Advanced Machining Processes
Dr. Manas Das
Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Module - 06
Lecture - 14
Electrochemical Machining (ECM)

Welcome to the course on advanced machining processes. Today we are going to discuss on electrochemical machining process. So as the name suggest it is a electrical type nontraditional machining process. This ECM process works on the principle of Faraday's law of electrolysis. So all of us all we know that this electroplating operation where atom by atom that some metal is deposited on a electrical conducting material. So it is a reverse of this electroplating operation. So here this metal is removed from the anode or from the workpiece atom by atom.

So this process it is very useful in industry. So in many industries like nuclear industry, aerospace industries, they use this process for machining of very high strength temperature resistant material and also this process also useful for machining of very complex surfaces.

So you have to generate a tool which is prototype of the which is the tool shape actually it is it is a replica of the workpiece to be made on the workpiece surface. So in ECM process that there is no wear out of this tool like in EDM process there is a wear out of the tool but in EDM process there is no wear out of the tool. So wear out of tool is very low or it is not there.

So like in EDM process that kind of relative electrode wear rate that thing are not there in ECM process. So now we shall discuss how this electrochemical machining process works. So that working principle of this electrochemical machining process.

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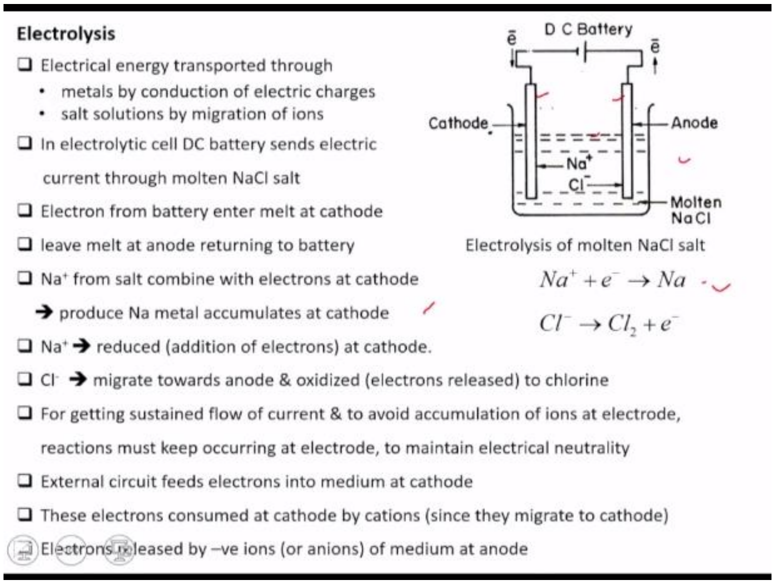

Electrolysis

☐ Electrical energy transported through
- metals by conduction of electric charges
- salt solutions by migration of ions

☐ In electrolytic cell DC battery sends electric current through molten NaCl salt

☐ Electron from battery enter melt at cathode

☐ leave melt at anode returning to battery

☐ Na^+ from salt combine with electrons at cathode

➔ produce Na metal accumulates at cathode

☐ Na^+ ➔ reduced (addition of electrons) at cathode.

☐ Cl^- ➔ migrate towards anode & oxidized (electrons released) to chlorine

☐ For getting sustained flow of current & to avoid accumulation of ions at electrode, reactions must keep occurring at electrode, to maintain electrical neutrality

☐ External circuit feeds electrons into medium at cathode

☐ These electrons consumed at cathode by cations (since they migrate to cathode)

Electrons released by –ve ions (or anions) of medium at anode

Electrolysis of molten NaCl salt

$$Na^+ + e^- \to Na$$

$$Cl^- \to Cl_2 + e^-$$

So you can see that this is the circuit where there is a DC battery is attached here. So this is the cathode and this is the anode here. So here electrical energy is transported through, in metals it is transported through by conduction of electrical charges but in salt solution it is, electrical energy is transported through the migration of ions. So in electrolytic cell DC battery sends electrical current through the molten NaCl salt. So here this molten NaCl salt is there.

So it is connected through a DC battery. So here left hand side this is the cathode and right hand side this is the anode here. So now so NaCl salt is there inside that container and this current is flowing because of it is connected to a DC battery. So now electrons from this DC power supply it will come to the cathode and then this sodium plus ion, sodium plus ion so this cations actually it will attracted to the cathode and it will be reduced here at the cathode.

So it will become sodium and it will be deposited on the cathode and then chlorine ion present in the chlorine that is negative ion so anion which is which is present here in the solution. So it will come to the anode here and it will release one electron and then this electron will come to this battery and again through this battery this electron will be pumped to the cathode and now this electrical circuit actually it will continues.

So now you can see here this this equations so sodium plus it takes that electron here and it is reduced here at the cathode and it will become sodium metal atom and it will be deposited at the cathode and chlorine ion that is negative ion it will be attracted towards the anode here and it will release one electron and it will generate this chlorine gas. So in electrolytic cell DC battery sends electrical current through the molten and sodium chloride salt.

So electrons from the batteries enter melt at the cathode and leave melt at the anode returning to the battery. So like this this total circuit actually continues, this power supply continues through this electrolyte. Sodium plus from the salt combine with the electrons at the cathode and produce sodium metal which accumulates at the cathode and sodium plus which is reduced here so reduction operation means addition of electrons at the cathode so it is reduced here, sodium plus it is reduced here at the cathode and chlorine it migrates towards the anode and it is oxidized.

Oxidized means electrons is released to the cathode and to become this chlorine gas. So for getting this sustained flow of current and to avoid accumulation of ions at the electrode, reactions must keep on occurring at the electrode to maintain the electrical neutrality.

So this battery, DC battery should supply power and so it will it will generate the sustained flow of current and it will avoid accumulation of ions at the electrode. So this external circuit feeds the electrons into the medium at the cathode that is electrons that is the DC battery here and these electrons are consumed at the cathode by the cations, here it is sodium plus ion since they migrate to the cathode and electrons are released by the negative ions that is chlorine ion or medium at the anode. So like this this reaction continues. So this is the typical electrolysis process for sodium chloride solution.

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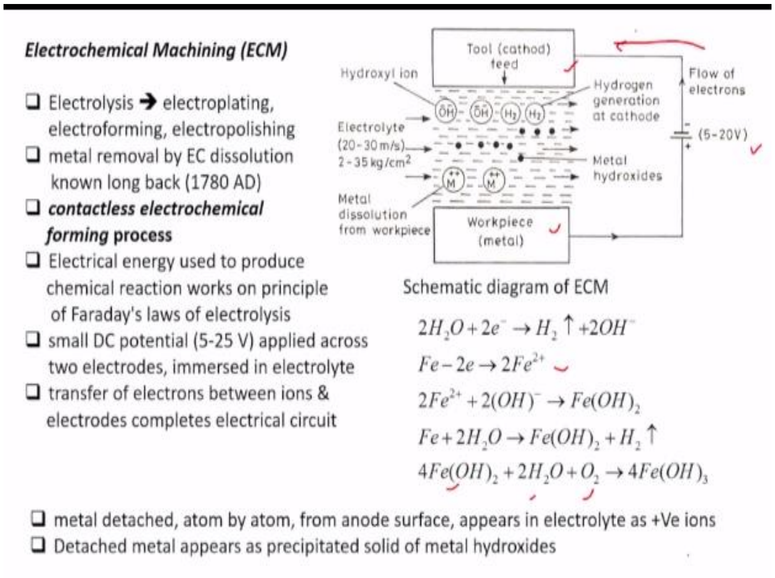

Electrochemical Machining (ECM)

- ❑ Electrolysis ➔ electroplating, electroforming, electropolishing
- ❑ metal removal by EC dissolution known long back (1780 AD)
- ❑ ***contactless electrochemical forming* process**
- ❑ Electrical energy used to produce chemical reaction works on principle of Faraday's laws of electrolysis
- ❑ small DC potential (5-25 V) applied across two electrodes, immersed in electrolyte
- ❑ transfer of electrons between ions & electrodes completes electrical circuit

Schematic diagram of ECM

$$2H_2O + 2e^- \rightarrow H_2 \uparrow + 2OH^-$$

$$Fe - 2e \rightarrow 2Fe^{2+}$$

$$2Fe^{2+} + 2(OH)^- \rightarrow Fe(OH)_2$$

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2 \uparrow$$

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$$

- ❑ metal detached, atom by atom, from anode surface, appears in electrolyte as +Ve ions
- ❑ Detached metal appears as precipitated solid of metal hydroxides

Now in electrochemical machining process this electrolysis like electroplating, electroforming, and electropolishing these all are actually electrolysis process. So this ECM process electrochemical machining process material removal by electrochemical resolution so or anodic resolution it was known long back in 1780 AD. So it is sometimes it is called as contactless electrochemical forming process. Because there is a tool actually does not touch to the workpiece surface so this cathode or tool here it does not touch to the workpiece surface so that is why it is called contactless process and forming process because this workpiece actually takes the shape of the work, shape of the tool okay so whatever shape of the shape of the workpiece you want to generate so you have to make a prototype into that tool so that so this shape of the tool will be made into the workpiece surface.

So electrical energy is used to produce the chemical reaction. Works on the Faraday's laws of electrolysis. So here electric energy is used to produce the chemical reaction here in the electrolyte. So here small DC potential 5 to 25 volt is applied but here current density is very high because in ECM process it depends on the its main property main thing is that you have to apply huge amount of current density.

So material removal rate mostly depends on the current density here. So small DC potential 5-25 V is applied across the 2 electrodes and these 2 electrodes actually cathode and anode it is immersed into the electrolyte. So here in this figure you can see this is the tool here, it is the cathode. So this feed is given to the cathode vertically in the downward direction and material is removed from the workpiece which is anode here.

So it is connected to the positive terminal and cathode is connected to the negative terminal. Here you can see 5-20 V potential is applied. So flow of electrons here, so this is the flow of electron here in this direction. So transfer of electrons between the ions and electrodes so whatever electrons are supplied so this electrons from the DC battery okay this transfers of electrons between the ions and electrodes completes the electrical circuit.

So here you can see this is the solution, water solution. So whatever electron is applied from the power supply, DC power supply okay so this electrons actually reacts with the hydrogen means H_2O or water molecule and generates hydrogen gas at the cathode and also it generates hydroxyl ion in the electrolyte. So you can see here whatever electrons is flowing to the cathode it reacts with the water molecule and it generates hydrogen gas so hydrogen gas is evolved at the cathode here and at the same time hydroxyl ions also generated at the electrolyte.

So at the same time whatever this metallic metals are there metal metallic ion break loose from the anode or disassociated from the anode and after releasing electron to the anode it comes to the electrolyte. So you can see here so if it is a iron the workpiece material is iron so here so this

Fe2+ actually this iron molecule atoms actually it will release the electrons to the anode and it will come as a ferrous ion Fe2+ here okay so this second equation second reaction, Fe2+ and this Fe2+ it will react with the hydroxyl molecule present in the electrolyte and you will it will generate ferrous hydroxide. So this is this ferrous hydroxide it is insoluble in water and sometimes this ferrous hydroxide also it reacts with the water molecule and oxygen present in the electrolyte and it will become ferric hydroxide also. So this ferrous hydroxide with water molecule and oxygen it will react and sometimes it will become ferric hydroxide also.

Because iron has 2 valency 2 and 3 so it may generate ferrous hydroxide or it may generate ferric hydroxide also. So this hydroxyl molecules here these are insoluble and it will precipitate there in the interelectrode gap. So you have to flow the electrolyte with a high pressure and high velocity so that whatever this debris particles are there whatever this hydroxyl ions, whatever hydroxyl compounds are generated or metal hydroxides are generated it has to be actually thrown out from the interelectrode gap.

Also it will throw out the hydrogen molecules hydrogen gas which is generated at the interelectrode gap at the cathode so that fixed flow of electron from the cathode should come and from the anode this electron will come back to the power supply. So this transfer of electrons between the ions and electrodes completes the electrical circuit here. So metal detached atom by atom from the anode surface and appears in the electrolyte as the positive ions and detached metal appears as the precipitated solid of metal hydroxide. Here you can see M, these are the metal ions after releasing electron into the anode it comes into the electrolyte.

So it is dissociated, this metallic ions are dissociated from the workpiece. So electrolyte flow velocity you have to maintain 20-30 m/s also you have to flow with a relative flow rate has to be maintained 2-35 kg/cm so that this whatever this hydrogen gas and hydroxyl metal hydroxide is generated so it has to be removed or removed from the interelectrode gap. So this hydrogens are generated at the cathode only not at the anode. So this hydrogen gas bubbles are generated at the cathode.

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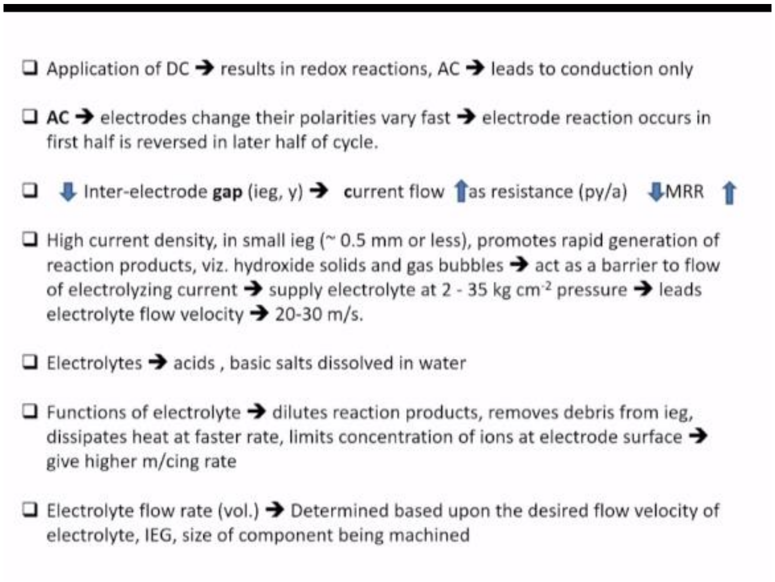

☐ Application of DC → results in redox reactions, AC → leads to conduction only

☐ **AC** → electrodes change their polarities vary fast → electrode reaction occurs in first half is reversed in later half of cycle.

☐ ⬇ Inter-electrode **gap** (ieg, y) → current flow ⬆as resistance (py/a) ⬇MRR ⬆

☐ High current density, in small ieg (~ 0.5 mm or less), promotes rapid generation of reaction products, viz. hydroxide solids and gas bubbles → act as a barrier to flow of electrolyzing current → supply electrolyte at 2 - 35 kg cm^{-2} pressure → leads electrolyte flow velocity → 20-30 m/s.

☐ Electrolytes → acids , basic salts dissolved in water

☐ Functions of electrolyte → dilutes reaction products, removes debris from ieg, dissipates heat at faster rate, limits concentration of ions at electrode surface → give higher m/cing rate

☐ Electrolyte flow rate (vol.) → Determined based upon the desired flow velocity of electrolyte, IEG, size of component being machined

So application of DC results in the redox reactions. So reduction reaction occurs at the cathode and oxidation reaction occurs at the anode. So it if you apply DC voltage then only this redox reactions occurs and if you apply only that AC current then it will leads to a conduction only because at the first half whatever the situation is there so electrodes changes their polarity in the first half and because there is a sinusoidal profile of the AC current so electrodes change their polarities very fast. So at the first half this whatever electrode polarities are there at the second cycle electrode polarity will change.

So electrode reaction occurs in first half is reversed in the later half of the cycle okay. So if you reduce the interelectrode gap, gap between this interelectrode means gap between this cathode and anode so this is called this interelectrode gap, IEG interelectrode gap. So if you reduce the interelectrode gap that is why gap between this interelectrode, current density current flow will increase because your if we decrease the gap in that case your y or y increases or y decreases and your resistance actually also decreases as the resistance is py by a.

So if you reduce the y your resistance, gap resistance in between this cathode and anode actually reduces and in that case material removal rate also increases. So material removal rate will be higher where your gap distance is very less. So high current density as small as high density in small interelectrode gap as small as 0.5 mm or less promotes the rapid generation of this reaction products. So I told that this reaction products are gas bubbles and also this metallic hydroxide. If we decrease the interelectrode gap there is a huge generation of this reaction products will be there and hydroxide solids and gas bubbles act as a barrier. So this hydroxyl metallic hydroxyl and gas bubbles it will make a barrier with the flow of current to flow to the flow of electrolyzing current. So you have to remove this debris from the interelectrode gap for the current to flow for the fresh reaction to takes place. So supply of electron at 2 to 35 kg/cm square pressure which lead to the electrolyte flow velocity of 20-30 m/s. So what kind of electrodes are used. You can use acidic electrolyte, you can use the base, basic salts dissolved in water, acid or basic salts dissolved in water as a electrolyte.

So what are the different functions of electrolyte. So you can now you can see the function of electrolyte is to remove the debris from the interelectrode gap for the fresh machining to takes place for the current to flow through the interelectrode gap. Also whatever the temperature is generated in between this interelectrode gap this that much heat is actually removed from the interelectrode gap. Whatever heat is generated that much heat is actually removed from the interelectrode gap. So it will dilutes it will dilute it dilutes the reaction products in between the interelectrode gap, removes the debris from the interelectrode gap, dissipate heat at a faster rate, and limits the concentration of ions at electrode surface.

