Advanced Machining Processes
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Week - 07
Lecture - 17
Introduction to Electric Discharge Machining, Mechanics of EDM – I

Hello and welcome back to this lecture on Microsystems Fabrication by Advanced Manufacturing Processes. So, a brief recap of what has been done so far, we have talked about different mechanical processes like ultrasonic machining and abrasive jet machining or powder blasting. And then we have also discussed some applications related to MEMS design or MEMS fabrication as such or microsystems fabrication by virtue of using some of these mechanical processes' removal, material removal processes. And as we saw that most of the time it is bulk micromachining, it is removal subtractively of the material from the bulk of the wafer which creates microstructures and features using some of these mechanical processes, mechanical fabrication processes. So, in principle what happens is it is the deliverance of mechanical energy by abrasive materials, or some other medium may be it is a slurry containing abrasives which actually hits the surface concerned and tries to abrade the surface away. So, that the features can be produced, and if it can be guided through masking step or masking process then the features can go extremely small and you can actually realize micro features and microstructures.

We also talked about some of the chemical electrochemical machining processes where on one instance it is basically the power of electrolysis using the Faraday's laws which actually leads in selective removal of material or deposition of the material depending on whatever the requirement is. And then there are corollary or associated processes the bunch of battery of associated processes with the electrochemical machining like ESD, electro stream drilling, electrochemical grinding ECG or electrochemical drilling ECD processes. And so, basically what you use is that you know you have conducting electrodes and one of the electrodes is the tool the other is the workpiece, and you can selectively by electrolysis remove the material. And we also did chemical machining at the beginning of our lectures when we talked about photolithography where materials known as resists, photoresists are used for selectively creating features and structures.

So, the idea of a resist is that it gets changed on exposure to photochemical energy of or you know photonic energy. And at a certain frequency if you expose the resists there is a photochemical change which is induced onto the resist in terms of either bonding, cross bonding, or debonding. And accordingly, the type of the resist can be defined as negative or positive. So, if there is a cross-bonding action between the different molecules because of photonic exposure it is called a negative resist, if it is a debonding operation which is happening it is called a positive resist. So, you can actually selectively pick and choose certain areas and make either crevices or features crevices or vias on the photoresist film as happens in the case of positive resist or features and structures as happens in the case of negative resist.

So, those are the chemical machining processes, and then a variety of chemical machining steps can be used by using medium which can be fluidic medium you know liquid medium or gaseous medium. For example, we talked about deep reactive ion etching where plasma is the medium which is used for selectively etching away the material on a masked surface, a suitably masked surface. So, you have to create a sacrificial mask which does not otherwise get affected by the plasma. And in that mask, there are windows where the gas molecules can actually go inside the window and attack the main substrate which is below the mask and then based on that it creates micro sizes and features and structures on those materials. So, you have a battery of again chemical, photochemical machining processes which we studied in deep details.

We also looked at some of the applications of such processes in terms of building microsystems or you know micro micro-manufactured parts or features. Now, given all these different techniques the third technique of consequential importance is the thermal technique of selective removal of material. And this technique is actually by means of using some kind of a thermal energy and this energy can be delivered in a variety of ways onto the surface. It can for example, be a stream of electrons which is generated either as a discharge which can remove selectively material by a process called EDM or electro discharge machining process or it can be alternately the high energy beam of electrons, continuous high energy beam of electrons which is produced using thermionic emissions from an intensely heated cathode. And then subsequently guided or streamlined by virtue of variety of anode perforated anode anodic electrodes.

So, that there is a narrow ultimately very narrow size of the beam which hits the surface at a certain point where it may create an effect, desirable effect on the surface because of this. Then you also talk about some other thermal processes like plasma beam machining, ion beam machining and there is a lot of micro nano size features and structures which can be created by virtue of either transport of material using the high power of a beam and the advantage that you have is the resolution at which you can transport this material and make it into distinct features and sizes. And also, you selectively remove away or etch out material using the high power of a beam. So, by increasing the power associated with the beam you are essentially creating a very high-frequency low-wavelength beam or radiation and the lower is the wavelength the better is the resolution at which the beam can be rastered over a surface which then produces some kind of an effect related to ultimately machining of the surface. So, higher is the power of the beam more is the resolution of the beam.

