it suppresses the formation of gas bubbles and that results in yielding a higher material removal rate. So, whatever gas bubbles are formulated here it gets suppressed and it was already the pressure ambient pressure is very high and therefore, slightly higher MRR is desirable in this particular zone because you are suddenly squeezing the electrolyte into a very small area region thus increasing the pressure likelihood of increasing of pressure.

So, whatever gas has been dissolved from the previous zone sort of bubbles out of the system. So, whatever chemical or electrochemical reactions which is the principal removal mechanism in zone 2 here takes place between the work and the tool it may result in the formation of a passive layer particularly on the workpiece surface. So, here in this particular surface, there may be a passive layer which is a deposit, because it is already very small and then there are diffusion limitations and the debris which has been generated here goes into the cell and comes back once you know the wheel rotates and the next cell comes in place. So, there is always a formation of a passive layer, because of debris redeposition in this particular zone 2.

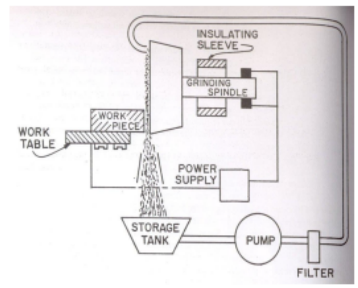
Of course, because the abrasive grains are also in contact. So, when this grain moves with the motion of the wheel in a direction opposite to that of the feed of the workpiece there is a tendency of scratching the workpiece, particularly the surface layer which has been formulated. So, whatever reactive oxides sorry non-reactive oxides are formulated here, because of may be deposit of debris or deposit of some electrochemical products from this flow cell they are being scratched. So, there is a removal of that layer the passive layer formulated here or the passive layer, because of any other electrochemical deposition as such which is taking place in this region. So, at the end of the day when this zone 2 is crossed, the surface is kind of brought back to fresh, because there is already a scratched mechanical action initiated by these abrasive grains towards the end of zone 2.

And there is a general removal of the non-reactive oxide layer. Finally, the zone 3 comes into picture where there is mostly electrochemical removal because there is a field which exists there is no direct contact of course, between the grains sticking out of the wheel and the surface. But then because of the ambient field and the presence of the electrolyte which in self has been thrown by the grinding wheel forward, there is always a tendency of the material to remove in an electrochemically dissoluting mode. So, it starts at the point where the wheel lifts from the work surface point here may be right where the there is a separation between the grain grinding grain and the surface. And suddenly there is a pressure release also which happens in this particular zone, because earlier the electrolyte was being trapped as a flow cell between the workpiece and these 2 grains and the wheel on the other side and suddenly the electrolyte has been thrown into the open. So, therefore, this zone sort of contributes the removal of those scratches or burrs which have been formulated because of the mechanical abrasion in zone 2.

So, those burrs are eliminated in zone 3. So, that is about the basic process of electrochemical grinding. There are certain other aspects associated with the machine tool as such. It has to be a rotor-driven tool as any other normal grinding process because there has to be relative rotation between the electrochemical wheel and the workpiece surface. So, this slide here illustrates briefly how the electrochemical grinding machine tool would look like. So, you have a workpiece here for example, and then you have a grinding spindle, and this is the grinding wheel and there is a flow of electrolyte past the grinding wheel.

ECG machine tool

- The ECG systems are very similar to conventional grinders.
- In ECG system, the machining area is made up of non-corrosive materials.
- Power is supplied through the spindle either with the help of brushes or mercury coupling.
- The latter can carry more current than the previous one.
- The probability of short-circuiting during ECG is very low because of the presence of protruding abrasives which create a positive IEG.



- Hence this system does not need many short circuit cut off devices.
- Four different kinds of ECG operations can be performed, viz., electrochemical cylindrical grinding, electrochemical form grinding, EC surface grinding and EC internal grinding.
- EC cylindrical grinding is slowest process because of the limited area of contact between the wheel and the work-piece.
- EC surface grinding in the fastest among all because of the high contact surface area between the cathode and anode.

So, you are flowing the electrolyte very close to this wheel here and the wheel starts working on the surface, workpiece surface by positioning relatively with respect to a high precise worktable. And whatever material comes out as debris or gases in the electrolyte is stored here in the tank which is again reused by a set of filtration techniques and pumping techniques. And there is, of course, a power supplied between the workpiece and the grinding tool to ensure the electrochemical transport. So, by and large, the following things need to be taken care of for designing such a system. The first thing is that material the machining area should be made as non-corrosive as possible because it is in direct touch with the electrolyte.