So whatever if it is not electrolyte if it is not flown so there is a concentration of ions at the electrode surface, so it will increase. So as the electrolyte is flown by doing all these actions, with the flow of electrolyte your machining rate will also increase. So this electrolyte flow velocity it is determined by the it is determined based upon the desired flow velocity of the electrolyte, interelectrode gap, size of the component being machined.

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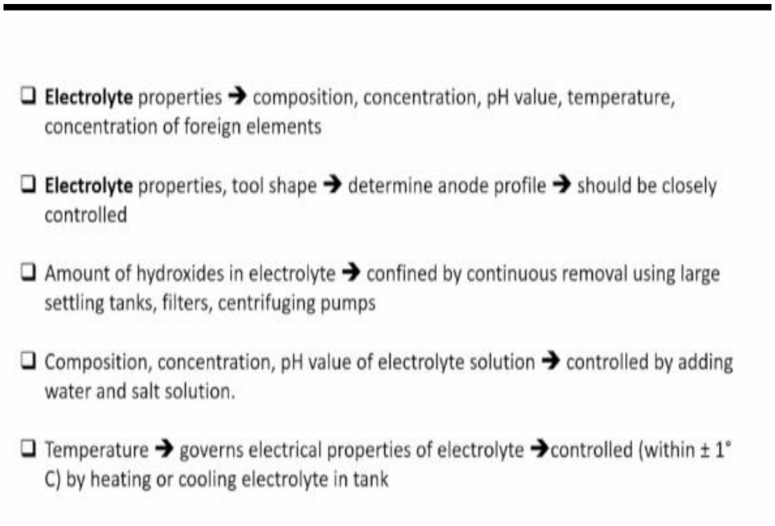

- ☐ **Electrolyte** properties → composition, concentration, pH value, temperature, concentration of foreign elements
- ☐ **Electrolyte** properties, tool shape → determine anode profile → should be closely controlled
- ☐ Amount of hydroxides in electrolyte → confined by continuous removal using large settling tanks, filters, centrifuging pumps
- ☐ Composition, concentration, pH value of electrolyte solution → controlled by adding water and salt solution.
- ☐ Temperature → governs electrical properties of electrolyte →controlled (within ± 1° C) by heating or cooling electrolyte in tank

And electrolyte properties composition, concentration, pH value, temperature, concentration of foreign elements oaky so you have to control the electrolytic electrolyte properties. So its composition, its concentration, its pH value, temperature, and concentration of foreign elements whatever this metal hydroxide you have to control. So because temperature actually changes the electrical conductivity of the electrolyte so machining rate will also change. If this concentration of electrolyte increases or whatever is vaporized in that case conductivity of, electrical conductivity of electrolyte will increase. So in that case your machining rate will increase.

So you want a if you want a constant machining rate, uniform machining rate so you have to change you have to maintain the concentration of electrolyte, temperature of electrolyte. So electrolyte properties, tool shape are determined by the anode profile and should be closely controlled. So amount of hydroxide in the electrolyte confined by the continuous removal using the settling tank, filters, and centrifugal pumps. So this whatever hydroxyl metal hydroxyl metallic hydroxides are generated that has to be filtered out from the electrolyte.

So concentration, composition, and pH value of the solution, electrolyte solution, controlled by adding water. Suppose this concentration changes so you can change you can re-modify the concentration of this electrolyte by adding salt or salt solution or adding water based on the need. So temperature also governs the electrical properties of the electrolyte so it is already I told that electrical conductivity of the electrode changes by changing the temperature. So this temperature should be controlled within plus minus 1 degree centigrade by heating or cooling the electrolyte by heating or cooling the electrolyte in the tank.

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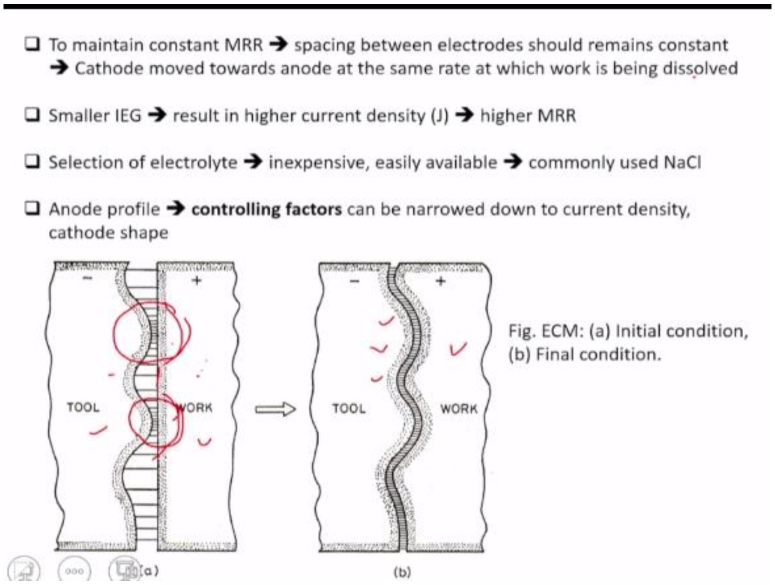

- ☐ To maintain constant MRR ➔ spacing between electrodes should remains constant
  ➔ Cathode moved towards anode at the same rate at which work is being dissolved
- ☐ Smaller IEG ➔ result in higher current density (J) ➔ higher MRR
- ☐ Selection of electrolyte ➔ inexpensive, easily available ➔ commonly used NaCl
- ☐ Anode profile ➔ **controlling factors** can be narrowed down to current density, cathode shape

Fig. ECM: (a) Initial condition, (b) Final condition.

So to maintain the constant material removal rate spacing between the electrodes should be maintained and cathode so to maintain the spacing between the electrode so cathode is feed cathode is moves towards the anode at the same rate at which the machining from the workpiece actually maintained okay. So spacing between the electrode should be maintained constant. Cathode moved towards the anode at the same rate at which work is being dissolved.

Smaller interelectrode gap result in high current density, it will result in high material removal rate. So selection of electrolyte it should be inexpensive, easily available, and commonly used electrolyte is sodium chloride. So now you can see here so this is the tool here and this is the workpiece so this tool profile has to generated into the workpiece surface. Now you can see in this zone current density is maximum. So here also you can see this current density will be maximum entire in the entire zone of the tool where it is interacting into the workpiece surface.

So as the current density is maximum here, so machining rate will be higher in this zone and also material removal rate will be higher in this zone. So initially in this zone will be machined and after that this zone will be machined. After that rest of the portion will be machined okay. So after some time you will see that this tool and this is the workpiece here.

So this workpiece will take the shape of the tool and which is to be generated into the workpiece. So after some time it will take the shape of the workpiece the shape of the workpiece will form according to the shape of the tool which is used for this machining. So now this main controlling factor you can see here this is the current density and shape of the cathode or shape of the tool. These are the main 2 controlling factors for anode profile.

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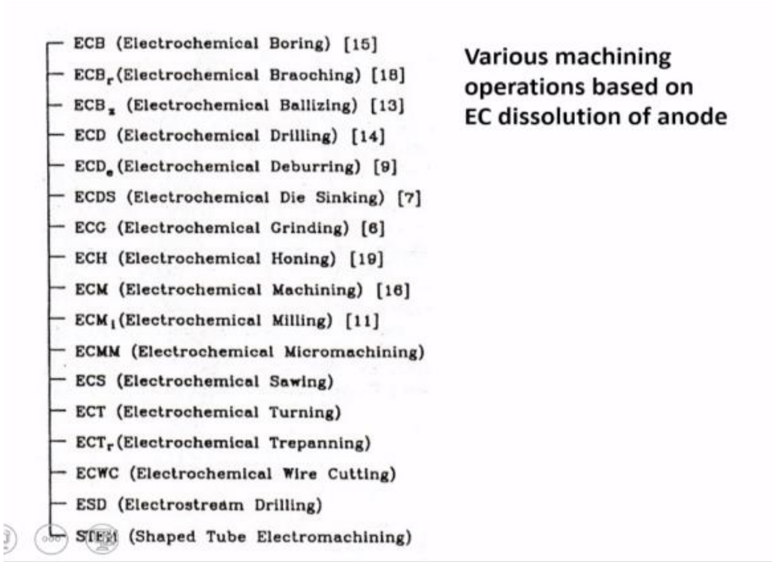

Various machining operations based on EC dissolution of anode

- ECB (Electrochemical Boring) [15]
- ECB_r (Electrochemical Braoching) [18]
- ECB_a (Electrochemical Ballizing) [13]
- ECD (Electrochemical Drilling) [14]
- ECD_e (Electrochemical Deburring) [9]
- ECDS (Electrochemical Die Sinking) [7]
- ECG (Electrochemical Grinding) [6]
- ECH (Electrochemical Honing) [19]
- ECM (Electrochemical Machining) [16]
- ECM_l (Electrochemical Milling) [11]
- ECMM (Electrochemical Micromachining)
- ECS (Electrochemical Sawing)
- ECT (Electrochemical Turning)
- ECT_r (Electrochemical Trepanning)
- ECWC (Electrochemical Wire Cutting)
- ESD (Electrostream Drilling)
- STEM (Shaped Tube Electromachining)

So these are the various operations can be done by electrochemical machining process. There are so many things, so many machining operations can be done by this electrochemical machining process like electrochemical boring operation. You can make a bore hole into that workpiece by using electrochemical machining. Electrochemical broaching operation; electrochemical ballizing operation; electrochemical drilling; you can make holes, small holes by using electrochemical machining process; electrochemical deburring operation.

So if some bars are actually generated by conventional machining process this bars can be removed by electrochemical deburring operation. Electrochemical die sinking operation, electrochemical grinding operation, electrochemical honing operation, electrochemical machining operation, and electrochemical micromachining operation. You can do the micromachining operations also but in that case you have to change the current and voltage all these parameters and you have to vibrate the tool with a very high frequency so many things you have to change if you use this electrochemical process for micromachining applications.

Electrochemical milling operation, this is one of another process; electrochemical sawing; electrochemical turning; electrochemical trepanning operation; electrochemical wire cutting operation; and electrochemical drilling operation; shaped tube electrochemical machining for high aspect ratio holes. So these are the various machining operation which are obtained by using electrochemical machining process. So now what are the different components of ECM process.

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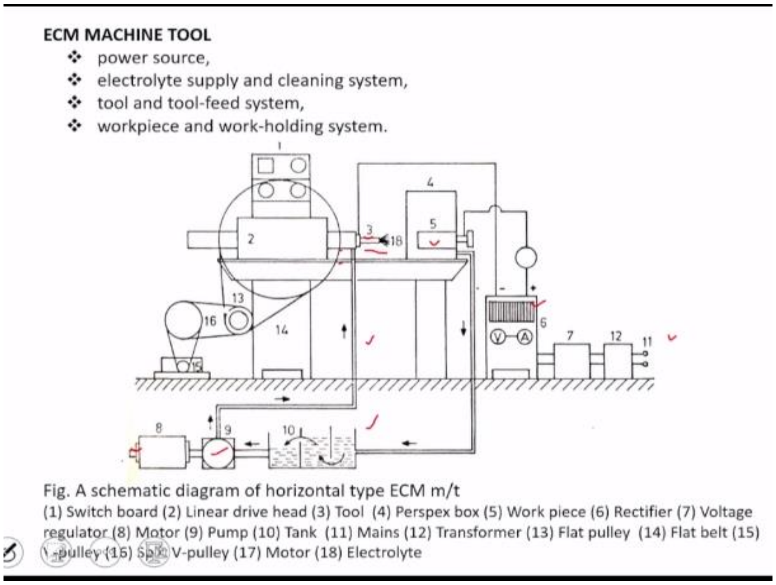

ECM MACHINE TOOL

- power source,
- electrolyte supply and cleaning system,
- tool and tool-feed system,
- workpiece and work-holding system.

Fig. A schematic diagram of horizontal type ECM m/t
(1) Switch board (2) Linear drive head (3) Tool (4) Perspex box (5) Work piece (6) Rectifier (7) Voltage regulator (8) Motor (9) Pump (10) Tank (11) Mains (12) Transformer (13) Flat pulley (14) Flat belt (15) V-pulley (16) Sp[illegible] V-pulley (17) Motor (18) Electrolyte

So first component is the power supply of this electrochemical machining process or power source of the process is the first element. Then electrolyte supply and cleaning system is the second element of this process. Tool and tool workpiece tool feed system is the third component of the process and workpiece and work holding device, workpiece and work holding device system is the fourth component of the process.

Now we shall discuss one by one different elements of the process. So here this is the schematic diagram of a electrochemical machining process. Here you can see power supply here. So this is the main switch. This is the power supply here. So current is applied. So this is the tool here. So it is connected to the negative terminal or cathode and this is our workpiece here. It is connected to the first two terminal. Now this tool is actually feed towards the workpiece by a fitting mechanism. Now this is the motor and this is the pump here. So electrolyte is flown into this Perspex chamber by this tubing system. Now it is coming back to this filtering system.

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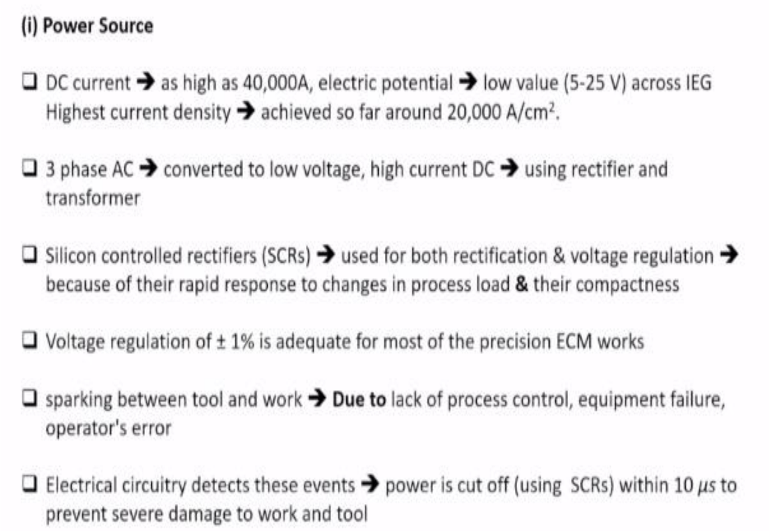

(i) Power Source

❑ DC current ➔ as high as 40,000A, electric potential ➔ low value (5-25 V) across IEG Highest current density ➔ achieved so far around 20,000 A/cm^2.

❑ 3 phase AC ➔ converted to low voltage, high current DC ➔ using rectifier and transformer

❑ Silicon controlled rectifiers (SCRs) ➔ used for both rectification & voltage regulation ➔ because of their rapid response to changes in process load **&** their compactness

❑ Voltage regulation of ± 1% is adequate for most of the precision ECM works

❑ sparking between tool and work ➔ **Due to** lack of process control, equipment failure, operator's error

❑ Electrical circuitry detects these events ➔ power is cut off (using SCRs) within 10 μs to prevent severe damage to work and tool

So power source we need a DC current, amount of voltage is 5-25 V, but amount of current is as high as 40,000A is required with electrical potential of low value of 5-25 V or electric potential across the interelectrode gap. So highest current density which is achieved so far is 20,000A per centimeter square. So this 3 phase AC is converted into the DC power supply to the low voltage high current DC using a rectifier and transformer. So silicon controlled rectifiers used for both rectification and voltage regulation because of the rapid response to changes in process load and their compactness. So voltage regulation of plus minus 1% adequate for most of the precision works.

So sometimes there is a spark between the tool and the workpiece because due to the lack of process control, equipment failure, and operators error. Electrical circuitry detects these events if there is a short circuit so electrical circuit will detect these events and power is cut off using silicon control resistor within 10 microsecond to prevent severe damage to the work and tool.