So, this is an advantage. So, because we are talking about microsystems design or microsystems fabrication if these means some of these means like EDM or EBM are selectively used there is a good possibility of getting microstructures and features well written at a certain defined resolution on the surface. The other important process is the interaction the light-matter you know the interaction of matter with photons. And when we talk about that the first name which comes into our mind is laser beam machining or LBM. And basically, what this form of machining does is it is a interaction of a high energy beam coherently super focused high energy beam of laser and laser stands for light amplification by stimulated emission of radiation.

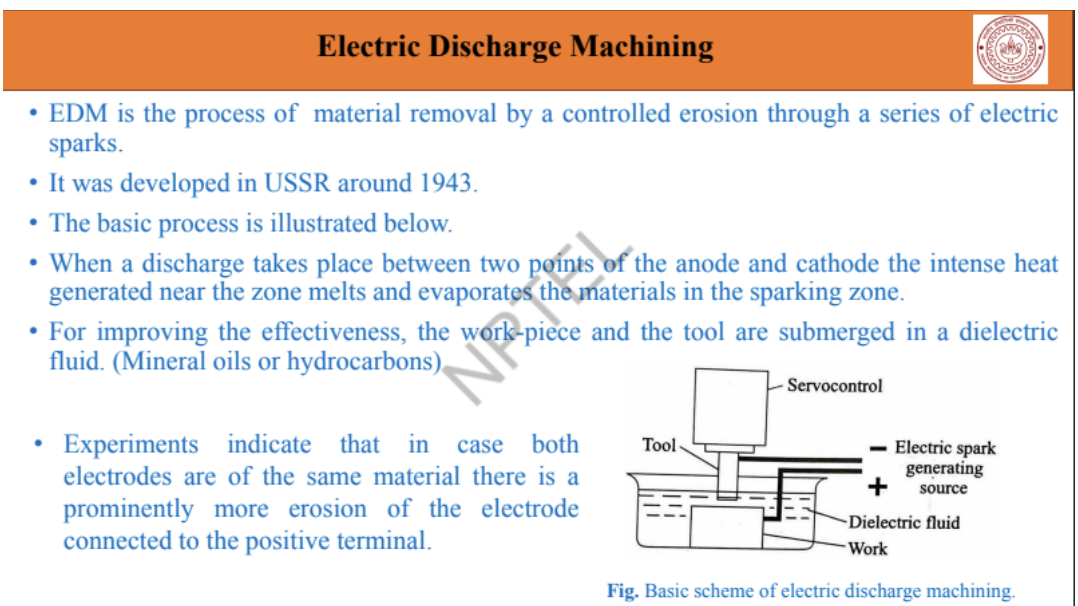
So, it is a laser beam which you are trying to focus on a narrow region of the surface and then the laser gets interactive with the matter as such. And the by virtue of this matter-light interaction there is a thermal energy which changes the nature of the substrate on which the beam falls. So, typically by ablation using the laser process you can thermally evaporate a part of the substrate on which the beam is super focused. So, laser beam definitely is used for doing a lot of high-resolution writing on surfaces in terms of micro features and structures. So, that is a very important process from the microsystems standpoint.

So, what we are going to do in this thermal machining is to look at some of these processes like maybe investigate the EDM and LBM these 2 processes in great details which are very often used for microsystems fabrication. And maybe look into also some of the E-beam-related processes. And then if time permits, we will also talk about this ion beam machining and there is a very modern instrument which has come up very recently for writing at the nanoscale which is called the focused ion beam machine or FIB which is used for either machining like drilling operations of even at the molecular level and is also subsequently used for both surface and bulk micromachining. So, one thing of importance that I would like to again reiterate here is that in case of EDM, the medium which is causing the thermal machining is the plasma beam which is the discharge of electrons and ions. And then this happens over a medium which is typically a high dielectric constant fluid.