So, things like let us say the workpiece holder or even the tool holder here right here has to be as non-corrosive as possible. Power must be supplied through the spindle either with the help of brushes or mercury coupling. So, there has to be a continuous power. So, this right here probably is the arrangement for the brush.

So, there is always tendency of the brushes to go past the rotating spindle. So, that there is continuous supply ensured on the wheel from the power supply side there should not be any break. And if you have mercury in between which sort of is a metal which is of you know it has a tendency to cohesive more than adhere. So, it basically formulates a thick layer between the outer which is the stator, and the rotor which is the inner spindle. So, there is a film of mercury which is continuously able to give a pathway to the flow of electrons and mercury coupling is always better than the brush contacts because brushes may get damaged or depreciated with time. But mercury owing to its cohesiveness can get reformulated as a continuous thin film between the stator and the rotor.

So, people prefer normally mercury coupling in comparison to the brushes although it is expensive.

And of course, one thing you have to ensure is that the probability of short-circuiting during ECG should not occur in the remaining part of the circuit. Because the ECG as such is a process which by virtue of the way it has been defined is very you know very less probable to the short-circuiting. Because it is a self-material removal process as such. So, after the dissolution has taken place after the debris has gotten deposited after there is a formation of a non-reactive oxide layer.

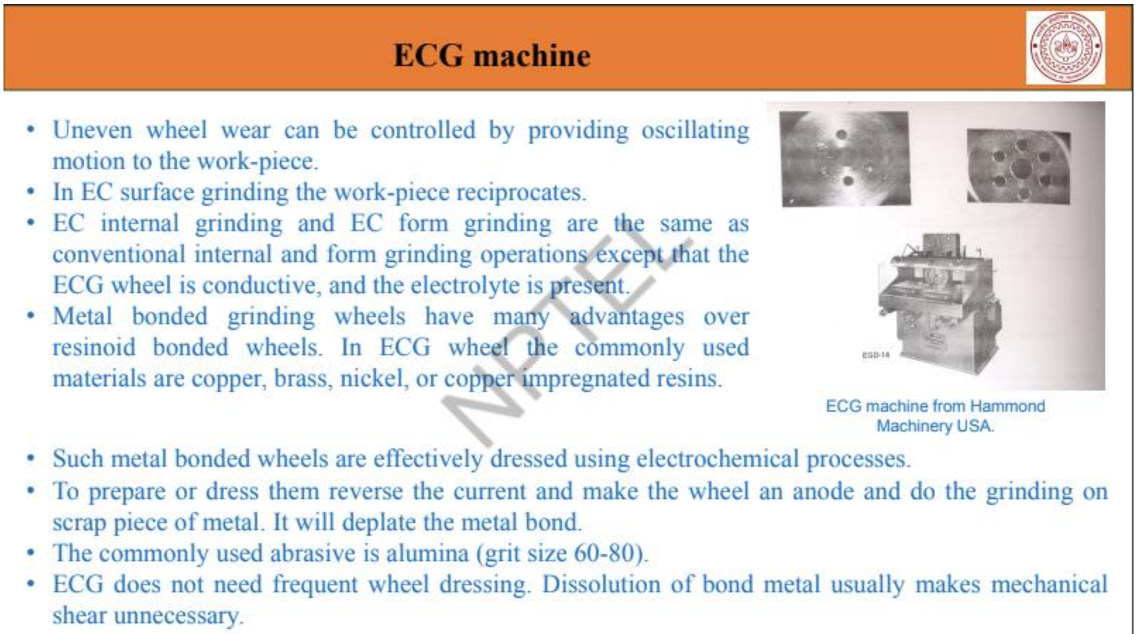
There is always a tendency of the material to get freshly exposed. So, therefore, there is a tendency of this ECG to not really have any short circuit. Because short circuits typically formulate when there is a chance of the metal of the metal binding of the grinding wheel coming in close operation to the surface. Here you are removing the surface there is mechanical abrasion which is following always the electrochemical deposition. So, there is a very less tendency of the ECG process as such to deposit a residue which may somehow interconnect the workpiece to the matrix of the abrasive wheel and short circuit is by and large self-avoided in the ECG process.