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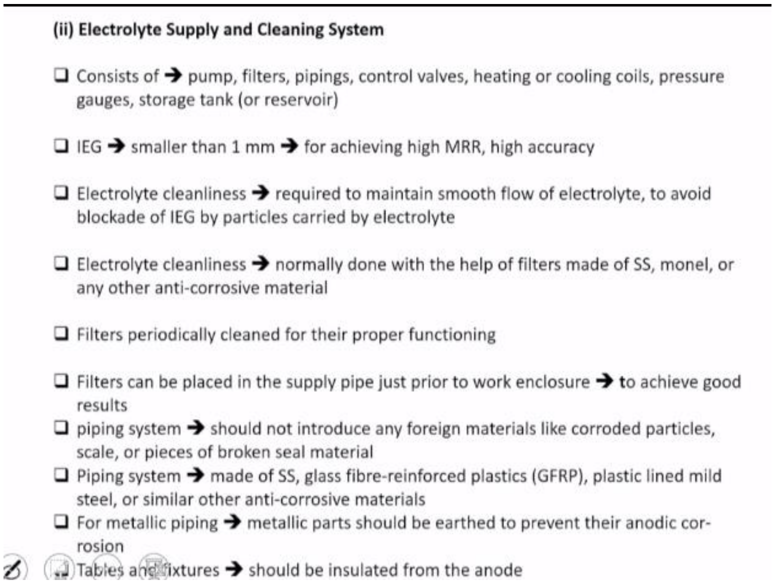

(ii) Electrolyte Supply and Cleaning System

- ☐ Consists of → pump, filters, pipings, control valves, heating or cooling coils, pressure gauges, storage tank (or reservoir)
- ☐ IEG → smaller than 1 mm → for achieving high MRR, high accuracy
- ☐ Electrolyte cleanliness → required to maintain smooth flow of electrolyte, to avoid blockade of IEG by particles carried by electrolyte
- ☐ Electrolyte cleanliness → normally done with the help of filters made of SS, monel, or any other anti-corrosive material
- ☐ Filters periodically cleaned for their proper functioning
- ☐ Filters can be placed in the supply pipe just prior to work enclosure → to achieve good results
- ☐ piping system → should not introduce any foreign materials like corroded particles, scale, or pieces of broken seal material
- ☐ Piping system → made of SS, glass fibre-reinforced plastics (GFRP), plastic lined mild steel, or similar other anti-corrosive materials
- ☐ For metallic piping → metallic parts should be earthed to prevent their anodic corrosion
- ☐ Tables and fixtures → should be insulated from the anode

So electrolyte supply and cleaning system consist of pump, filters, piping, control valves, heating, cooling, pressure gauge, storage tank. So these electrolyte has to be flown to the electrolyte chamber then it is taken away from the chamber by electrolytic flowing system. A smaller gap less than 1 mm for achieving high material removal rate is required. Electrolyte cleanliness required to maintain smooth flow of electrolyte and to avoid blockade of interelectrode gap particles carried by electrolyte.

So electrolyte cleaning is normally done with the help of filters made of stainless steel, monel, or any other anti-corrosive material. So filters are periodically cleaned for their proper functioning. So filters can be placed in the supply pipe just prior to the work enclosure to achieve good results. This piping system should be should not introduce any foreign materials like corroded particles, scale, or pieces of broken seal material.

Also piping system made of stainless steel, glass fibre-reinforced plastics, plastic lined mild steel or similar other anti-corrosive materials are used for piping and anti-corrosive for piping system. So piping systems are made of silicon stainless steel, glass fibre-reinforced plastic, plastic lined mild steel, similar other non-corrosive materials are used for piping system. For metallic piping metallic parts should be earthed to prevent their anodic corrosion. This table and fixtures should be insulated from the anode.

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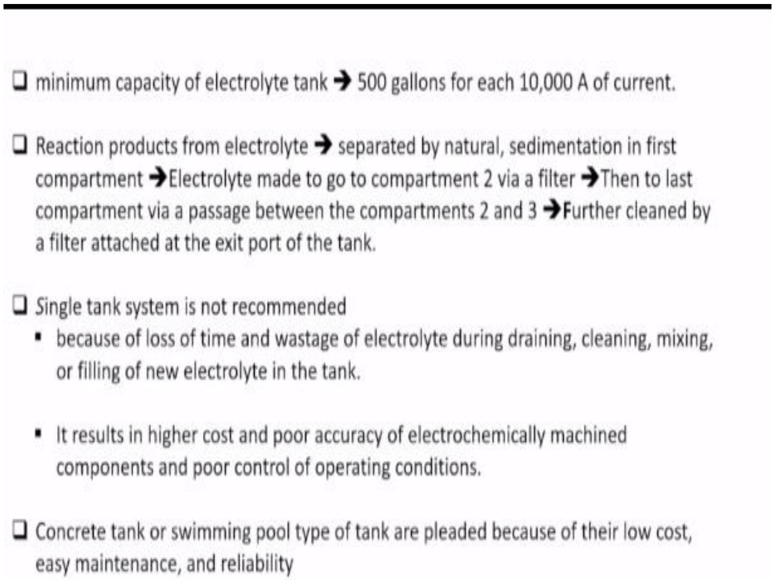

❑ minimum capacity of electrolyte tank → 500 gallons for each 10,000 A of current.

❑ Reaction products from electrolyte → separated by natural, sedimentation in first compartment →Electrolyte made to go to compartment 2 via a filter →Then to last compartment via a passage between the compartments 2 and 3 →Further cleaned by a filter attached at the exit port of the tank.

❑ Single tank system is not recommended
  - because of loss of time and wastage of electrolyte during draining, cleaning, mixing, or filling of new electrolyte in the tank.
  - It results in higher cost and poor accuracy of electrochemically machined components and poor control of operating conditions.

❑ Concrete tank or swimming pool type of tank are pleaded because of their low cost, easy maintenance, and reliability

So minimum capacity of this electrolyte tank is 500 gallons for each 10,000 A of current. So this reaction products from the electrolyte are separated by natural, sedimentation in the first component. Then electrolyte is made go to this component 2 compartment 2 via a filter then to the last compartment via a passage between the compartment 2 and 3. Further it is cleared by a filter attached to the exit port of the tank.

So you can see here this is the container here used for filtering purpose. So in the first container actually it is electrolyte is coming from the machining zone. So whatever this electrolyte is there it is allowed to precipitate there. Then from first to second one first to second chamber there is a filter is placed here.

Now from this second to third component it will go to another filter and at the exit of this filter it will go to the pipe connecting to the electrolytic chamber. So electrolyte cleanliness required to maintain the smooth flow of electrolyte to avoid blockade of interelectrode gap by particles carried by electrolyte. So electrolyte cleanliness normally done with the help of a filters made of stainless steel or any other anti-corrosive material.

Filters periodically cleaned for their proper functioning. Filters can be placed in the supply pipe just prior to the work enclosure to achieve good results. Piping system should not introduce any foreign materials like corroded particles, scales, pieces of broken seals. Piping system are made of stainless steel, glass fibre-reinforced plastics, plastic lined mild steel, or similar other anti-corrosive materials. For metallic piping metallic parts should be earthed to prevent any anodic corrosion. So any metallic part it should be earthed. Table and fixture should be insulated from the anode.

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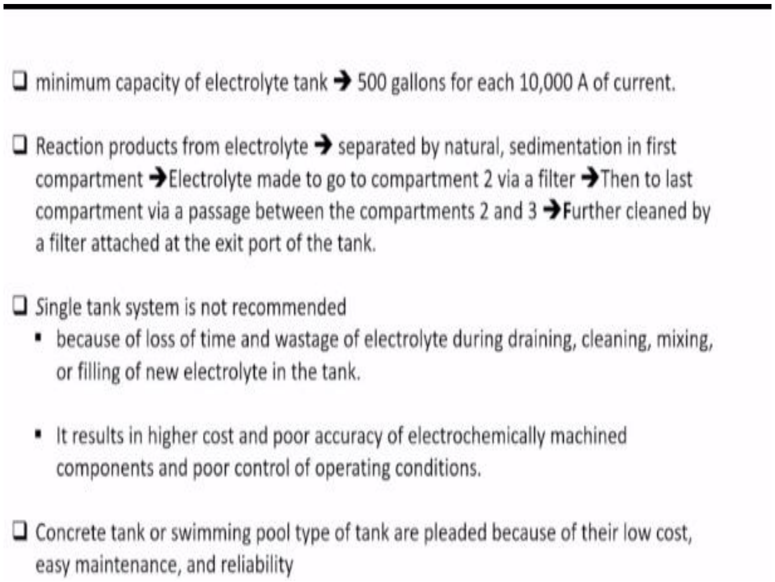

☐ minimum capacity of electrolyte tank → 500 gallons for each 10,000 A of current.

☐ Reaction products from electrolyte → separated by natural, sedimentation in first compartment →Electrolyte made to go to compartment 2 via a filter →Then to last compartment via a passage between the compartments 2 and 3 →Further cleaned by a filter attached at the exit port of the tank.

☐ Single tank system is not recommended
  - because of loss of time and wastage of electrolyte during draining, cleaning, mixing, or filling of new electrolyte in the tank.
  - It results in higher cost and poor accuracy of electrochemically machined components and poor control of operating conditions.

☐ Concrete tank or swimming pool type of tank are pleaded because of their low cost, easy maintenance, and reliability

So minimum capacity of electrolyte is 500 gallons for each 1000 A of current. So single tank system is not recommended because of loss of time and wastage of electrolyte during the draining, cleaning, and mixing, or filling of new electrolyte in the tank. So it results in higher cost and poor accuracy of electrochemical machining components and poor control of operating conditions. Concrete tank or swimming pool type tank type of tank are pleaded because of their low cost, easy maintenance, and reliability.

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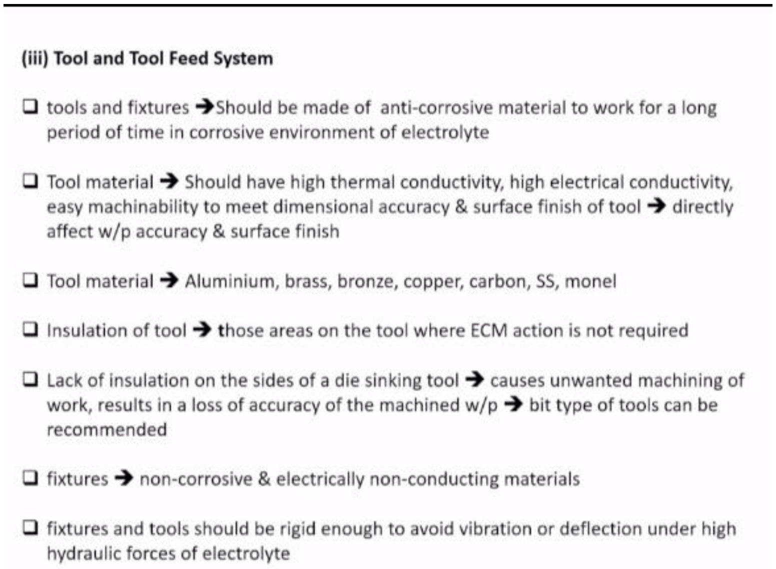

(iii) Tool and Tool Feed System

☐ tools and fixtures →Should be made of anti-corrosive material to work for a long period of time in corrosive environment of electrolyte

☐ Tool material → Should have high thermal conductivity, high electrical conductivity, easy machinability to meet dimensional accuracy & surface finish of tool → directly affect w/p accuracy & surface finish

☐ Tool material → Aluminium, brass, bronze, copper, carbon, SS, monel

☐ Insulation of tool → those areas on the tool where ECM action is not required

☐ Lack of insulation on the sides of a die sinking tool → causes unwanted machining of work, results in a loss of accuracy of the machined w/p → bit type of tools can be recommended

☐ fixtures → non-corrosive & electrically non-conducting materials

☐ fixtures and tools should be rigid enough to avoid vibration or deflection under high hydraulic forces of electrolyte

So tool and tool feed system. Tool is fed towards the workpiece because material removal rate there anodic resolution due to the anodic resolution of the material so you have to feed the tool towards the workpiece at the same rate this anodic resolution is going on. So tools and fixture should be made of anticorrosive material, this tools should be made of anticorrosive material to work for a long period of time in corrosive environment of electrolyte.

Tool material should have high thermal conductivity, high electrical conductivity, easy machinability, and dimensional accuracy and surface finish to of work. So directly affect workpiece accuracy and surface finish. Tool materials very soft materials are used for this tool in ECM because there is no wear out of the tool material.

So aluminium, brass, bronze, copper, carbon, stainless steel, monel these are the materials which are used as the tool material. Insulation of tool is required. So those areas of the tool where ECM action is not required are insulated. So lack of insulation on the sides of the die sinking tool causes unwanted machining and the work results in the loss of accuracy of the machined workpiece where bit type of tool can be recommended.

Either this tools may be coated to remove the unwanted metallic resolution at the side of the workpiece so all this tool should be coated or you can do one thing you can use a bit type tool. So fixture should be noncorrosive also it should be electrically non-conducting materials, fixture also it should be electrically non-conducting materials and fixture and tool should be rigid enough so that it will not vibrate due to the deflection under high hydraulic forces of the electrolyte. So it should not vibrate, tool should not vibrate during electrolyte flow. So it should be rigid enough.

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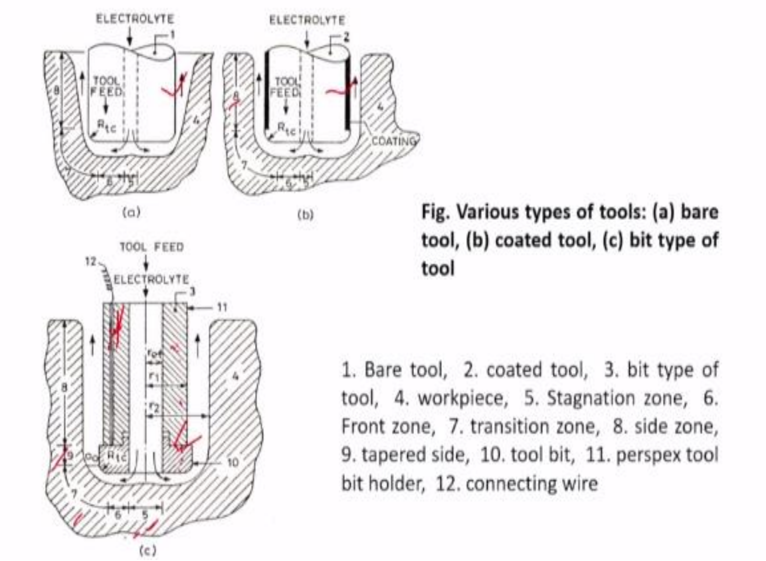

Fig. Various types of tools: (a) bare tool, (b) coated tool, (c) bit type of tool

1. Bare tool, 2. coated tool, 3. bit type of tool, 4. workpiece, 5. Stagnation zone, 6. Front zone, 7. transition zone, 8. side zone, 9. tapered side, 10. tool bit, 11. perspex tool bit holder, 12. connecting wire

So you can see there are this is the bare tool. This is the coated tool here, coated outside. So this is the bit type tool here. So this is the Perspex body. Here a through hole is there. Through this hole actually this wire is coming inside the at the at the bottom surface of the tool bit. So there are different zones are there. So this is the stagnation zone 5, then 6 is the front zone, 7 is the transition zone, 6 is the front zone, 7 is the transition zone, 8 is the side zone, 9 is the tapered side, and 10 is the tool bit.

So here you can see this is the bit type metallic tool is attached. So this is non-conducting material. This is the conducting material. It is attached to this non-conducting material by using this kind of thread here okay. So as this portion is made of Perspex so it is made a there is a hole is made inside the Perspex and this titanium electrode is inserted and it will touch to the (()) (39:52).

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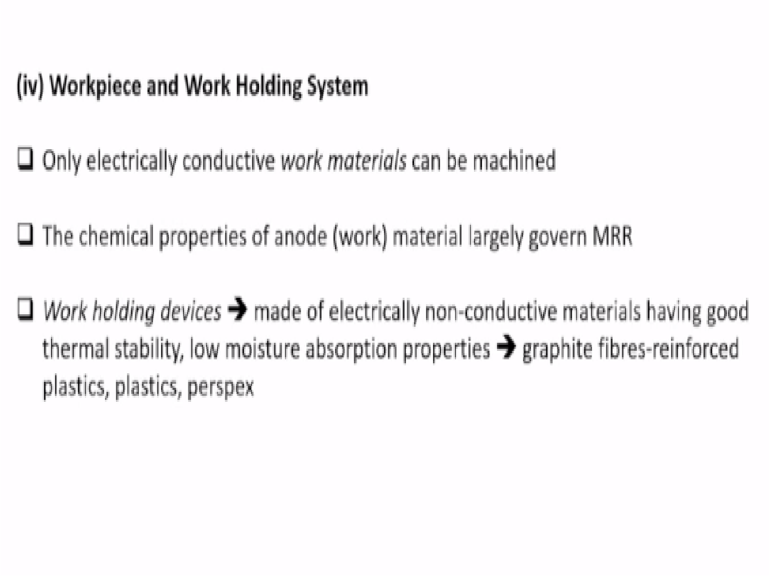

(iv) Workpiece and Work Holding System

❑ Only electrically conductive *work materials* can be machined

❑ The chemical properties of anode (work) material largely govern MRR

❑ *Work holding devices* → made of electrically non-conductive materials having good thermal stability, low moisture absorption properties → graphite fibres-reinforced plastics, plastics, perspex

So workpiece and work holding system. Only electrically conductive workpiece materials can be machined. The chemical properties of the anode material largely governed by the material removal rate. So work holding devices made of electrically non-conducting materials having good thermal stability, low moisture absorption properties, graphite fibre-reinforced plastics, plastics, perspex. These are actually used for workpiece and work holding system.