It can be something like let us say completely deionized water or it can be something like kerosene oil which is high dielectric constant fluid. So, the workpiece typically is flooded with that, and the ion-electron column is created between the tool and the workpiece through this dielectric medium. In case of E-beam as you see there is a vacuum in between. So, the effect which of striking is gathered together by a beam of electron which surpasses a very high vacuum column, and at the other end of the vacuum you have workpiece. So, the beam interacts with the workpiece by transferring the electrons kinetic energy to the bond vibration energy of the material and that is the principle cause or mechanism of material removal if you do the machining by using an E-beam.

So, when we talk about similarly LBM or laser beam machining it is basically bunch of photons which are coherently spaced with respect to one another and high intensity is suddenly released in a very small area and the medium through which this energy is transferred to workpiece is just air. So, it is one of the simpler processes because laser beam machine can allow workpiece sizes up to any length and breadth whereas, the more specialized processes like E-beam although they are capable of writing really super fine or very small the problem is that because you have to maintain a vacuum around the workpiece it is limited by the workpiece size that you can really machine is limited by the nature or type or the vacuum column that you are using for housing this E-beam system. So, in general, there are some very basic fundamental principle-based differences between all the different machining processes that we have been illustrating. So, in general, we can also conclude that thermal machining removes the machining allowance by melting or vaporizing the workpiece material and many secondary phenomenon occurs like micro-cracking of surfaces, formation of heat-affected zones, striations, etc. and the source of heat could be plasma as during EDM or photons as during LBM, electrons as an E-beam machine and ion beam machine so on so forth.

So, let us look at the first process of thermal machining that is the electric discharge machining EDM which was in fact developed in USSR around 1943 and it is really a process of material removal by a controlled erosion through a series of electric sparks. So, it is a short discharge which we are talking about when we talk about sparks. So, it is a very brief amount of discharge of electron of a single tip and there are several such discharges which are happening wherever the breakdown field of the medium is exceeded by the external electric field that is being applied and there is always a removal of the electron owing to that. So, let us look at this basic process. So, when a discharge takes place between 2 points of the anode and cathode, the intense heat generated near the zone melts and evaporates the materials in the sparking zone.



Now, if supposing there is a difference of melting which would happen from 1 of the electrodes to the other then we can successfully use that process for machining which means that in the tool side if supposing the melting rate is lower because of whatever properties the tool may have and in the workpiece side if the same is higher than we can say that the process is used or is amenable for machining applications or machining purposes. So, EDM has been designed in a manner so that this iron column which is established between the tool electrode and the workpiece electrode damages the workpiece more appropriately than the tool electrode and that is how the erosion in the workpiece is higher than the tool although the tool does erode in the case of EDM, but the workpiece erodes at a much faster rate and that creates a situation where EDM can be used successfully for machining of very small size features with good amount of machine surface allowance. So, for improving the effectiveness of the workpiece and the tool they are submerged in dielectric fluid which can be hydrocarbons like maybe kerosene oil or some mineral oils and one very important aspect of EDM which comes during experimentation is that even if the electrodes that you are using are of the same material that means both the cathode and the anode as in this particular case you can see they are made of the same material there is somehow a prominently more erosion of the anode connected to the positive terminal. So, the anode in this particular case is always eroded more than the cathode. So, erosion at anode is more than the erosion at cathode.

There is a very distinct reason why the erosion is different at different electrodes and for doing or for understanding why the erosion is different we need to really look at very closely what is going on between the anode and the cathode in an EDM operation. So, let us say we talk about EDM machine as you can see in this figure here you have a small stage which is able to feed the tool surface which is mounted on this stage in the negative y direction. And there is a workpiece which is kept in a dielectric in a tank which is filled with and recirculated with this dielectric fluid. So, you can see this is that tank right and it is flooded with this dielectric fluid which may be kerosene oil or any other mineral oil or hydrocarbon. And in this manner, the tool is fed towards the workpiece thus giving a very high field between the tool and the workpiece.

