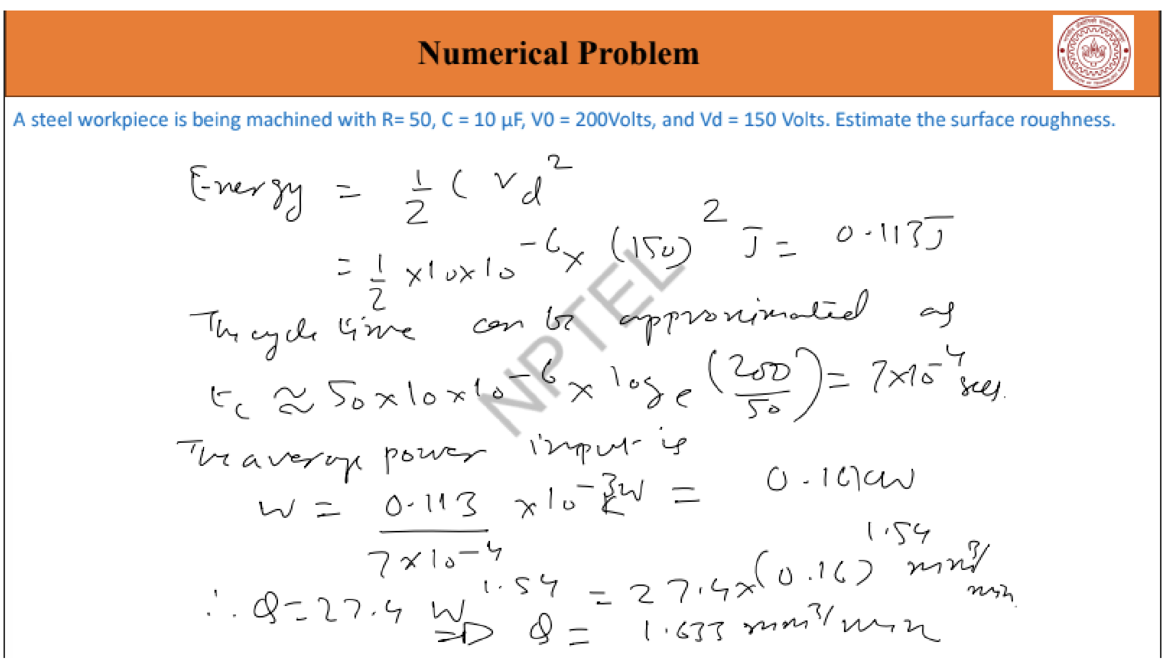
Advanced Machining Processes
Prof. Shantanu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur
Week - 8
Lecture – 21

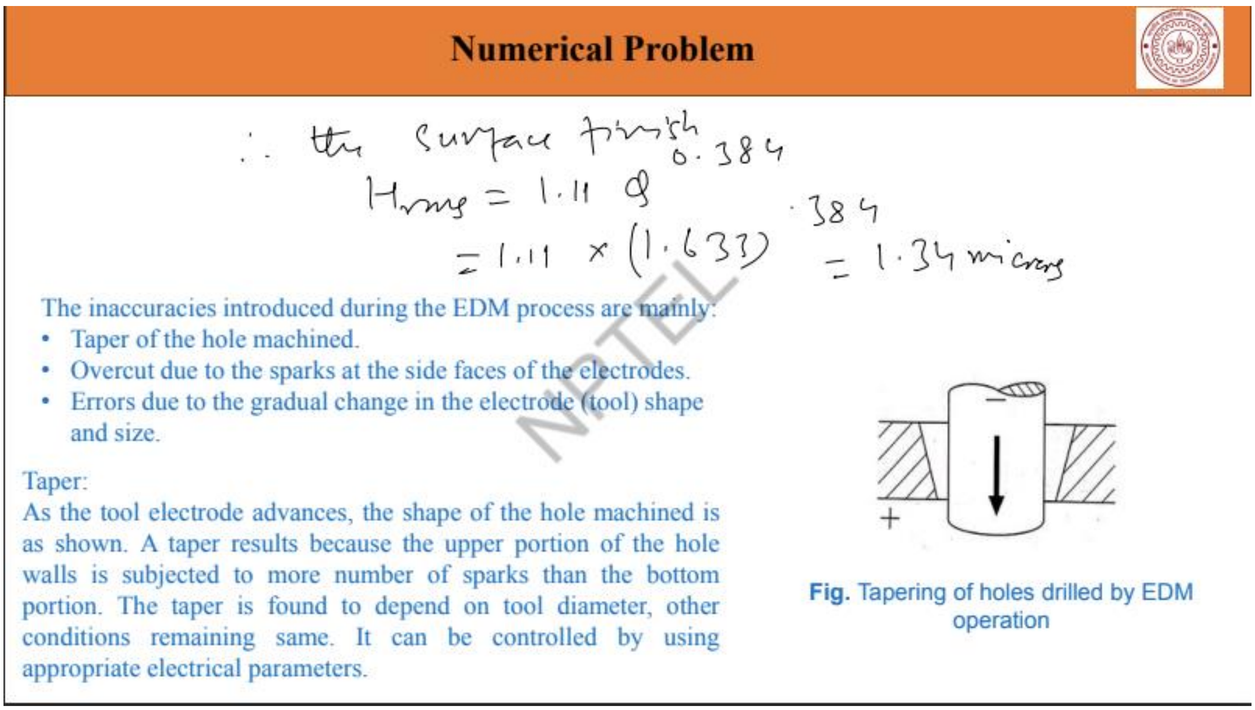
Derivation of Functional characteristics of EBM, Power requirement in EBM, Mechanics of EBM process