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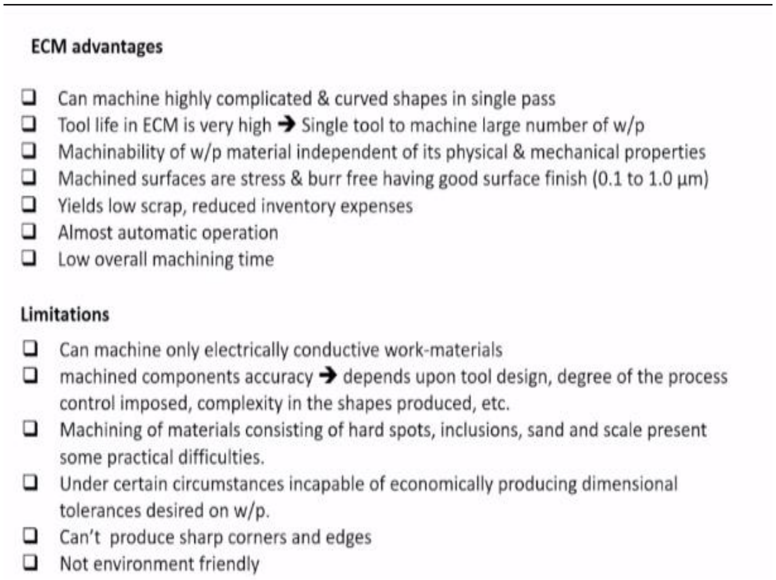

ECM advantages

❑ Can machine highly complicated & curved shapes in single pass
❑ Tool life in ECM is very high → Single tool to machine large number of w/p
❑ Machinability of w/p material independent of its physical & mechanical properties
❑ Machined surfaces are stress & burr free having good surface finish (0.1 to 1.0 μm)
❑ Yields low scrap, reduced inventory expenses
❑ Almost automatic operation
❑ Low overall machining time

Limitations

❑ Can machine only electrically conductive work-materials
❑ machined components accuracy → depends upon tool design, degree of the process control imposed, complexity in the shapes produced, etc.
❑ Machining of materials consisting of hard spots, inclusions, sand and scale present some practical difficulties.
❑ Under certain circumstances incapable of economically producing dimensional tolerances desired on w/p.
❑ Can't produce sharp corners and edges
❑ Not environment friendly

So what are the advantages are there. So it can machine only highly complicated and curved shapes in a single pass. Tool life in ECM is very high because there is no tool here, practically there is no tool here. So single tool to machine large number of workpiece. Machinability of workpiece material independent of their physical and mechanical property which does not depend on the physical and mechanical properties of the workpiece material.

So low scrap rate, reduced inventory expenses almost automatic operations and low overall machining time. Can machine only electrically conducting workpiece material. These are the disadvantages few limitations are there for this same process. It can work on the electrically conductive material for electrically non-conductive material this process is not suitable. So this machine component accuracy it depends on the tool design, degree of the process control imposed and complexity in the shapes of the shapes produced.

So machining of materials consist of hard spots, inclusions, sand and scale that are present in the some practical difficult means some practical difficulties. Under certain circumstances incapable of economically producing dimensional tolerances desired on the workpiece. Cannot produce sharp corners and edges. Not environment friendly. Because of this chemicals are used. So it is not economically friendly. Also can produce sharp corners and edges in case of electrocehmical machining process.

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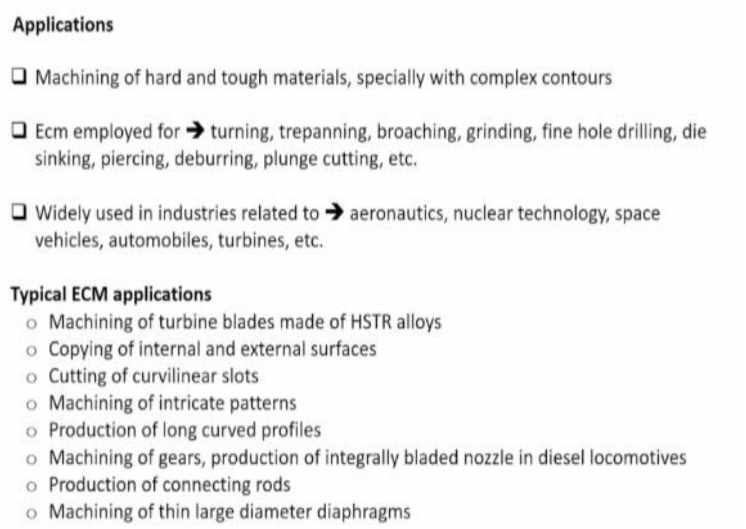

Applications

☐ Machining of hard and tough materials, specially with complex contours

☐ Ecm employed for ➔ turning, trepanning, broaching, grinding, fine hole drilling, die sinking, piercing, deburring, plunge cutting, etc.

☐ Widely used in industries related to ➔ aeronautics, nuclear technology, space vehicles, automobiles, turbines, etc.

Typical ECM applications

- Machining of turbine blades made of HSTR alloys
- Copying of internal and external surfaces
- Cutting of curvilinear slots
- Machining of intricate patterns
- Production of long curved profiles
- Machining of gears, production of integrally bladed nozzle in diesel locomotives
- Production of connecting rods
- Machining of thin large diameter diaphragms

So what are the applications of ECM process. So it is used for machining very hard materials, high strength temperature resistant materials. Also it is used for measuring very complex contours on the workpiece surface so which is not possible for conventional machining process. So machining hard and tough materials especially with complex contours. ECM is used for turning, trepanning, broaching operations, grinding operation, for fine hole drilling operation, die sinking operation, piercing operation, deburring operation, and plunge cutting operation. So these are the so many operations can be done by this ECM process. So it is widely used in industries. Commercial machines are available in industry. So it is used in aeronautics, nuclear technology, space vehicles, automobiles, and turbines. These are the industries where this ECM machines are extensively used.

So typical applications are, it is used for machining of turbine blades which is made of high strength temperature resistance material. So you can see that in the turbine blade so many complex surfaces are there on the turbine blades. How to machine by normal conventional machining process. Also these turbine blades are made of this high strength temperature resistance resistant materials. So this turbine blades are actually machined by this ECM process.

Copying of internal and external surfaces.

Cutting of curvilinear slots, any kind of curvilinear slots you want to cut. So you have to generate a tool so whatever surface you want to generate so you have to generate on the tool and you can cut the workpiece using the tool. So generally these tools are made of very soft material so you can generate any kind of complex profile on the tool and something can be replicated into the workpiece surface by electrochemical machining process.

So production of long curved profiles you can generate by this ECM process. So any kind of long curved profile you can generate. Machining of gears, production of integrated blade nozzles in diesel locomotives, production of connecting rods, machining of thin large diameter diaphragms. These are the some applications of electrochemical machining process.

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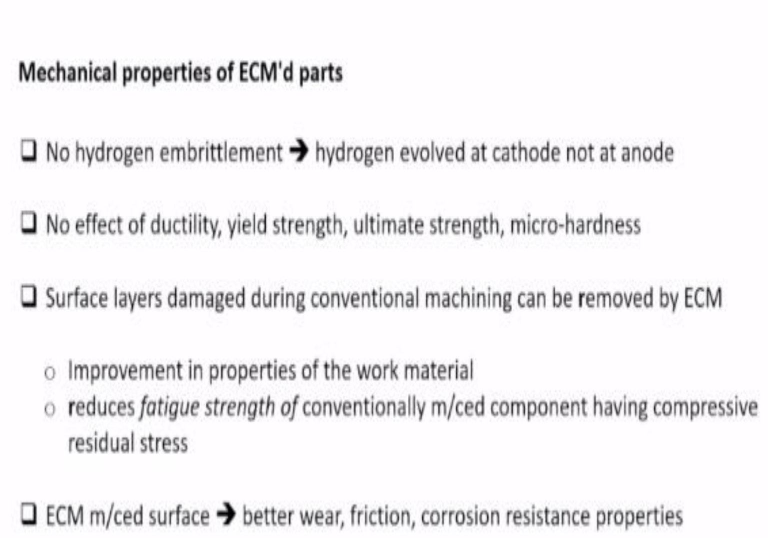

Mechanical properties of ECM'd parts

- ☐ No hydrogen embrittlement → hydrogen evolved at cathode not at anode
- ☐ No effect of ductility, yield strength, ultimate strength, micro-hardness
- ☐ Surface layers damaged during conventional machining can be removed by ECM
    - o Improvement in properties of the work material
    - o reduces *fatigue strength of* conventionally m/ced component having compressive residual stress
- ☐ ECM m/ced surface → better wear, friction, corrosion resistance properties

So now what will be mechanical properties for this ECM process. Now in conventional machining process you know there is a compressive residual stress is generated. So because of this compressive residual stress this fatigue life of the workpiece is increased okay. So in ECM process there is no hydrogen bubbles are generated so there maybe chances of hydrogen embrittlement into the workpiece surface but you can see we have discussed that hydrogen is hydrogen gas is generated into the cathode into the cathode surface.

So it is not generated into the anode surface. So anode actually basically it is used as workpiece. So as it is not generated into the anode so there is no chance of hydrogen embrittlement into the workpiece. So effect of ductility, yield strength, tensile strength, ultimate tensile strength, micro-hardness these things does not change in ECM process.

These are the mechanical properties like ductility, yield strength, ultimate tensile strength, micro-hardness this these things does not change into the workpiece surface. Surface layers damaged during conventional machining process can be removed. So whatever this surface layers I told that this compressive residual stress are generated so this in conventional machining process because of this compressive residual stress this outer layer becomes very harder okay. So whatever this surface layer damaged during this conventional machining process can be removed by ECM process.

Also suppose in EDM process there is a brittle material whatever this molten material it is redeposited there. So these this deposited redeposited material it is very hard okay. So also in EDM process it changes the property of this material. So this material can be removed whatever this property material property whatever this material property changes that layer also that layer also recast layer also can be removed by this EDM process by this electrochemical machining process. So surface layers damaged during conventional machining can be removed by this ECM process. So improvement in properties of this work material.

So reduces fatigue strength of the conventional machining component having compressive residual stress. So as the compressive residual stress is not generated in ECM process which is generated in EDM in conventional machining process so machine parts produced by ECM process and machine parts produced by conventional machining process, in conventional machining process this fatigue life is more than ECM process. So in ECM machine surface has better wear, friction, and better corrosion resistance properties.

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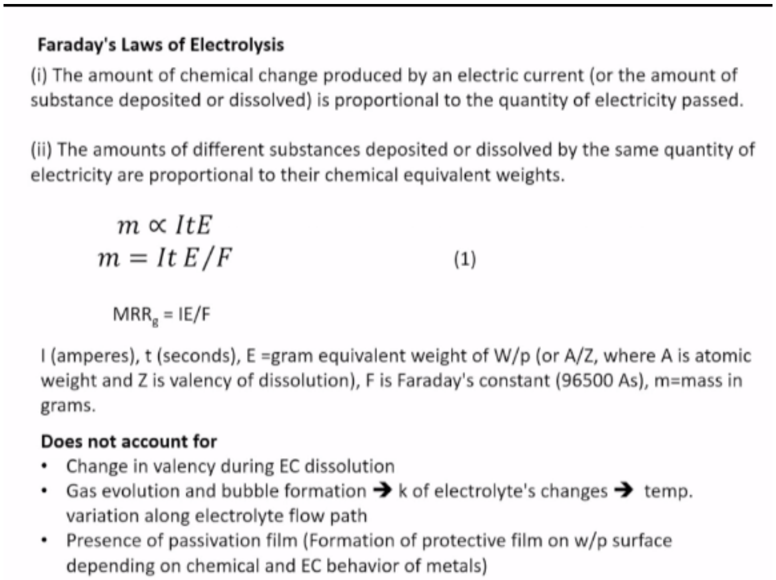

Faraday's Laws of Electrolysis

(i) The amount of chemical change produced by an electric current (or the amount of substance deposited or dissolved) is proportional to the quantity of electricity passed.

(ii) The amounts of different substances deposited or dissolved by the same quantity of electricity are proportional to their chemical equivalent weights.

$$m \propto ItE$$
$$m = It\,E/F \qquad (1)$$

$MRR_g = IE/F$

I (amperes), t (seconds), E =gram equivalent weight of W/p (or A/Z, where A is atomic weight and Z is valency of dissolution), F is Faraday's constant (96500 As), m=mass in grams.

Does not account for

- Change in valency during EC dissolution
- Gas evolution and bubble formation ➔ k of electrolyte's changes ➔ temp. variation along electrolyte flow path
- Presence of passivation film (Formation of protective film on w/p surface depending on chemical and EC behavior of metals)

Now this ECM process works on the Faraday's law of electrolysis. So what is the Faraday's law of electrolysis? So amount of material removed from the workpiece depends on the quantity of electro quantity of current flowing through the workpiece. So this amount of chemical change produced by an electric current so amount of chemical change produced into the workpiece surface by an electric current or the amount of substance deposited or dissolved. In our ECM process the amount of material is dissolved is proportion to the quantity of electrolyte electricity passed through the material. So amount of material dissolved or deposited is proportional to the quantity of electricity passes through the workpiece okay.

So this mass you can if you if you consider this mass this amount of material dissolved from the due to the ECM process if it is m is proportional to I into t, I is the current t is the time. So it is proportional to the I into t. Now this Faraday's second law tells that the amount of different substance deposited or dissolved, suppose substance a and substance b into substance if you flow same current same amount of current to this 2 different substances, amount of material dissolved from the workpiece will be different, it depends on the electrochemical equivalent weight of the material.

So this amount of different substance deposited or dissolved by the same quantity of electricity are proportion to their electrochemical equivalent weight. Or m proportional to E, E is the electrochemical equivalent weight and also from the first law m is proportional to I into t, I into t is the quantity of the current electricity flowing the workpiece okay. So now you can write m proportional to I into t into E. Now m equal to It into E by F.

F is the Faraday's constant, so its value is 96500 As. So if you write in terms of material removal rate MRR g m dot or m dot so you can write it is IE by F so m by t will come so m by t will give the m dot, m dot equal to metal MRR g material removal rate in gram per second it is it will give IE by F. So here I is the ampere current E is the second, current flowing through the workpiece, E is the gram equivalent weight. So E can be represented as A by Z, A is the atomic weight, Z is the valency here and F is the Faraday's constant which will give 96500 As and m is the mass in grams.

So now this Faraday's law does not consider few things like change in valency during electrochemical dissolution. Suppose iron you are machining. So iron has 2 valency, valency 2 and valency 3. So while generating this metallic hydroxide it will be ferric hydroxide or ferrous hydroxide. So what will be the valency of this metallic ions while resolution so it does not tell about that. So change in valency during electrochemical resolution it does not account for this. Also it does not account for gas evolution and bubble formation.

So gas also evolved, hydrogen gas is evolved at the cathode. Also oxygen gas and bubbles also generated during ECM process. Because of that electrolytes, electrical conductivity also reduces when hydrogen gas evolve electrical conductivity of this electrolyte reduces or changes and there is a change in temperature also of this electrolyte. Because of this increase in temperature of this electrolyte, electrolytes electrical conductivity increases along the electrolyte flow path okay. So that is why this key electrolytes electrical conductivity changes so material removal rate also changes. So but this Faraday's law actually does not account for this things.

So there is a presence of passivation layer. So formation of this protective film on the workpiece surface because of this passivation layer this metal hydroxide it is deposited on the workpiece surface also there is a passivation layers are generated on the workpiece surface so it is depends on the chemical and electrical behavior of the material. So this passivation layer has to be removed for machining to takes place. So this Faraday's laws also does not account of this passivation layer on the anode surface.

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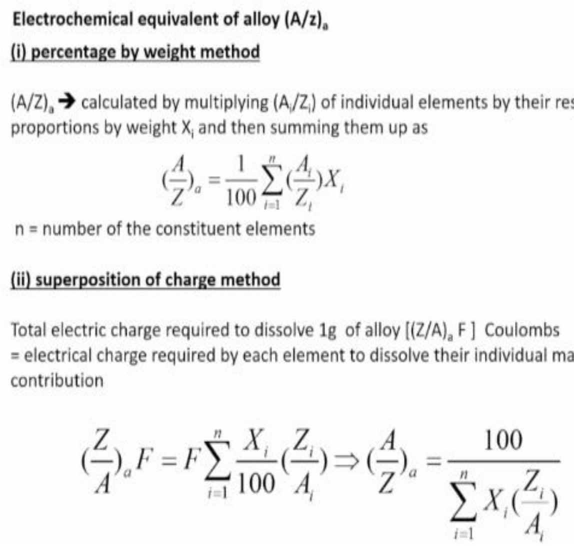

Electrochemical equivalent of alloy $(A/z)_a$

(i) percentage by weight method

$(A/Z)_a$ → calculated by multiplying (A_i/Z_i) of individual elements by their respective proportions by weight X_i and then summing them up as

$$\left(\frac{A}{Z}\right)_a = \frac{1}{100}\sum_{i=1}^{n}\left(\frac{A_i}{Z_i}\right)X_i$$

n = number of the constituent elements

(ii) superposition of charge method

Total electric charge required to dissolve 1g of alloy $[(Z/A)_a F]$ Coulombs = electrical charge required by each element to dissolve their individual mass contribution

$$\left(\frac{Z}{A}\right)_a F = F\sum_{i=1}^{n}\frac{X_i}{100}\left(\frac{Z_i}{A_i}\right) \Rightarrow \left(\frac{A}{Z}\right)_a = \frac{100}{\sum_{i=1}^{n} X_i\left(\frac{Z_i}{A_i}\right)}$$

Now we already told that it does not account for the valency at which it is actually this metal is dissolved and also for this for machining of alloy where there is a mixture of different metals are there. Suppose you are doing electrochemical machining of an alloy which consists of n number of metals. So how to calculate the electrochemical equivalent weight of the metal of the alloy, electrochemical equivalent weight of the alloy. So there are 2 process are there which take care of the electrochemical equivalent weight of the alloy. So first one method is the percentage by weight method and second one is the superposition of the charge method.