Use typically servo control for feeding this system towards the workpiece. So, let us see what happens. So, just because as we have experimentally sort of tried to figure out and found that the anode erodes more intuitive thinking would allow the anode to be made the workpiece because the material removal rate is much more as it becomes the anode. So, in an EDM process the electrons that emanate from the cathode first strike the neutral molecules of the electrolyte. Let us look at before even starting the electrons emanating out, let us understand the reason for why the electrons are emanating out.

Let us suppose you have two electrodes the anode and the cathode and they are approaching one another at a certain pace. So, what is going to change in between this electric in the set of electrodes is the electric field right which varies as a function of the distance as we have seen in ECM as well as the tool moves closer and closer to the workpiece the distance between the two reduces because of which under a certain constant potential you can say that the field value is slowly increasing to a certain value. Now supposing this field between the anode and cathode exceeds the breakdown field of the medium that we are talking about. And breakdown field means that a situation where the medium is amenable to electrical breakdown or in other words it gives a conducting path through it for the electrons of one side that is the cathode side to flow into the anode side. So, in that situation, of course, the electrons will start emanating out of the cathode.

And those electrons which are emanating out of the cathode the first light that they see are in terms of those hydrocarbon molecules which are present in the solution which are immersing both the electrodes. The moment they start seeing these hydrocarbon molecules they would definitely like to let those molecules go in their ionic state. So, they be they may knock off electrons and make them positive ions and there may be more and more electrons and ions combination which is like a chain reaction which is set up between this anode and the cathode unless whatever electrons have been discharged into the fluid are translated all the way to the anode side. So, and in the process of doing that because there is a field which is driving those electrons and ions there is always a tendency of the ions of the electrons to accelerate as well because there is an external field which is doing a work on those set of ions and electrons. So, therefore, the electrons are accelerated once they start emanating and once they start breaking down the neutral molecules of the electrolyte.
So, this is actually a dielectric fluid. So, the in the EDM process the electrons emanating from the cathode first strike the molecules that it sort of meets in the dielectric fluid. They are by and large neutral molecules at the time when the electrons are first emanated into the fluid and this dielectric fluid then kind of breaks down and undergoes some dissociation and produces in turn cations, positive ions and more electrons. So, you are breaking down the neutral medium between the 2 electrodes by the electron which is emanating out of the cathode towards the anode thus creating cations and electrons and a huge density of this is created throughout the column and it is a chain reaction once the electrons starts emanating continuously from the cathode surface towards the anode. So, now if you can maintain or sustain this process typically what happens is that if supposing there is a bunch of electrons which comes out of the cathode they would get extinguished the moment they reach the anode because they are grounding and they are getting discharged.

But if you can somehow sustain this mechanism of emanation of electrons from one surface to other then you can have a situation where there can be multiple dancing sparks which are there depending on wherever the closest proximity is between both the surfaces where the field has exceeded the breakdown field of the medium. Because field is actually voltage per unit distance and distance is the minimum depending on whether it is a hill-to-hill separation between the tool and the electrode. So, the EDM is made a self-sustained process by generating a suitable gap which is known as a spark gap which you have to maintain between the tool and the workpiece surfaces. These the sparks are made to discharge at a high frequency with a suitable source and since the spark occurs at a spot where the tool and the workpiece surfaces are the closest and since the spot changes after each spark, the spark travels all over the surface. So here, it is very important for me to point out that any surface that we are considering has a certain amount of surface roughness.

It is not really a perfectly flat surface. So, there is some nanometer level at least value of roughness even if it is a super polished surface. So, there are going to be hills and there are going to be valleys, and therefore, the distance of proximity between the tool surface and the workpiece surface varies greatly depending on what is the relative orientations of those hills and valleys on one surface with respect to the other. So, 2 hills for example, on both surfaces would have minimum distance, or 1 hill with 1 valley or 2 valleys on both the surfaces will have the maximum distance. So, as you already know that this emanation process of the electrons is dependent on the electric field which is actually inversely proportional to the distance.