Hello, and welcome back to this lecture on Microsystems Fabrication by Advanced Manufacturing Processes. A quick recap of what we did in the last lecture, we talked about the analysis of discharging part of the RC relaxation circuit. We also discussed about the material removal rate in EDM, particularly in case of mild steel there is an established empirical relationship depending on the amount of power which is given in kilowatts, and the amount of material removal in millimeter cube per minute. We also talked about several general characteristic trends of the material removal rate with respect to various circuit parameters like resistance, capacitance, the total discharge current so on so forth, spark gap. We talked about surface finish and machining accuracy, and then finally, we had a close discussion about the dependence of surface finish on pulse energy of the EDM system. So, today we will just try to go ahead, and try to look at an estimation, numerical estimation of the surface roughness in a particular situation.



Now, this problem here represents such a situation here where a steel workpiece is being machined, and the circuit parameters are given to be resistance R equal to 50 ohms, capacitance C equal to 10 microfarads, and total operating voltage of 200 volts, discharge voltage of 150 volts. And you have to estimate the surface roughness which is also the Hrms value, and if you may recall from the previous lecture the Hrms is represented as 1.11 Q to the power of 0.384, where the Hrms is in microns, and Q is in mm cube per minute.

The energy here which is delivered is actually dependent on this resistance and capacitance, and also the various parameters like operating voltage, and discharge voltage. And we do have in case of particularly mild steel very active relationship to derive the Q empirically as 27.4 W to the power of 1.54, where W is the power, the pulse power in kilowatts. And how we calculate W is by looking at the energy which is half C Vd square, and capacitance C is 10 microfarads, 10 to the power of minus 6, and discharge voltage is 150.

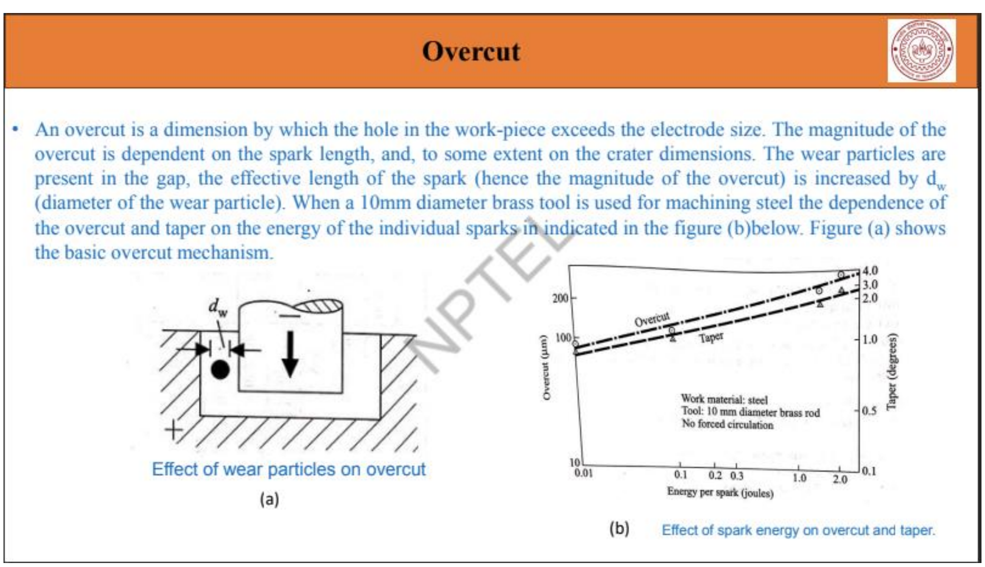


So, this comes out to be equal to 0.113 joules. And this total cycle time can be calculated as tc which is actually equal to the resistance times the capacitance RC log of V0 by V0 minus Vd. In this particular case, this happens to be 200 volts, and this comes out to be 50 volts, and so the R the total time cycle, cycle time is represented as 50 times of 10, 10 to the power of minus 6 log, and this is to the base e log to the base e of 4, 200 by 50, and this comes out to be 7, 10 to the power of minus 4 seconds or around 700 microseconds. The average input power is energy per unit time can be represented as 0.113 divided by 7, 10 to the power of minus 4 that is 0.16 kilowatts, and the total Q material removal rate comes out to be 27.4 times of 0.16 to the power of 1.54 mm cube per minute, and this equals 1.633 mm cube per minute, and based on that subsequently, we can find out the surface finish by using the expression Hrms equals 1.11 Q to the power of 0.384, this is 1.11into 1.633 to the power of 0.384 becomes 1.34 microns. So, essentially this is how the Hrms value comes out to be equal to.