So this percentage of weight method so here this E equal to A by Z a it is calculated by multiplying individual electrochemical equivalent weight multiplied by their percentage weight percentage multiplied by their respective properties by weight Xi and then summing them up as shown in this equation. So here A by Z is the electrochemical equivalent weight of this alloy element and here individual electrochemical equivalent weight Ai by Zi multiplied by this their percentage, weight percentage and it is summed up for all the elements equal to 1 to n here and divided by divided by 100 here and after simplification it will give the electrochemical equivalent weight of the alloy. So n is the number of constituent elements in the alloy and the second method is the superposition of the charge.

So now total charge, total electric charge required for dissolution of 1 g of this alloy is Z by A into F. So total electric charge required to dissolve 1 g of alloy is Z by A of the alloy multiplied by F this much Coulombs of charges required. Now it is equal to the electrical charge required for individual element to dissolve their individual mass contribution. So now here Z by A here Z by A into F it is the charge required for 1 g of alloy.

Now here Zi by Ai multiplied by their weight percentage and divided by 100 and summation i equal to 1 to n will give the charge sum or charge required for individual element multiplied by F will give the sum of charge required for individual element. Now after simplification it will give A by Z equal to 100 by summation i equal to 1 to n Xi into Zi by Ai. So electrochemical equivalent weight calculated from both the methods almost it will give the similar results but their results differs slight there is a slight variation in their results is there. So we can calculate electrochemical equivalent weight of alloy by any one of these 2 methods.

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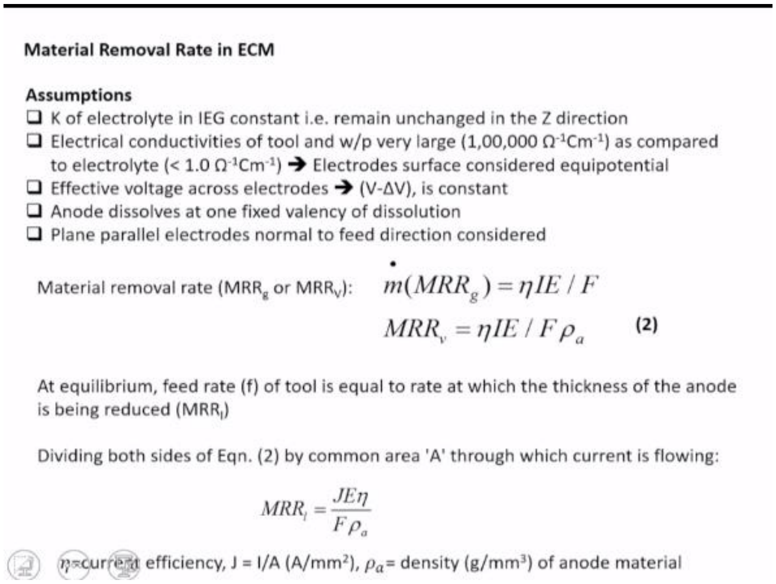

Material Removal Rate in ECM

Assumptions

- ☐ K of electrolyte in IEG constant i.e. remain unchanged in the Z direction
- ☐ Electrical conductivities of tool and w/p very large (1,00,000 $\Omega^{-1}Cm^{-1}$) as compared to electrolyte (< 1.0 $\Omega^{-1}Cm^{-1}$) ➔ Electrodes surface considered equipotential
- ☐ Effective voltage across electrodes ➔ (V-ΔV), is constant
- ☐ Anode dissolves at one fixed valency of dissolution
- ☐ Plane parallel electrodes normal to feed direction considered

Material removal rate (MRR_g or MRR_V):

$$\dot{m}(MRR_g) = \eta IE / F$$

$$MRR_v = \eta IE / F\rho_a \qquad (2)$$

At equilibrium, feed rate (f) of tool is equal to rate at which the thickness of the anode is being reduced (MRR_l)

Dividing both sides of Eqn. (2) by common area 'A' through which current is flowing:

$$MRR_l = \frac{JE\eta}{F\rho_a}$$

η= current efficiency, J = I/A (A/mm^2), ρ_a= density (g/mm^3) of anode material

So now how to calculate the volumetric material removal rate by using the electrochemical machining process. So for doing this one actually there are few assumptions are there. Electrical conductivity of the electrolyte in the interelectrode gap does not change, so it is constant. Although this electrical conductivity of the electrolyte changes with temperature and changes with the hydrogen gas bubbles but for the sake of calculation here for the simplification of the calculation it is assumed as constant.

So k electrical conductivity of the electrolyte does not change in the interelectrode gap. So electrical conductivities of the tool and workpiece is very high. It is around 1 lakh per ohm per centimeter for the tool and workpiece as compared to the electrolyte, so electrolyte it is 1 ohm 1 power ohm per centimeter. So in that case as the electrical conductivity of the electrolyte is very less as compared to the cathode and anode so this tool and workpiece may be considered as the equipotential.

So effective voltage across the electrodes is V minus del V. So del V, V is the applied potential, del V is the potential which is actually used for this tool which is observed in the tool and in other cases okay. So this is the total applied voltage V minus del V.

So this del V is the applied potential here. So also anode dissolves at one fixed valency of dissolution. Although for different materials different valency of dissolution maybe there but here only one valency of the metal actually considered. So here we have considered plain parallel electrodes and feed is given to the electrode here normal to the feed direction so electrolyte is flowing in this direction normal to the feed direction. So material removal rate volumetric this material removal rate gram MRR g is calculated as I by F.

Now eta is the current efficiency means whatever current you are applied so total current is not used for this material removal rate. So only few percentage of that current is used for this material removal of the workpiece. So that is why there is a current deficiency of eta is considered here. Now to get the volumetric material removal rate so you have to apply you have to divide this right hand side by rho by density of this workpiece material.

If you divide that then it will give the volumetric material removal rate which is eta I by F into rho a, rho a is the density of this workpiece material. At equilibrium feed rate of the tool is equal to the dissolution rate from the workpiece. So at equilibrium feed rate f of the tool is equal to the rate at which the thickness of the anode of thickness of the anode being reduced. So at equilibrium rate this thickness of the anode being reduced which is the linear material removal rate. Now how to calculate this linear material removal rate, now this in equation 2 if you divide both side by cross sectional area of the common area A cross section area of the tool if you divide by that in the both the both side then it will give the linear material removal rate MRRL. So left hand side you divide by A cross section area of the tool, right hand side also you divide by cross sectional area A. So it will give I by A equal to J here, J is the current density.

So J eta E F by here left hand side it will give the linear material removal rate. So this linear material removal rate is nothing but penetration rate or millimeter per second. So eta is the current efficiency here, J is the current density, current density equal to I by A here, I is the current, A is the cross sectional area ampere per millimeter square, rho is the density gram per millimeter cube or anode material or workpiece material.

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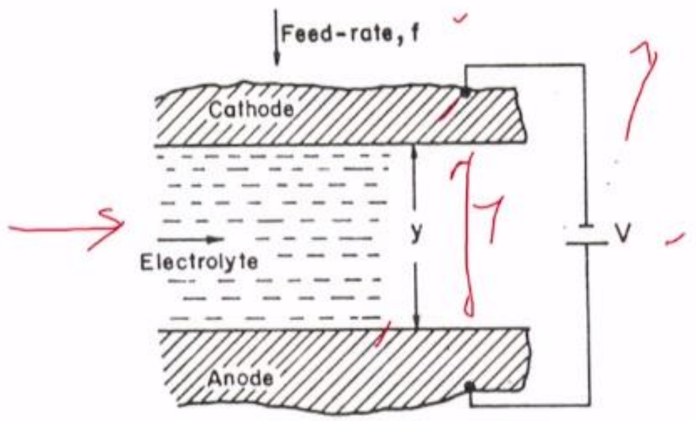

So here you can see this is the cathode here and this is the anode. Electrolyte is flowing in this direction from left to right. So distance between this tool and workpiece this is the y distance between the tool and workpiece. This tool cathode and anode it is connected to a power supply DC power supply here, feed f is given to the cathode towards the anode here and jet direction there is no change in the electrolyte electrical conductivity it does not change in the electrical conductivity of the electrolyte. So in the jet direction actually we are not considering so we are considering only two dimension of this.

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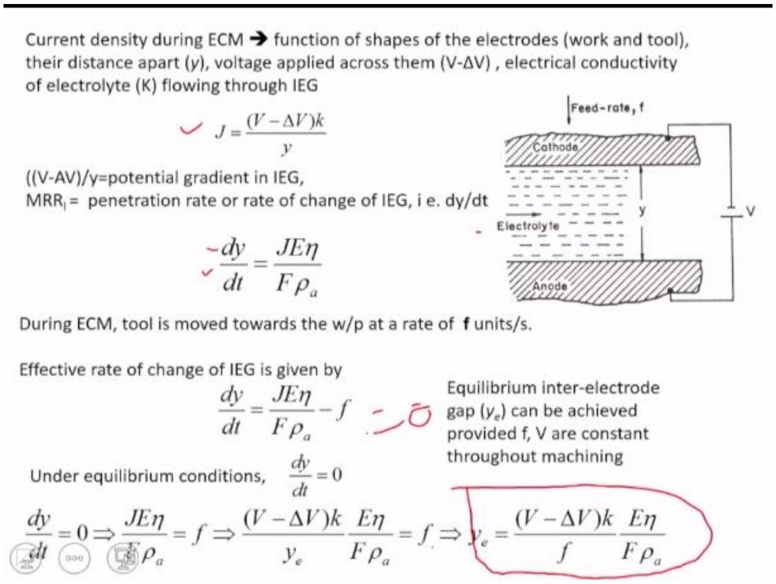

Current density during ECM ➔ function of shapes of the electrodes (work and tool), their distance apart (*y*), voltage applied across them (V-ΔV) , electrical conductivity of electrolyte (K) flowing through IEG

✓ $$J = \frac{(V-\Delta V)k}{y}$$

((V-AV)/y=potential gradient in IEG,

MRR$_l$ = penetration rate or rate of change of IEG, i e. dy/dt

✓ $$\frac{dy}{dt} = \frac{JE\eta}{F\rho_a}$$

During ECM, tool is moved towards the w/p at a rate of **f** units/s.

Effective rate of change of IEG is given by

$$\frac{dy}{dt} = \frac{JE\eta}{F\rho_a} - f \quad -0$$

Equilibrium inter-electrode gap (y_e) can be achieved provided f, V are constant throughout machining

Under equilibrium conditions, $\frac{dy}{dt} = 0$

$$\frac{dy}{dt} = 0 \Rightarrow \frac{JE\eta}{F\rho_a} = f \Rightarrow \frac{(V-\Delta V)k}{y_e}\frac{E\eta}{F\rho_a} = f \Rightarrow y_e = \frac{(V-\Delta V)k}{f}\frac{E\eta}{F\rho_a}$$

So now current density during ECM as a function of shape of the electrode so now we have to calculate the current density. So it depends on the shape of the electrode. Here plain parallel shape of the electrodes we have considered work and tool and the distance between these 2 electrode this is y and voltage applied across them it is V minus del V, V is the applied voltage and del V is the work potential.

So total voltage applied is V minus del V and electrical conductivity of the electrolyte. So J can be represented as V minus del V into k by y, y is the gap interelectrode gap k is the electrical conductivity of the is electrolyte and V minus del V is the total applied voltage. So V minus del V by y is the potential gradient in interelectrode gap.

Now linear MRR l equal to penetration rate or rate of change of interelectrode or MRR l you can write this one as penetration rate or rate of change of this interelectrode gap or you can write this one as dy dt. So here in this equation you can write MRR l equal to dy by dt this one minus F. So you can write this one as dy dt equal to J this is the linear material removal rate MRR l you can write as dy dt right hand side it is J E eta F into rho a so it is already there J E eta F into rho a here okay.

Now during ECM tool is moved towards the workpiece at a rate of f millimeter units per second. So now effective rate of change of interelectrode gap is given by dy dt equal to JE eta F rho a minus f. Now for equilibrium condition dy dt equal to 0. So dy dt will be 0.

Now so you can write for equilibrium condition JE eta by F rho a minus f equal to 0 here okay because dy dt there is no change in interelectrode gap for equilibrium condition. So now you can put it as 0 here. So you can write this one as dy dt equal to 0 or it will become JE eta by F rho a equal to f, equal to feed rate. J now you put it as V minus del V into k by y, V minus del V into k into y, y e is the equilibrium gap. Now you put it here this eta E eta by F rho a equal to f. Now after simplification you will get this equilibrium gap.

So this is the y is the equilibrium gap in between this tool and workpiece. So equilibrium interelectrode gap y can be achieved provided f and V are constant feed rate and voltage are constant throughout the machining, throughout machining feed and voltage are constant throughout the machining. So y e can be calculated as V minus del V into k E into eta by f into F rho a. So from this equation you can calculate this equilibrium gap.

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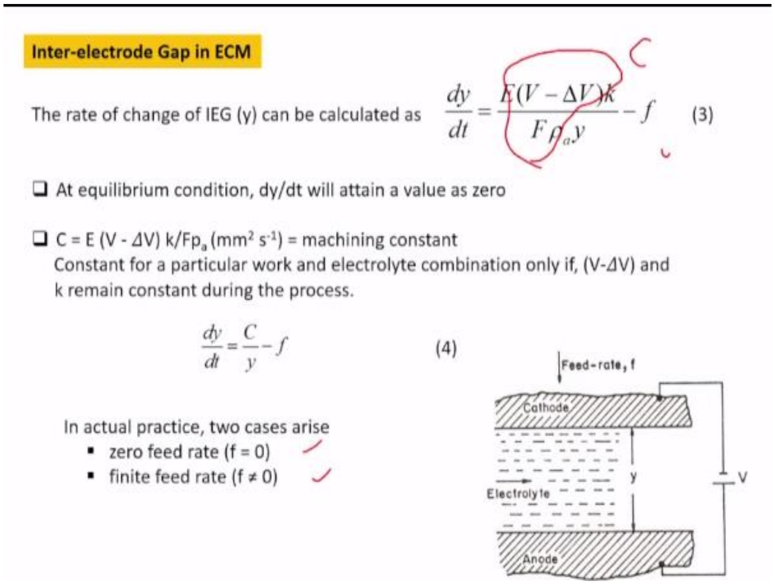

Inter-electrode Gap in ECM

The rate of change of IEG (y) can be calculated as

$$\frac{dy}{dt} = \frac{E(V-\Delta V)k}{F\rho_a y} - f \qquad (3)$$

C

☐ At equilibrium condition, dy/dt will attain a value as zero

☐ C = E (V - ΔV) k/Fρ_a (mm^2 s^{-1}) = machining constant
Constant for a particular work and electrolyte combination only if, (V-ΔV) and k remain constant during the process.

$$\frac{dy}{dt} = \frac{C}{y} - f \qquad (4)$$

In actual practice, two cases arise
- zero feed rate (f = 0) ✓
- finite feed rate (f ≠ 0) ✓

Now interelectrode gap in ECM so similar equation I can write it here dy dt equal to E V minus del V into k by F rho a into y minus f here. So now in equilibrium condition this dy dt will attain a value of 0. So now this one this E V minus del V into k by F into rho a can be considered as a constant. It can be considered as a constant so dy dt we can write is write as dy dt equal to C by y constant machining constant by y minus f.

C is the machining constant here. Constant for a particular work and electrolyte combination only if V minus del V and k remain constant during the process. We have considered this total applied voltage, applied potential is constant and also electrolyte, electrical conductivity is constant in between this 2 electrodes.

So now we can write this one this dy dt equal to C by y minus f. So now there are 2 conditions are there. One is finite feed rate and another one is the zero feed rate. So now your machining is going so you can feed give a feed to the tool with a finite feed rate or you can keep fixed this tool may be kept fixed or f equal to 0 feed equal to 0 feed of the tool is 0 or you can give a finite feed rate to the towards the tool. So in actual practice 2 cases are there zero feed rate f equal to 0 and finite feed rate f not equal to 0.