The points on both the surfaces which are the closest space are the ones where the spark should first generate because those are the areas where is for a certain proximity between both the surfaces, the highest point on one surface facing the highest point on another surface the field has exceeded the breakdown field and there is an emanation of the electron. Now, if I assume that if there is a selective removal of the material because of the thermal energy which has been transported by this electron emanation from one electrode to other and if we further assume that this energy is more amenable to removal of the material from the anode side then the anodic hill which was there will get disappeared. Therefore, the distance will again increase, and the field will go below the breakdown field value and there would be again another distance of close proximity which will be searched by that emanation process to again happen. So, there is a tendency of the spark to sort of oscillate between two such high rises or two such hills on both the surfaces as this process continues. So, it results in a uniform material removal eventually because first one of the hills which are the highest with respect to another hill of the workpiece side is isolated, the hill on the workpiece side melted away and then the next hill to hill spacing is isolated and then it is melted away.

So, that way the whole surface has a self-smoothing effect because of the EDM process. So, in a nutshell, this is also like a die-sinking process although the material transport kinetics here is totally different it is based on the thermal actuation which happens because of generation of the spark, and eventually even in this process whatever is the tool surface is impregnated on to the workpiece surface. So, some other issues that for maintaining the predetermined spark gap normally a servo control unit with accurate and precise feed-forward of the tooling with respect to the workpiece is generally used and there is a sensing mechanism which is designed in a manner that the gap voltage, the average voltage across the gap that is being continually sensed and there is a predetermined or preset value and you compare the gap voltage and the variation there in with that preset value to be able to estimate how much feed forward or feed backward of the tool is needed with respect to the workpiece. So, a difference is used to control in turn the servo motor which does this feed forward or feed backward. Of course, a solenoid control is also possible for maintaining the gap voltage and here you can see actually how this solenoid control works.

So, it is illustrated here that depending on the voltage across this capacitor right here which is also the voltage across the gap. The solenoid can take a decision of whether to feed the tool in the forward direction or take the tool in the reverse direction. So, whatever is the voltage between these two is a reason for actuation of this solenoid with respect to a DC source. Supposing this voltage here is more than the voltage of the DC source here then the current of the solenoid would flow in the higher voltage to lower voltage direction and because of that the magnetic field which would be generated would try to take this particular electrode in the reverse direction. That means, feed backward and vice versa if Vd is higher than V0 then it would take the electrode in the forward direction.

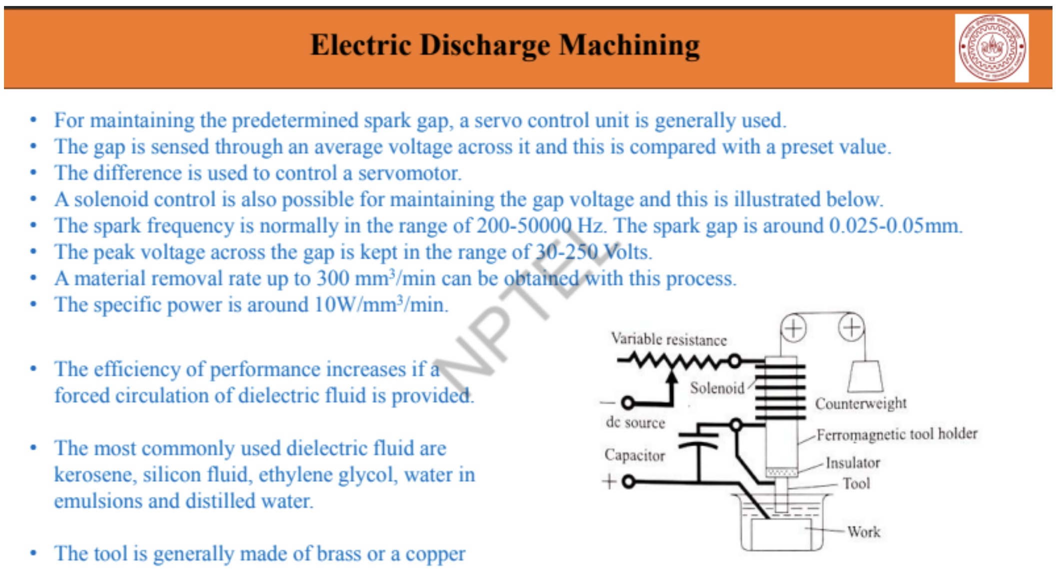


Fig. Solenoid controlled electric discharge machine.