So, therefore, you have to be extra careful about designing circuitry. So, there should not be any issues about short-circuiting of the circuitry as such. Particularly when you are talking about the grinding wheel getting in close proximity to the workpiece holder you should avoid any such systems which would provide any shorting between the 2. So, 4 kinds of different ECG performed operations can be performed. They can be cylindrical grinding, can be formed grinding or can be surface grinding, and internal grinding, and variety of component shapes, complex shapes can result from these 4 processes out of which the cylindrical grinding probably is the slowest process and that is because there is always a limited area of contact between the tool surface and the machine surface as such.

So, there is always almost a line of contact. Cylindrical grinding is done when there is a grinding roller which is moving with a straight line contact with another workpiece. So, the zone of machining is very small and therefore, there is a tendency to of the dissolution rate to also fall down because of a line contact or probably at the most a very small surface area in contact during the contact between the tool and the workpiece. So, therefore, the ECG is slowest when you talk about cylindrical grinding, and among all the processes the surface grinding happens to be the fastest process because the whole surface is in contact as such. So, that is some information about the ECG machine. Of course, you know you can further add some additional actions to improve the efficiency of the ECG process and 1 of them is that the wear can be controlled of the grinding wheel by oscillating motion provided onto the workpiece.

So, if you have the workpiece moving from 1 side to another and you are having the grinding action by rotation motion maybe the clockwise manner or even the anticlockwise manner it is always a high-efficiency system. So, you can oscillate. So, that there is always a tendency of the work zone to come back and forth between this grinding wheel, and that way by the frequency of the oscillation as such the material or the material surface can be smoother based on and also the wheel wear rate can also be reduced because of that because in 1 motion you are typically going in the direction of the feed and in the other motion you are going away from the direction of the feed. So, the abrasive action of 1 cycle is kind of a dressing action for the other cycle.

So, it is a self-dressing mechanism which happens. So, the EC surface grinding typically necessitates the workpiece to reciprocate with respect to the tool. For example, this is a tool which is shown where you can see this stage here which is containing the workpiece, and it has a rectilinear motion in both the x and minus x-direction as the tool moves in clock or anticlockwise direction. So, in the EC internal grinding and form grinding the basic concept is same as the conventional internal and form grinding operations. The only thing is that you are using a conducting ECG wheel and electrolyte.



So, the material removal mechanism has connotations which have been already discussed. There are some other associated benefits of the ECG process 1 of them is that as I told you the ECG wheel is made up of metals. So, instead of a resinoid you know combination with particles, you are actually having a metal wheel combining the metal wheel or making the metal of the resinoid the wheel as the resinoid and the abrasive grain sticking out of that metal wheel. So, therefore, there is a tendency of those wheels to have long-lasting effects because resinoid otherwise can needs a frequent amount of dressing which this process will not. So, the ECG wheel again commonly uses materials that are copper, brass, nickel, or copper-impregnated resins for the purpose of you know making the grinding wheel.

And such metal-bonded wheels are effectively dressed using the electrochemical process. So, there does exist a dressing option here, but it has to be very less frequently used and the only thing which is needed for dressing is that because in the ECG process, you have electrochemical dissolution. So, you have to just reverse the dissolution. So, that the dissolution happens from the tool side rather than the workpiece side. So, if it is a copper-impregnated resin then you make sure that there is the electrolyte which goes in dissolves the copper with respect to a workpiece which displaces copper from its metal state into the solution.

So, it is the reverse of the ECM process as such. So, it is the machining on the tool that you are talking about, but the dressing has to be in an electrochemical sense which is done in this particular operation. So, the commonly used abrasive that is used is alumina in the grid size about 60 to 80. And as we have already indicated the ECG does not need frequent wheel dressing and because already there is a mechanical action followed by electrochemical dissolution action which takes away the debris or carries away the debris. So, I think we are probably at the end of this lecture, and we have completed 2 processes which are associated processes the electrochemical drilling and electrochemical grinding. We would also like to explore a little bit of electro-stream drilling which is important for high aspect ratio, hole formation, etc.

And MEMS structures following which we will give some practical applications from the industry where ECM is used for micro-manufacturing or microsystems fabrication. Thank you.