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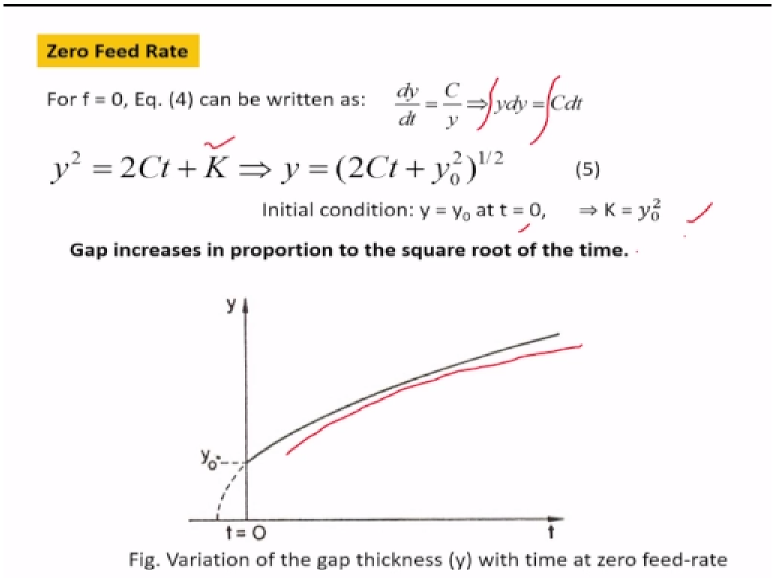

Zero Feed Rate

For f = 0, Eq. (4) can be written as: $\frac{dy}{dt} = \frac{C}{y} \Rightarrow \int y\,dy = \int C\,dt$

$$y^2 = 2Ct + K \Rightarrow y = (2Ct + y_0^2)^{1/2} \qquad (5)$$

Initial condition: $y = y_0$ at $t = 0$, $\Rightarrow K = y_0^2$

Gap increases in proportion to the square root of the time.

Fig. Variation of the gap thickness (y) with time at zero feed-rate

So in case of zero feed rate so in that case dy dt equal to C by y because F equal to 0 here so dy dt equal to C by y zero feed rate or ydy equal to Cdt. Now if you integrate this one if you integrate this one in both side it will become y square by 2 so 2Ct here Ct C into t 2Ct plus K, K is the constant of integration. Now if you put at t equal to 0 there is a interelectrode gap of y square. So at t equal to 0 there is a interelectrode gap of y equal to y0.

Now if you put in this equation here so K equal to y0 square K equal to y0 square. Now put this K equal to y0 square here now you will get y equal to root over 2Ct plus y0 square so root over of this 2Ct plus y0 square. So this is the interelectrode gap for a zero feed rate.

So now plot this one. For t equal to 0 here the interelectrode gap was y0 now with time if we increase the time this interelectrode gap will increase means if we increase the time to a infinite value this interelectrode gap will also increase. So this is not the practical case. If we increase the time after some time this interelectrode gap will increase if we do not give any feed and after that this machining will stop because this machining will start when a minimum interelectrode gap is maintained.

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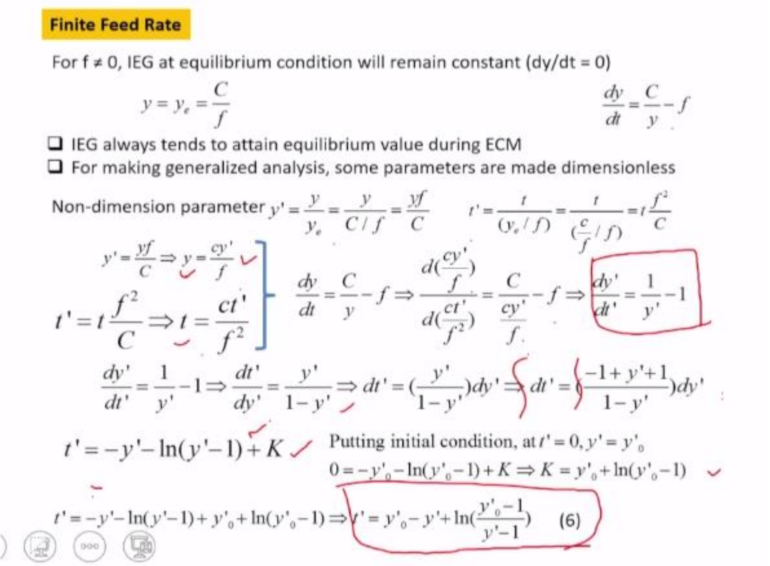

Finite Feed Rate

For f ≠ 0, IEG at equilibrium condition will remain constant (dy/dt = 0)

$$y = y_e = \frac{C}{f} \qquad \frac{dy}{dt} = \frac{C}{y} - f$$

- ☐ IEG always tends to attain equilibrium value during ECM
- ☐ For making generalized analysis, some parameters are made dimensionless

Non-dimension parameter $y' = \frac{y}{y_e} = \frac{y}{C/f} = \frac{yf}{C}$ $\quad t' = \frac{t}{(y_e/f)} = \frac{t}{(\frac{c}{f}/f)} = t\frac{f^2}{C}$

$$\left.\begin{array}{l} y' = \frac{yf}{C} \Rightarrow y = \frac{cy'}{f} \\ t' = t\frac{f^2}{C} \Rightarrow t = \frac{ct'}{f^2} \end{array}\right] \frac{dy}{dt} = \frac{C}{y} - f \Rightarrow \frac{d(\frac{cy'}{f})}{d(\frac{ct'}{f^2})} = \frac{C}{\frac{cy'}{f}} - f \Rightarrow \boxed{\frac{dy'}{dt'} = \frac{1}{y'} - 1}$$

$$\frac{dy'}{dt'} = \frac{1}{y'} - 1 \Rightarrow \frac{dt'}{dy'} = \frac{y'}{1-y'} \Rightarrow dt' = (\frac{y'}{1-y'})dy' \Rightarrow \int dt' = \int (\frac{-1+y'+1}{1-y'})dy'$$

$$t' = -y' - \ln(y'-1) + K$$

Putting initial condition, at $t' = 0, y' = y'_0$

$$0 = -y'_0 - \ln(y'_0 - 1) + K \Rightarrow K = y'_0 + \ln(y'_0 - 1)$$

$$t' = -y' - \ln(y'-1) + y'_0 + \ln(y'_0 - 1) \Rightarrow \boxed{t' = y'_0 - y' + \ln(\frac{y'_0 - 1}{y' - 1}) \quad (6)}$$

Now for the finite feed rate what will be the y, what is the value of y for the final feed rate or feed f not equal to 0. For f not equal to 0 IEG at the equilibrium condition will remain constant. Interelectrode gap for the equilibrium condition will become constant or dy dt equal to 0. So if we put dy dt equal to 0 y equal to y e so in this equation if you put dy dt equal to 0 so here y equal to y e equal to C by f. So in this equation y equal y equal to C f C by f.

So here if you put dy dt equal to 0 for the equilibrium condition so if we give a finite feed rate f not equal to 0 interelectrode gap at equilibrium condition will remain constant or dy dt will become 0 or y equal to y e equal to C by f. Interelectrode gap always tends to attain a equilibrium value during electrochemical machining process. So interelectrode gap always tends to attend a equilibrium value during electrochemical machining process. For making generalized analysis some parameters are made dimensionless okay. So now y is made dimensionless. So non-dimensionalization is done, y dash equal to y by interelectrode gap by equilibrium interelectrode gap. So now y you already have calculated here equal to C by f.

So now put this y value equal to C by f now it will become yf by C. Time also non-dimensionalized like this t dash equal to t by y by f. So here it means how much time is required to machine interelectrode gap so equal to t dash equal to t by y e by f, t by y e already we know this C by f so it will become t into f square by C. now y dash equal to here y f by C now you can get this y equal to c y dash by f here. Now t equal to t dash equal to t e into f square by C. Now you will get t equal to c t dash by f square. Now put this value of this y and t into this equation, so dy dt equal to C by f C by y minus f now put this d y equal to c y dash by f and this d, t equal to you put c t dash by f square equal to c by f, c by y. Now y equal to c y dash by f minus f. now it will come in this in this form dy dash by dt dash equal to 1 by y dash minus 1. Now put it in this form 1 minus y dash minus y so dt dash by dy dash equal to y dash by 1 minus y dash. Now dt dash equal to y dash by 1 minus y dash into dy dash.

Now dt dash equal to minus 1 plus y dash plus 1 by 1 minus y dash into dy dash. Now integrate in both the sides you integrate now it will become t dash this one it will become minus y dash then this one 1 by 1 minus y dash it will become l n y dash minus 1 plus K, K is the integration constant. So it can be calculated as putting the initial value at t equal t dash equal to 0 y dash equal to y0 dash.

Now you put this value here. Now we will get the value of K as y 0 dash plus l n y 0 dash minus 1 here. Now put this value of K here in this equation so now we will get this t dash equal to minus y dash minus l n y dash minus 1 plus y 0 dash plus l n y 0 dash minus 1. So now t dash we will get this y 0 dash minus y dash plus l n y 0 dash minus 1 by y dash minus 1. So this is the equation for this t dash.

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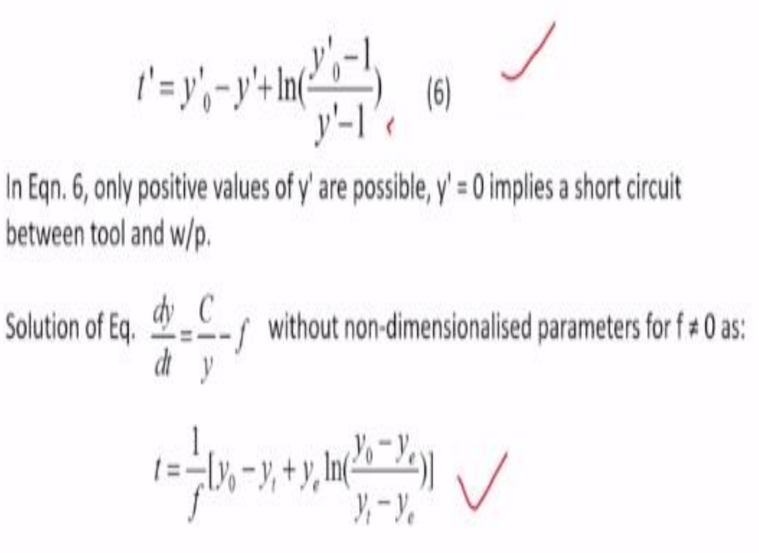

$$t' = y'_0 - y' + \ln\left(\frac{y'_0 - 1}{y' - 1}\right) \qquad (6)$$

In Eqn. 6, only positive values of y' are possible, y' = 0 implies a short circuit between tool and w/p.

Solution of Eq. $\frac{dy}{dt} = \frac{C}{y} - f$ without non-dimensionalised parameters for f ≠ 0 as:

$$t = \frac{1}{f}\left[y_0 - y_t + y_e \ln\left(\frac{y_0 - y_e}{y_t - y_e}\right)\right]$$

So t dash you can calculate so y0 dash minus y dash plus l n y0 dash minus 1 y dash minus 1. Now equation 6 only positive values of y dash are possible because if you put y dash equal to 0 this means that it implies that a short circuit between the tool and workpiece is there. So only positive values of y dash you can put here in this equation. So solution of this equation dy dt equal to C by y minus f or non-zero f or finite feed rate without any non-dimensionalization will get in this form so t equal to 1 by f y0 minus y t plus y e l n y0 minus y e by y t minus y e. So y t is the gap in time t. So you can calculate this t dash by non-dimensionalization or without non-dimensionalization also you can calculate this t.

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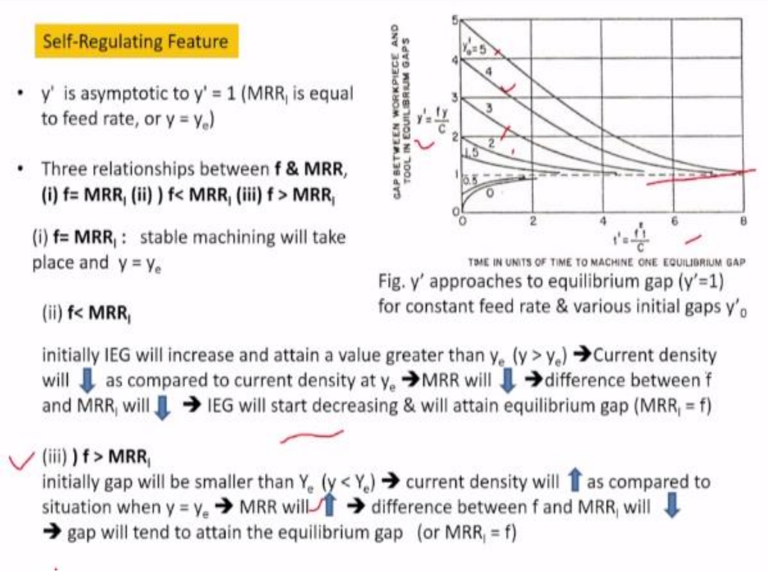

Self-Regulating Feature

- y' is asymptotic to $y' = 1$ (MRR_l is equal to feed rate, or $y = y_e$)
- Three relationships between **f & MRR**, **(i) f= MRR_l (ii)) f< MRR_l (iii) f > MRR_l**

(i) **f= MRR_l :** stable machining will take place and $y = y_e$

(ii) **f< MRR_l**

initially IEG will increase and attain a value greater than y_e ($y > y_e$) ➔Current density will ⬇ as compared to current density at y_e ➔MRR will ⬇ ➔difference between f and MRR_l will ⬇ ➔ IEG will start decreasing & will attain equilibrium gap ($MRR_l = f$)

✓ (iii) **) f > MRR_l**
initially gap will be smaller than Y_e ($y < Y_e$) ➔ current density will ⬆ as compared to situation when $y = y_e$ ➔ MRR will ⬆ ➔ difference between f and MRR_l will ⬇ ➔ gap will tend to attain the equilibrium gap (or $MRR_l = f$)

Fig. y' approaches to equilibrium gap ($y'=1$) for constant feed rate & various initial gaps y'_0

So now if we plot this y dash here so y dash is plotted and here y axis it is y dash equal to f y by C. X axis it is plotted t dash. Now we can see whatever value of this y0 initial value whatever initial value you take initial interelectrode gap so here in this case if it is 5 it is initial interelectrode gap is 4, 3, 2, 1.5, 0. So in both the cases in all the cases you will see it will asymptote to a value of y dash equal to 1. So y dash equal to 1 means here if you put y dash equal to 1 means y equal to y e so it will reach to the equilibrium gap, so it will reach to the this interelectrode gap will reach the equilibrium gap.

So y dash t is asymptotic to y dash equal to 1 or linear material removal rate is equal to the feed rate or y equal to y e. So whatever value of initial interelectrode gap you will take so linear material removal rate will achieve will take the value of this linear feed rate or y interelectrode gap will achieve the equilibrium interelectrode gap.

So this is called stable regulating characteristics of ECM process. There are 3 cases of 3 cases are there. When feed rate is equal to the linear material removal rate, when feed rate is greater than linear material removal rate, and when feed rate is less than linear material removal rate. So in the first case when feed rate is equal to the linear material removal rate in that case stable machining will take place and in that case interelectrode gap is equal to the equilibrium gap and in the second case when feed rate is less than linear material removal rate in that case we are not giving at the same feed with the machining or machining is going on from the workpiece.

So you are giving less feed so in that case what will happen gap between this tool and workpiece will increase. If gap between tool and workpiece increases then current density will decrease. If current density decreases then machining rate will decrease or material removal rate will decrease. So if material removal rate decreases means gap between the difference between the linear material removal rate and feed rate will decrease or ultimately it will take the shape it will take linear material removal rate will take the value of feed rate.

So here it is written initial interelectrode gap will increase and attain a value of greater than equilibrium gap or y is greater than equilibrium gap. Current density will decrease as compared to the current density at the equilibrium interelectrode gap and that is why material removal rate will also decrease and if this material removal rate decreases the difference between the feed rate and the linear material removal rate will decrease.

So if this gap between this difference between the feed rate and linear material removal rate decreases interelectrode gap will start decreasing and will attain a equilibrium gap or MRR l will become a equilibrium gap equal to f and if feed rate is greater than in the third case if feed rate is greater than material removal rate initially this gap will become more than the equilibrium gap. So if gap between is becoming more than the equilibrium gap, equilibrium interelectrode gap, your current density will increase, if current density increases more material removal will be there. If more material removal is there this difference between the linear material removal rate and f will decrease and ultimately it will take the it will take the equal to the feed rate. Or initially this gap will be smaller than the equilibrium gap y e y less than equilibrium gap.

Current density will increase as the gap reduces as compared to the situation when y equal to gap interelectrode gap is equilibrium gap. So that is why if current density increases your material removal rate will increase and difference between the f feed rate and linear material removal will become small and that is why gap will tend to attend the equilibrium gap or linear material removal rate will become f. So this is the self-regulating characteristics of ECM process.