Some other parameters about the process the spark frequency is normally in the range of 200 to about 50 kilohertz. The spark frequency is really atomistic process it is dependent on how many hills or how many valleys are there with respect to each other which come face to face in the process of the tool material being fed with respect to the workpiece material. Although the control of the feedforward is very stable, but it always can have a close to micrometer displacement sidewise as well while it comes down because of the high pressure that the dielectric fluid would have between the gap. And therefore, which part of the surface comes opposite to which part of the workpiece surface it is not really predictable. So, any part of the tool can at any point of time come in front of any part of the workpiece surface for example.

So, it is a very randomized process, and controlling spark frequency is not possible because it is done at the atomistic level by even small movements between the two surfaces. So, the gaps that we were talking that we are talking about where the spark is generated this varies between about 0.025 to 0.05 millimeters. So, that is about 2.5 to 50 microns and that is how small the gap is actually. And the peak voltage across the gap is always kept in the range of about 30 to 250 volts. So, you can understand the kind of fields that we are talking about 250 volts divided by let us say 50 microns 10 minus 6 makes the electric field equal about 5 into 10 to the power of 6 or 5 million volts per meter. So, it is very high field that we are talking about between the small gap even at a small voltage of 250 volts between the two electrodes. Now, the material removal rate can go up to about 300-millimeter cube per minute.

So, it is reasonably high material removal rate, and if you look at how much power is needed per unit increase in the material removal rate this comes to be about 10 watts per millimeter cube per minute. That means, if 1 unit of MRR material removal rate is increased it leads to about the additional consumption of about 10 watts of power. So, it is a power-intensive process, and naturally, because the requirement of this process is really thermal means of degradation of the material. Therefore, whatever the higher the better you know the more power you are sending in a focused area through a spark the better it is for the machining rates or the material removal rates. So, the efficiency of performance, for example, increases if there is a forced circulation which is which was also true as you saw for the electrolytes, but in case of electrolytes, there was a problem that the boiling point of the electrolyte was the main design guidelines or set the main design guidelines for determining the flow velocity.

Here there is no such limit as this is a hydrocarbon and although there is a dissociation associated with this hydrocarbon which produces a small deposition layer on the cathode particularly because these are all cationic components and electrons which are generated by the emanated electrons on the hydrocarbon, but then it is of not very high consequence. So, there is not much significance in the dissociation of the dielectric fluid, and flow rates typically are more driven by what final material removal rates or machining rates you want from the EDM process. Because again you have to remember that the fluid is flowing across the gap and the material which gets thermally ablated because of the spark has to diffuse into this fluid and fluid is also acting as a carrier medium for the diffused mass. So, whatever machining is being done by means of creating a melt pool on the surface is being diffused into the circulating fluid and that fluid circulations increase would in turn mean that more of such mass is displaced away from the machining zone. So, the MRRs get significantly higher if you increase the velocity of flow of the dielectric fluid.

So, you have to be concerned about issues like laminarity or how you know you can have these local eddies and vortices which may create problems in the material removal. Similar manner as we talked about in ECM. Most commonly used dielectric fluid is this kerosene oil, it is a hydrocarbon, and the tool generally is made up of brass or a copper alloy and very good fine calibrations of this tool has been done in terms of the tool wear rate. So, as we have initially mentioned, and we have still we are still to ascertain the reason why the tool surface would have lesser erosion in comparison to the workpiece surface even though both the surfaces are handling the same iron column. So, we will just look into that aspect a little bit later, but then the idea is that a metal tool made up of copper or brass is found suitable to machine let us say iron workpieces by virtue of EDM just by minimum possible wear rate that is possible for a tool surface.

So, let us look at again the mechanics of the EDM process in a little more details you know. So, let us see, for example, this figure here we are talking about how the hills and valleys of one surface is placed. So, these are different hills and valleys on the tool surface and the same goes true for the workpiece side as well. The workpiece also has these hills and valleys no surface can be completely smooth there is some atomistic scale roughness which exists even if it is a super polished surface that we are talking about. And this we have made the workpiece by connecting it to the anode and this to the cathode.

Electric Discharge Machining

- The figure below shows the state of electrode surfaces.
- Even if the surfaces look smooth there exist some asperities and irregularities.
- As a result, the local gap varies, at a given instant .
- It is minimum at one point say 'A'.
- When a suitable voltage is built up across the tool and the work-peice, an electrostatic field of sufficient strength is established at 'A' connecting the two electrodes.
- In an EDM process electrons emanating from the cathode first strike the neutral molecules of the electrolyte and these undergo electrolytic dissociation producing cations and more electrons.
- The electrons are accelerated due to the electric field and may ultimately dislodge other electrons and ions.
- Ultimately a narrow column of ionized dielectric fluid molecules is established between the two spots on both electrodes responsible for the spark (which is an avalanche of electrons due to the already high conductivity positive ion column).

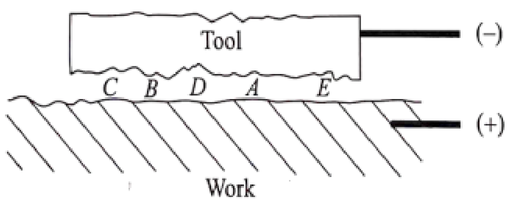


Fig. Details of electrode surface characteristics.

And so, the local gap really varies between these 2 surfaces based on what all features are there on both the surfaces facing each other. Supposing if I consider this gap here to be the minimum. So, this minimum gap is at some point of time some instance of time at the point A. And you have also applied a suitable voltage across the tool and work which has been built up. So, you have the V versus time the voltage versus time across this gap this gap voltage Vg being built up from 0 to some value let us say Vg prime.

So, the moment the breakdown field of whatever is inside here the dielectric material is reached, there is going to be a dissociation and there is going to be an electrostatic field of sufficient strength probably more than the breakdown field being established at A. And the moment that happens there is a discharge of electrons from this point right here on the tool. So, A point on the tool towards A point on the workpiece there is an electron discharge. So, the electrons emanating from the cathode they first strike the neutral molecules, the molecules are spaced in the gap here and then they undergo electrolytic dissolution. So, whatever is this dielectric fluid here gets dissociated and this produces cations and more electrons.

The cations are typically positive ions. So, whatever is there in the kerosene would tend to lose electrons and get into positive ions. So, then these electrons and the cations are accelerated in both directions by virtue of the electric field. So, for example, the cations here which are produced the let us say positive ions which are produced they would rush towards the tool, and the electrons which are there they would try to rush towards the anode side or the workpiece side because of obvious differences in the nature of the 2 surfaces in terms of the charge that they contain. So, due to the electric field, the electrons are accelerated towards the anode and because of this acceleration process, there is a change in their kinetic energy. So, because of this the overall electron kinetic energy increases, and an increased energy if delivered onto a local surface will ultimately dislodge the material which is there on the surface.

But before reaching the surface there is a tendency of the electrons to create more electrons and ions. So, supposing some electron is emanated from just about this part of the surface right here. So, the electron is emitted just about here in the part of this surface indicated here in the tool and it faces some dielectric fluid creates a breakdown, creates a positive charge, creates additional electrons. So, this electron again which is created also would get accelerated.

So, these are secondary electrons. So, there is one kind of electrons being emanated which is the primary electron, the secondary electron which is generated inside the ion column. So, the generated electrons would produce further generated electrons. So, it is an avalanche process. So, it is a sort of chain reaction and therefore, there exists ultimately a narrow column of ionized dielectric fluid molecules and this establishes between both the spots which is corresponding to this location A and on both electrodes. And these are responsible for the spark because the column which is created here is highly ionic in nature shown by the shaded area and they would give away to the discharge of the electrons from one surface to other.