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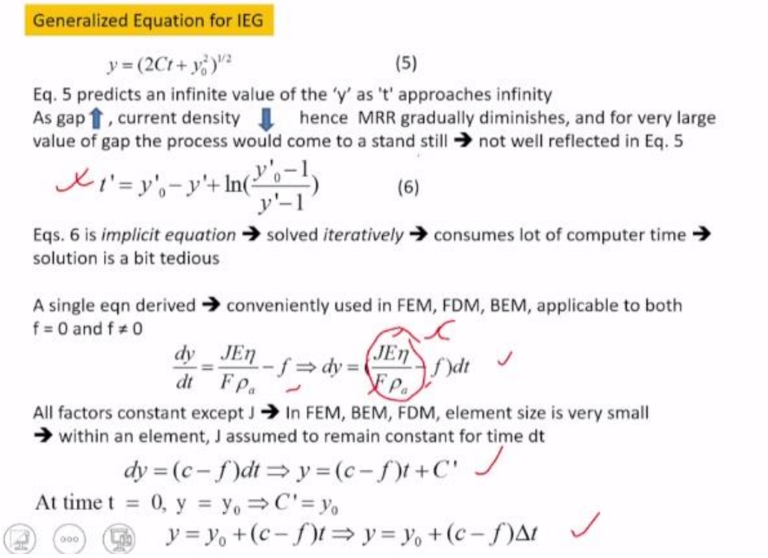

Generalized Equation for IEG

$$y = (2Ct + y_0^2)^{1/2} \qquad (5)$$

Eq. 5 predicts an infinite value of the 'y' as 't' approaches infinity
As gap ↑, current density ↓ hence MRR gradually diminishes, and for very large value of gap the process would come to a stand still ➔ not well reflected in Eq. 5

$$t' = y'_0 - y' + \ln\left(\frac{y'_0 - 1}{y' - 1}\right) \qquad (6)$$

Eqs. 6 is *implicit equation* ➔ solved *iteratively* ➔ consumes lot of computer time ➔ solution is a bit tedious

A single eqn derived ➔ conveniently used in FEM, FDM, BEM, applicable to both f = 0 and f ≠ 0

$$\frac{dy}{dt} = \frac{JE\eta}{F\rho_a} - f \Rightarrow dy = \left(\frac{JE\eta}{F\rho_a} - f\right)dt \quad ✓$$

All factors constant except J ➔ In FEM, BEM, FDM, element size is very small ➔ within an element, J assumed to remain constant for time dt

$$dy = (c - f)dt \Rightarrow y = (c - f)t + C' \quad ✓$$

At time t = 0, y = $y_0 \Rightarrow C' = y_0$

$$y = y_0 + (c - f)t \Rightarrow y = y_0 + (c - f)\Delta t \quad ✓$$

So now generalized equation for this interelectrode gap. For dy by dt equal to C by y minus f in that equation. For f equal to 0 we have seen that if we increase the t for in an infinite value of t there is a infinite value so this interelectrode gap also increases infinitely nonlinearly. So it is not the case so it is not the practical case.

Practically actually this linear if you increase the time over time and with the zero feed rate after some time it will become the this interelectrode gap will become will increase after some time this machining rate will stop, machining will stop there will not be any electrochemical machining because minimum interelectrode gap should be maintained for the machining to take place and for the second case, this one, this t dash this non-dimensional case when f there is a finite feed rate is there.

So this is the implicit form of the equation. To solve this implicit form we have to take help of the (()) (1:24:25) analysis and you have to take help of the finite difference method or finite element method or boundary element method. So in the equation in the first equation when f equal to 0 this y equal to root over 2Ct plus y0 square. So it predicts an infinite value of y as t approaches infinity. As the gap increases current density will reduce and hence material removal rate gradually diminishes and very large value of gap this process would come to a standstill not well reflected in equation 5.

Now for the second case when f equal to 0 in that case it is a implicit form of the equation. It is solved iteratively and it consumes lot of computer time and this solution is a bit of tedious. So that is why a single equation is derived conveniently used in FEM, finite difference method, and boundary element method which is derived by Jain et al., Jain and Pandey which is applicable to both f equal to 0 feed rate 0 feed rate and finite feed rate. So now you can write this one dy dt equal to JE eta by F into rho a minus f then dy dt equal you can write in this form JE eta F rho a minus f multiplied by dt. So in this equation all factors actually constant except this J because E eta Faraday's constant rho a density of this anode, all these are actually constant except this J.

So you can write all factors are constant except this J. So in FEM finite element method, bounded element method, finite difference method, this element size is very small. So in that very small element size you can consider this current density is constant. So within that element you can consider this current density J assumed to be constant for a time for a very small time of dt, we can consider. So this one so now we can write this dy equal to c minus f so you can consider this one as a constant for a very small domain and very for a very small time.

So you can write this one dy equal to c minus f into dt. Now integrate this equation y equal to c minus f into t plus C dash, C dash here actually integration constant. Now for t equal to 0 if you put this initial condition for t equal to 0 y equal to y0. Initial interelectrode gap is y0. So if you put this one in this equation then C dash will become y0. Now you put this C dash equal to 0 in this equation. Now we will get this one as y equal to y0 c minus f into del t. So del t here it is del t is taken because this equation is valid because this current density is constant for a very small time del t.

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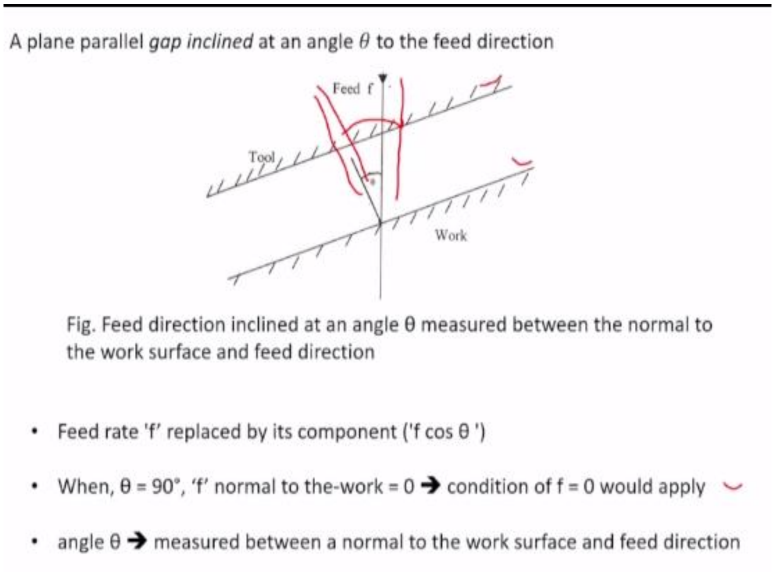

A plane parallel *gap inclined* at an angle θ to the feed direction

Fig. Feed direction inclined at an angle θ measured between the normal to the work surface and feed direction

- Feed rate 'f' replaced by its component ('f cos θ ')
- When, θ = 90°, 'f' normal to the-work = 0 ➔ condition of f = 0 would apply
- angle θ ➔ measured between a normal to the work surface and feed direction

So this single equation can be used for both the cases of finite feed rate and zero feed rate and also it takes very less amount of computational time for solving the to calculate the interelectrode gap between cathode and anode. So now in some cases when feed rate or this cathode and anode it is inclined to an angle theta to the feed rate. So this is cathode and this is the anode, it is inclined at an angle theta to the feed rate. So in that case we have to take the component of the feed f cos theta instead of f okay. So feed rate f is replaced by the component f cos theta. When theta equal to 90 degree f is normal to the workpiece.

When theta equal to 90 degree then f is normal to the workpiece so then feed is zero. So condition of f equal to 0 would apply so in that case condition of f equal to 0 will apply. Angle theta is measured between the normal to the workpiece so this is the normal to the workpiece and in between the feed direction. So this is the feed direction, this is the normal to the workpiece and this is the angle theta.

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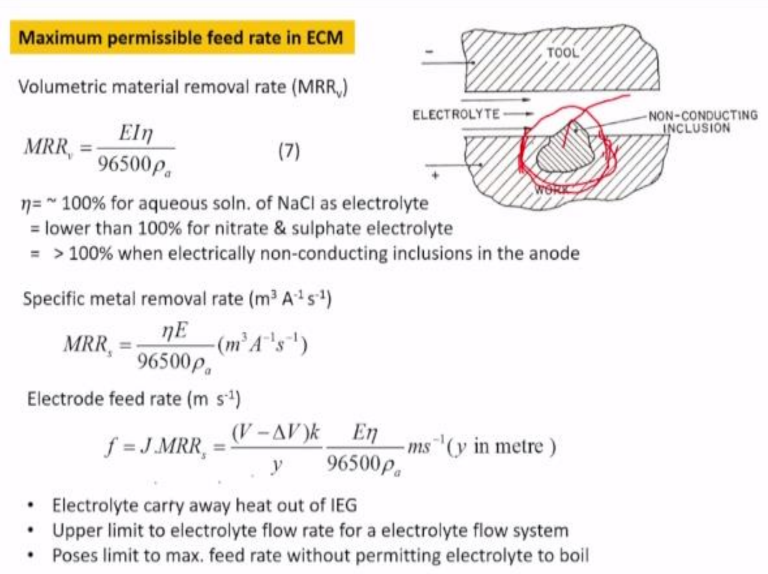

Maximum permissible feed rate in ECM

Volumetric material removal rate (MRR_v)

$$MRR_v = \frac{EI\eta}{96500\rho_a} \qquad (7)$$

η= ~ 100% for aqueous soln. of NaCl as electrolyte
= lower than 100% for nitrate & sulphate electrolyte
= > 100% when electrically non-conducting inclusions in the anode

Specific metal removal rate ($m^3 A^{-1} s^{-1}$)

$$MRR_s = \frac{\eta E}{96500\rho_a}(m^3 A^{-1} s^{-1})$$

Electrode feed rate ($m\ s^{-1}$)

$$f = J.MRR_s = \frac{(V-\Delta V)k}{y}\frac{E\eta}{96500\rho_a}ms^{-1}(y \text{ in metre})$$

- Electrolyte carry away heat out of IEG
- Upper limit to electrolyte flow rate for a electrolyte flow system
- Poses limit to max. feed rate without permitting electrolyte to boil

Now how to calculate the maximum permissible feed rate in electrochemical machining process. Now this volumetric material removal rate can be calculated as EI by eta by 96500, this is the value of F, Faraday’s constant by rho a. So eta is the current efficiency. So it almost 100% for a initial solution, initial as electrolyte. So it is almost 100% for aqueous solution of NaCl as electrolyte. So it is lower than 100% when we will take nitrate or sulphate as the electrolyte and it is more than 100% when it electrically nonconducting inclusions are there in the anode. Suppose this kind of electrically nonconducting inclusions are there so in that case this outside this materials will be removed. When this material is removed by ECM process this one also will be removed automatically okay. So it is a electrically nonconducting inclusions are there. So this material is not removed by ECM process because outside materials are removed by ECM process so this material also it is removed from the from that from the workpiece. So in that case automatically your current efficiency will become more than 100%, so when electrically nonconducting inclusions are there in the anode.

Now one concept is there, specific material removal rate that is meter cube per ampere per second. Specific material removal rate can be calculated as volumetric material removal rate by current. MRR v by current i will give the specific material removal rate. MRR v volumetric material removal rate by current will give the specific material removal rate. So in equation 7 if you divide left hand side by MRR v by i then it will become eta e 96500 into rho a. Now this feed rate can be written as J into current density into volumetric material removal rate. Now current density we can write as V minus del V into k by y we have seen earlier and now specific material removal rate can be written as eta e by f into rho a.

So this is feed rate meter per second. So now we are going to calculate what should be the maximum permissible feed rate in ECM process because if we increase the feed rate then this gap between this interelectrode gap will decrease. If gap decreases then current density will increase. If current density increases then more material removal will be there. So at the same time huge amount of temperature will be generated.

So this temperature is generated then electrolyte has to be flown away from that gap whatever because this temperature will be dissipated to the electrolyte. So this electrolyte has to be removed or flown away from the interelectrode gap. So if it is not removed from the interelectrode gap what will happen? Electrolyte will boil in between this interelectrode gap because already we are maintaining very small gap.

In that small gap if we increase the current density automatically this ohmic hitting will be there because of this ohmic hitting this electrolyte will boil. So to reduce to avoid this boiling of this electrolyte we have to remove that electrolyte from the interelectrode gap. So you have to electrolyte will carry away the heat from the interelectrode gap so upper limit of electrolyte flow rate. So there is a upper limit of the electrolyte flow rate may be there for a electrolyte flow system. So which poses a limit to maximum feed rate without permitting the electrolyte to boil.

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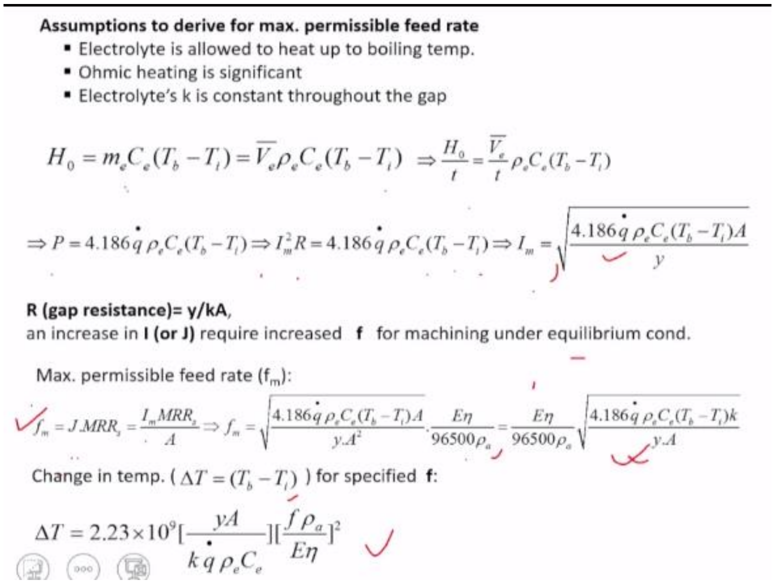

Assumptions to derive for max. permissible feed rate

- Electrolyte is allowed to heat up to boiling temp.
- Ohmic heating is significant
- Electrolyte's k is constant throughout the gap

$$H_0 = m_e C_e (T_b - T_i) = \overline{V}_e \rho_e C_e (T_b - T_i) \Rightarrow \frac{H_0}{t} = \frac{\overline{V}_e}{t} \rho_e C_e (T_b - T_i)$$

$$\Rightarrow P = 4.186 \dot{q} \rho_e C_e (T_b - T_i) \Rightarrow I_m^2 R = 4.186 \dot{q} \rho_e C_e (T_b - T_i) \Rightarrow I_m = \sqrt{\frac{4.186 \dot{q} \rho_e C_e (T_b - T_i) A}{y}}$$

R (gap resistance)= y/kA,

an increase in **I (or J)** require increased **f** for machining under equilibrium cond.

Max. permissible feed rate (f_m):

$$f_m = J.MRR_s = \frac{I_m MRR_s}{A} \Rightarrow f_m = \sqrt{\frac{4.186 \dot{q} \rho_e C_e (T_b - T_i) A}{y.A^2}} . \frac{E\eta}{96500 \rho_a} = \frac{E\eta}{96500 \rho_a} \sqrt{\frac{4.186 \dot{q} \rho_e C_e (T_b - T_i) k}{y.A}}$$

Change in temp. ($\Delta T = (T_b - T_i)$) for specified **f**:

$$\Delta T = 2.23 \times 10^9 [\frac{yA}{k \dot{q} \rho_e C_e}][\frac{f \rho_a}{E\eta}]^2$$

So there are few assumptions are there to derive the maximum permissible feed rate. So electrolyte is allowed to heat up to a boiling temperature. So electrolyte is allowed to heat up to a boiling temperature. So it is not allowed to boil. So after boiling temperature it is allowed. So from its initial temperature Ti to it is allowed to up to this boiling temperature. So when only the ohmic heating is significant. Other than ohmic heating like viscous heating and any other heating is not so because these electrodes also will become heated up so this heat due to the from the hot electrode so it is not considered because electrode will become heated so this heat is actually dissipated into the convected into the electrolyte. So that heat is not considered only that ohmic heat is considered.

So also we have considered this electrolytes electrical conductivity is constant, so k is constant, electrolytes electrical conductivity does not change with temperature so we have considered that thing. So heat generated because from Ti initial temperature electrolyte from initial temperature to the up to boiling temperature m e C is specific heat Tb minus T. So heat generated from electrolyte from initial temperature to the boiling temperature. So m s t. So m e mass of electrolyte C is the specific heat of that electrolyte and Tb electrolyte is from initial temperature it is it has come to the boiling temperature Tb.

So now you can write m e equal to mass of electrolyte as volume of electrolyte multiplied by density of this electrolyte C Tb minus T. Now H0 by T equal to Ve by T rho e Ct Tb by Ta. Now power required for the electrolyte so it should be multiplied by 4.2 to convert it into joule, so 4.18 and q dot is actually volumetric flow rate of the electrolyte here into rho e C Tb minus Ti.

Now power you can convert this one as I square R, I is the maximum permissible current I m into R. So equal to 4.186 q dot, volumetric flow rate of electrolyte, C is specific heat, rho e is the density of this electrolyte Tb minus Ti. So I m after simplification it will take this form I m equal to 4.186 q dot rho e C Tb minus Ti into a divided by y. So here gap resistance is y by k, y is the interelectrode gap, k is the conductivity, a is the cross sectional area.