So, it is basically an avalanche of electrons due to the already existing high conductivity of the positive ion column which we call a spark. So, let us look at what would happen after this spark is generated. So, as this spark is produced it actually results in a very high movement rate of motion or velocity. Let me just exemplify a small situation. For example, in your last 12 days, you may have been used to the idea of why the light bulb blows even if you have switched on a electrical switch which is quite far away from the bulb almost with the speed of light.

So, what happens is that there is an electron wave which is actually the kinetic energy of the electrons which moves very fast through that conductor which has a sea of electrons, the bulk of electrons and it is the wave property of that electrons which gets transmitted as the response that you are seeing on the light bulb. So, basically, it is not really the electrons that are getting physically transported, but it is an energy of those electrons which is getting transmitted from a very high distance towards the source. So, here also the same thing is happening you know. So, there is a slight motion towards the emanate of the electron, emanated electrons very near the tool surface and they would generate oscillatory motions of other electrons subsequently created as secondary electrons in the ion column and it is the motion which is transferring onto all the way across the ion column to the workpiece surface. So, this motion is so intense that it is essentially acts as a compression shock wave.

So, the medium which is the dielectric fluid which has been now ionized in that ion column is having different compression and rarefactions, and this particularly on the tool surface because of the workpiece surface because of a high electron pressure has a compressed zone which travels almost more than the speed of sound in the medium producing a shock wave. So, this compression shock wave is responsible for creating huge amount of thermal energy in the medium which it interacts with. So, the obvious conclusion that would come is that once this compression shock wave is generated near the surface in question it results in a very high temperature because the energy has to somehow be converted and the only means of conversion of the energy there is thermal because there is no other means which is available. So, it will immediately raise the temperature of the material across which this shock wave has come and stricken and that generates sometimes the melt pools of the material and sometimes it is also so hot and so full of energy that it vaporizes a part of this weld pool. And therefore, there is a melt and vaporization action on the anodic material because of that.

Now, the compression shock wave comes at a very high velocity and is almost always followed by a mechanical blast. So, the electron pressure which is being developed at the surface is kind of leading the inertial movement of the material which is there in the dielectric column, and electron motion because of the small size of the electron is always very fast very high velocity and the remaining part of the column is not able to keep pace with the electrons motion because of its own inertial components associated with it. So, it generally arrives at a later point of time before the electrons have created the effect on the surface. So, electrons have by virtue of the compression shock wave have created an extremely high region which has melted and vaporized the material and the mechanical blast is just following that electron which comes after a few units of time after the instant where the temperature has gone up and it is able to remove the melt pool or sometimes whatever vapor is confined to that pool and it basically removes it into the dielectric fluid.

So, this results in the pitting action on the surface of the electrode. So, mechanical blast because which follows the electron pressure and resulting in pitting action is the basic removal mechanism of material in these discharges. So, some facts and figures about this process are that the temperature in the melting zone sometimes goes in the range of about 10,000 to 12,000 degrees Celsius and this may result in small craters in both the electrode surfaces. And as soon as this happens the gap between electrodes at A increases and the next location of the shortest gap is somewhere else say some other gap B here. So, A has already degraded the self-flattening has happened here in the workpiece and so the next point of closest reaches the point B. So, as the cycle is kept on repeating the shortest gap now at B and subsequently the machining takes place at B.

So, after A the next round of machining happens at B. So, if you consider this phenomena to be a regular process it keeps on repeating over the whole surface, and eventually, it results in a dancing spark over the whole surface because wherever there is a close proximity between the 2 surfaces the spark is placed there. So, it is a high-frequency oscillating spark which kind of walks over the whole surface based on that atomistic difference in terms of the facings of both the surfaces. So, that is in a nutshell the mechanics of material removal in the ECM process. So, today we are at the end of this lecture, but then in the next subsequent lectures we will talk a little more on what is the material removal mechanism, how can we predict with the model mathematical model the removal mechanism. And then we will also look at some other aspects which are very important in ECM design like what kind of feeding circuit can be designed for an ECM system.

So, that this electron emanation process can be self-sustained one and so on so forth. Alright, thank you.