So R is written as y by k a. So an increase in the I or current density if we if we increase the distance then current density will increase and it will require increased feed rate so it will require increased feed rate for machining under equilibrium condition. So maximum permissible feed rate can be calculated as F m equal to current density into specific material removal rate. So current density already you have you know I m by a current by area I m already you have calculated here. So now put this I m here and specific material removal rate is eta e into f into rho a okay so now it will take in this shape.

So change in temperature is Tb minus Ti for a specific feed. So this is the maximum permissible feed rate which is allowed for to avoid electrolyte to boil. So what is the maximum permissible temperature rise which is Tb minus Ti maximum permissible temperature rise of the electrolyte can be calculated from this equation. So here you it can be calculated from this equation.

So del T equal to 2.23 into 10 to the power 9 yA by k q dot rho e C f rho a by eta E. So y is the interelectrode gap is the cross sectional area is the electrolytes electrical conductivity q dot is the volumetric flow rate of electrolyte rho is the density of this electrolyte C is the specific heat of the electrolyte f is the feed rate rho is the density of this electrolyte E is the electrochemical equivalent weight eta is the current efficiency.

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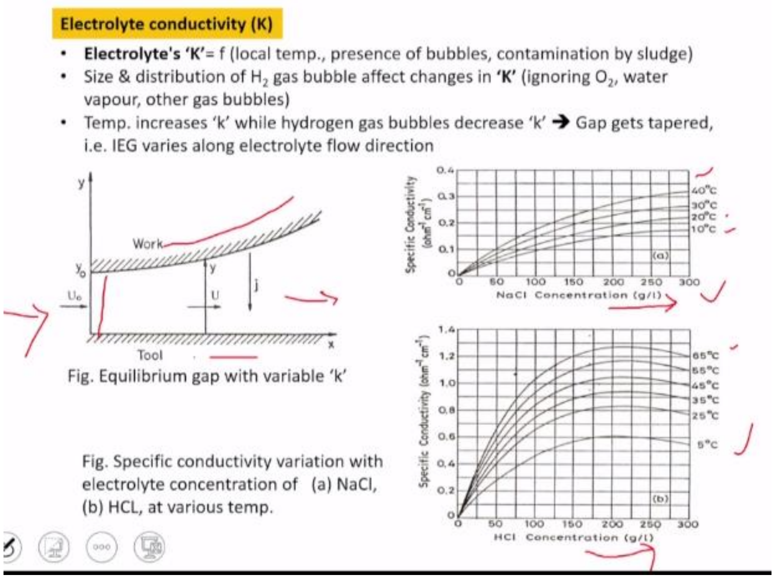

Electrolyte conductivity (K)

- **Electrolyte's 'K'**= f (local temp., presence of bubbles, contamination by sludge)
- Size & distribution of H_2 gas bubble affect changes in **'K'** (ignoring O_2, water vapour, other gas bubbles)
- Temp. increases 'k' while hydrogen gas bubbles decrease 'k' ➔ Gap gets tapered, i.e. IEG varies along electrolyte flow direction

Fig. Equilibrium gap with variable 'k'

Fig. Specific conductivity variation with electrolyte concentration of (a) NaCl, (b) HCL, at various temp.

So now electrical conductivity of this electrolyte actually increases because of this rise in temperature. When temperature rises electrical conductivity of the electrolyte also increases. Suppose if we consider this initial solution if we increase the temperature from 10 degree to 20 degree you can see this specific conductivity electrical conductivity of this electrolyte increases from 10 degree to 20 degree, 20 to 30 degree and 30 to 40 degree you can see electrical conductivity of this electrolyte increases,

Also initial concentration if we increase then also electrical conductivity of this electrolyte increase. Same case for this HCl solution also, if we increase the concentration of this electrolyte HCl solution then your electrical conductivity increases and also if you increase the temperature of this electrolyte then also from 5 degree to 65 degree you can see electrical conductivity of this electrolyte increases.

So electrolyte conductivity is a function of temperature of this electrolyte and also it is a function of presence of bubbles, hydrogen gas, contamination by the sludges because sludges are there this contaminated into the interelectrode gap, so if more sludges are there electrical conductivity of this electrolyte will change. Presence of bubbles also will reduce the electrical conductivity of the electrolyte. So size and distribution of this hydrogen gas bubble affect the changes in the K if we ignore this oxygen and water vapour and other gas bubbles. If we consider only hydrogen gas bubbles are (()) (1:42:05) at the cathode so its size hydrogen gas bubble size and its concentration also affects the changes in K.

Temperature increases K electrical conductivity while hydrogen gas bubble decreases the electrical conductivity of this electrolyte. So gap gets trapped that is interelectrode gap varies so that is why at the downstream direction so electrolyte is flowing at U0 velocity at the downstream direction if you see this gap, interelectrode gap actually varies. Suppose this is the tool here so workpiece actually moving towards the tool here so initially this gap is y0 here. Now you can see this gap actually varies in between this tool and workpiece because this electrolyte is flowing so in downstream direction you will see there is a concentration of this hydrogen gas bubbles.

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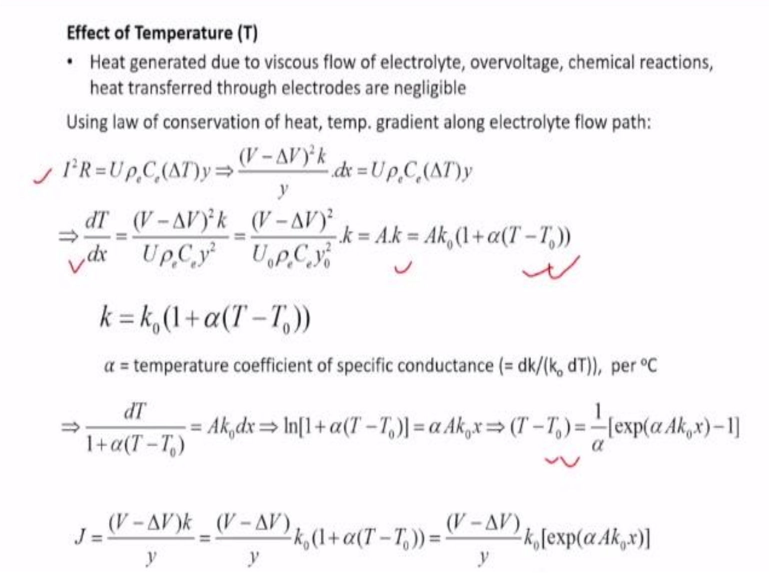

Effect of Temperature (T)

- Heat generated due to viscous flow of electrolyte, overvoltage, chemical reactions, heat transferred through electrodes are negligible

Using law of conservation of heat, temp. gradient along electrolyte flow path:

$$I^2R = U\rho_e C_e(\Delta T)y \Rightarrow \frac{(V-\Delta V)^2 k}{y}.dx = U\rho_e C_e(\Delta T)y$$

$$\Rightarrow \frac{dT}{dx} = \frac{(V-\Delta V)^2 k}{U\rho_e C_e y^2} = \frac{(V-\Delta V)^2}{U_0\rho_e C_e y_0^2}.k = A.k = Ak_0(1+\alpha(T-T_0))$$

$$k = k_0(1+\alpha(T-T_0))$$

α = temperature coefficient of specific conductance (= dk/(k$_o$ dT)), per °C

$$\Rightarrow \frac{dT}{1+\alpha(T-T_0)} = Ak_0 dx \Rightarrow \ln[1+\alpha(T-T_0)] = \alpha Ak_0 x \Rightarrow (T-T_0) = \frac{1}{\alpha}[\exp(\alpha Ak_0 x)-1]$$

$$J = \frac{(V-\Delta V)k}{y} = \frac{(V-\Delta V)}{y}k_0(1+\alpha(T-T_0)) = \frac{(V-\Delta V)}{y}k_0[\exp(\alpha Ak_0 x)]$$

So now effect of temperature on electrolytes electrical conductivity. So here for doing this one heat generated due to the viscous flow of electrolyte, overvoltage, chemical reactions, heat transferred through the electrodes are negligible. We are not considering heat generated due to viscous flow of electrolyte, overvoltage, or chemical reactions we are not considering here. So heat transferred through the electrodes are also negligible.

So now using the conservation of heat, temperature, gradient along the electrolyte flow path you can see I square R equal to U equal to U is the flow velocity of this electrolyte, rho e C into del T into y delta I square R. So here same thing actually we are using. Now we can consider I equal to V minus del V square into k by y into dx and you put R equal to y by k so after putting this it will become in this form dT dx equal to V minus del V square into k U rho e C e into y square.

So now V minus del V square U0 rho e C by y0 square you can consider this one as constant so we can write it A and here ultimately you can write it A into k.

Now k is the electrical conductivity of this electrolyte. Now we can write this one k equal to k0 1 plus alpha T minus T0. So temperature, it rises from initial temperature T0 to certain value of T. So k equal to k0 into 1 plus alpha T minus T0, alpha is temperature coefficient of specific conductance. It can be written as dk by k0 into dT per degree centigrade.

So now after simplification this equation will come dT by 1 plus alpha T minus T0 equal to Ak0 into dx. So now if you take a if you do the integration here it will become ln 1 plus alpha T minus T0 alpha k0 A into x so now T minus T0 you can write this one as 1 by alpha exponential alpha Ak0 x minus 1. So now J current density you can write as V minus del V into k by y so V minus del V by y k equal to we can write 1 plus k0 1 plus alpha T minus T0. So this is V minus del V by y k0 1 plus alpha T minus T0 you can write as exponential alpha k k0 x okay.

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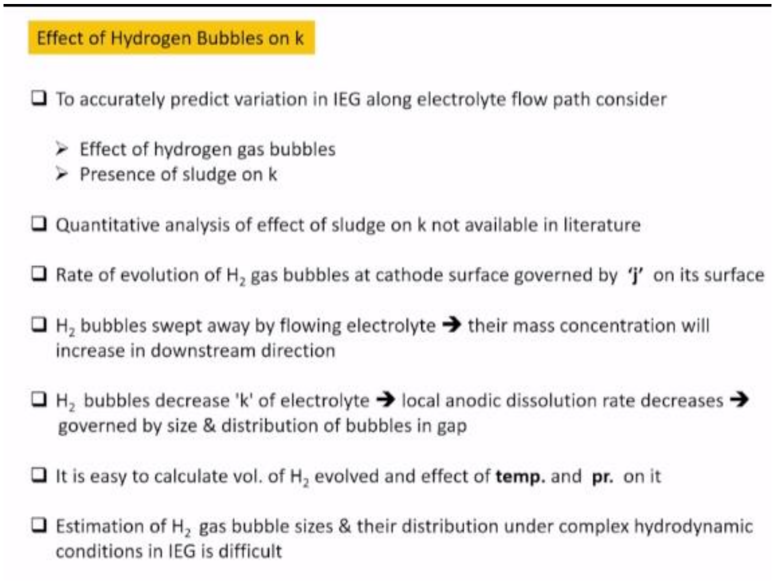

Effect of Hydrogen Bubbles on k

- ☐ To accurately predict variation in IEG along electrolyte flow path consider
  - ➢ Effect of hydrogen gas bubbles
  - ➢ Presence of sludge on k
- ☐ Quantitative analysis of effect of sludge on k not available in literature
- ☐ Rate of evolution of H_2 gas bubbles at cathode surface governed by **'j'** on its surface
- ☐ H_2 bubbles swept away by flowing electrolyte → their mass concentration will increase in downstream direction
- ☐ H_2 bubbles decrease 'k' of electrolyte → local anodic dissolution rate decreases → governed by size & distribution of bubbles in gap
- ☐ It is easy to calculate vol. of H_2 evolved and effect of **temp.** and **pr.** on it
- ☐ Estimation of H_2 gas bubble sizes & their distribution under complex hydrodynamic conditions in IEG is difficult

So this is the effect. So current density you can write in this form okay. So current density will become will change if we increase the temperature of the electrolyte. So effect of hydrogen gas bubbles on k. So to accurately predict the variation of variation in the interelectrode gap along the electrolyte flow path consider effect of hydrogen gas bubbles, presence of sludge in the k. So quantitative analysis of the effect of sludge on the electrolyte electrical conductivity there is no reference in the literature. So effect of sludge on k on electrical conductivity of this electrolyte is not considered here. Only that effect of hydrogen gas bubbles on the electrical conductivity of this electrolyte is considered here.

So rate of evolution of hydrogen gas bubble at the cathode surface governed by the current density on its surface. Hydrogen gas bubble are swept away by the flowing electrolyte, so their mass concentration is more at the downstream side in the downstream direction. So hydrogen gas bubble decreases k conductivity of this electrolyte and local anodic dissolution rate decreases so as the hydrogen gas bubble evolve so its electrical conductivity of this electrolyte actually decreases and also anodic dissolution also decreases.

So it is governed by the size and distribution of the hydrogen gas bubbles in the interelectrode gap. So it is easy to calculate the volume of hydrogen gas evolved and effect of temperature and pressure on it. Estimation of hydrogen gas bubbles sizes and their distribution under complex hydrodynamic condition in the interelectrode gap is difficult.

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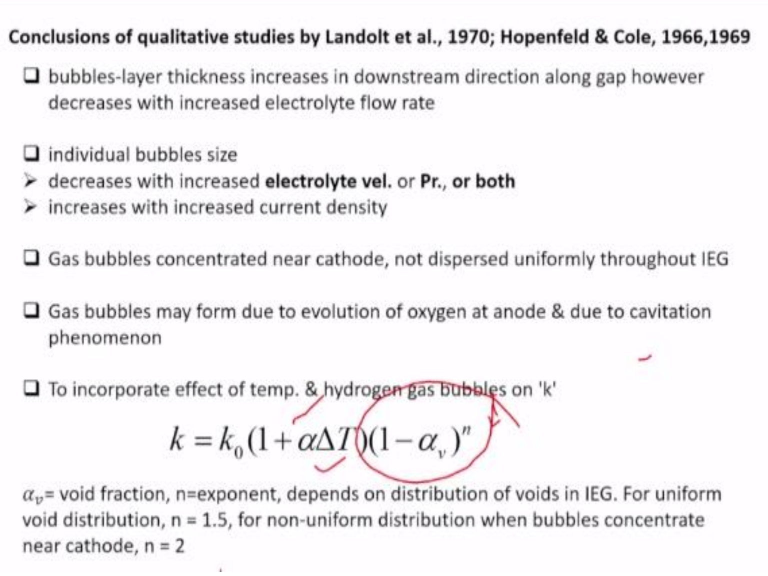

Conclusions of qualitative studies by Landolt et al., 1970; Hopenfeld & Cole, 1966,1969

- ☐ bubbles-layer thickness increases in downstream direction along gap however decreases with increased electrolyte flow rate
- ☐ individual bubbles size
- ➢ decreases with increased **electrolyte vel.** or **Pr.**, **or both**
- ➢ increases with increased current density
- ☐ Gas bubbles concentrated near cathode, not dispersed uniformly throughout IEG
- ☐ Gas bubbles may form due to evolution of oxygen at anode & due to cavitation phenomenon
- ☐ To incorporate effect of temp. & hydrogen gas bubbles on 'k'

$$k = k_0(1+\alpha\Delta T)(1-\alpha_v)^n$$

α_v= void fraction, n=exponent, depends on distribution of voids in IEG. For uniform void distribution, n = 1.5, for non-uniform distribution when bubbles concentrate near cathode, n = 2

So these are the conclusions of qualitative studies by Landolt et al 1970 and Hopenfeld and Cole in 1966 and 1969. They proposed that bubble layers thickness increases in the downstream direction and on the gap however decreases with the increased electrolyte flow rate. If we increase the electrolyte flow rate then hydrogen gas bubbles concentration will decrease and this hydrogen gas bubble concentration is there more at the downstream direction. So individual bubble sizes decreases with the increase in electrolyte flow velocity, pressure and both and it increases with increase in increasing current density.

If we increase the current density this size and concentration of this hydrogen gas bubble also will increase or it decreases with pressure with increase in the electrolyte flow velocity. Gas bubbles are concentrated near the cathode, not dispersed uniformly throughout the interelectrode gap. So gas bubbles may form due to the evolution of oxygen at anode and due to the capitation phenomena also but it is not considered here.

So to incorporate the effect of temperature and hydrogen gas bubbles on electrolyte conductivity electrical conductivity of this electrolyte so this k or electrical conductivity of this electrolyte is equal to k0 into 1 plus alpha into del T this temperature effect into 1 minus aloha v whole to the power n. So this term is actually multiplied along with the existing term here. So here alpha is the void fraction n is the exponent.

The value of this exponent actually this depends on the distribution of the voids in the interelectrode gap. So for uniform distribution this value of n is 1.5. For non-uniform distribution when the bubbles concentrate near the cathode it is value is n equal to 2. So for average case actually n equal to 1.75 is considered for most of the cases okay. So up to this we shall complete today. So in the next session we shall discuss electrochemical grinding, shaped tool electrochemical machining and other electrochemical machining processes.

Thank you.