Now, there are few aspects which need to be mentioned here, and those are about the inaccuracies while considering the EDM process or electro-discharge machining process. So, the main kind of problems which come in an EDM process are because of the amount of the difference in the time that a particular hole, various portions or various portions on the wall of a particular hole is exposed to in terms of receiving the sparks from the EDM machine.

So, the taper of the machined hole in an EDM is a major inaccuracy, due to which you have to suitably design the electrode sometimes, so that it compensates for this taper, and you can have a straight cut. There are other problems like overcuts due to sparks at the side faces of the electrodes, and then there are errors due to the gradual change in the electrode tool shape and size. So, principally these are the three categories into which you can determine or classify all the inaccuracies produced by the EDM process. So, let us look at the details of how a taper would be produced. So, as we know that the electrode, this electrode here advances towards the workpiece, the shape of the machined hole is shown here, and if you look you know when the electrode is coming here in the top portion, right about this portion, the spark exposure to this surface starts immediately, and then because of which there is local melting, and there is material which goes away.

But as the tool proceeds downwards, slowly the spark exposure increases to the side walls, but the tendency of the spark to formulate near the surface is still remaining. So, the surface gets exposed for a longer time to sparks, causing a greater diameter of the surface hole in comparison to the hole at a certain depth. So, it is found to depend on the tool diameter of course, and what you can do is, you can either appropriately insulate the tool or you can create a suitable condition by you know changing the electrical parameters so that this problem of tapering can be minimized. So, that is one aspect of causing an inaccuracy. The other is an overcut, which typically means that there is always some kind of an extra size of the hole in comparison to the tool diameter.



So, typically an overcut is a dimension by which the hole in the workpiece exceeds the electrode size, the magnitude of the overcut is dependent on the spark length, and to some extent on the crater dimensions. Supposing there are wear particles which are present in the gap here, like this is a wear particle, the effective length of the spark, and hence the magnitude of the overcut is somehow increased by this wear particle, because if you consider the spark length to be some you know equal to the overcut in this particular case, the spark is facing its own metal particle which has been removed, and it should get extended by exactly the same diameter. So, from here it goes to here, supposing this were d, so this is d plus dw, dw is the diameter of the particle. So, this is a perennial problem of taper and overcut of EDM machines. And again, this really when the tool is approaching this point, the only this zone is being exposed, but as the tool goes inside the side zones are being exposed.

So, this can be controlled in a way in a limited manner by again side insulating the tools, so that there is no extra spark length which is formulated, and no extra overcut which is formulated. So, if you look at the energy versus taper in most of these tools, and as a matter of fact even the energy versus the overcut, as you can see that if the spark energy is increased both the overcut as well as the taper they vary. If you look at only the overcut size spark energy is more, the overcut is linearly increasing as you can see. And on the other hand, if spark energy is more, the taper also is substantially increasing. So, all these defects or all these aberrations are really related to the spark energy in joules of that the EDM process has to offer.

Let us also talk a little bit about tool and electrode, the tool electrode and the dielectric fluid. As is obvious that electrodes play a very important role in determining how successful an EDM operation could be, and how what are the different electrical parameters of an electrode also somehow matters for the formulation and generation of the spark. So, the material selection for the electrode is a very important aspect in any EDM process. Given a particular material combination of the tool and the workpiece, the other thing which is of significant importance is the tool wear, the tool electrode wear. And that is because, of course, there is a sparking action going on continuously between the workpiece and tool.

So, there is erosion which happens due to this sparking action both at the workpiece which is the causative for all the MRR or the machining removal, material removal rate, and the electrode side where actually the electrode gets melted because of repeated sparking. So, a material should be chosen which has a relatively good electrode wear characteristics meaning thereby that it machines the workpiece, but then the electrode wear is minimum. So, one of the principle materials that are that is used for the tool is graphite, it goes directly into the vapor phase without any melting. And you can define this wear ratio RQ as 2.25 r theta to the power of minus 2.3, is again an empirical relationship where the r theta is really the ratio of the melting points of the work and the tool, and RQ is the wear ratio. So, if you have a good choice and the material of the tool has a melting point which is greater than that of the workpiece, the RQ the wear ratio automatically improves and vice versa. So, the selection criteria of the electrode material really depends on what kind of material removal rate you need to use, what is the tool wear ratio that you are targeting, and also what is the ease of machining these electrodes because you can have the exact negative shape of what you are going to machine on a plate, and also the cost has to be kept in mind of the particular electrode in question. So, most of the commonly used electrode materials that are used are brass, copper, graphite, aluminum alloys, copper, tungsten alloys, silver tungsten alloys etcetera. The methods that are used for making the electrodes are either just normal conventional machining, and sometimes micromachining with great precision and accuracy this has become a really major aspect, and some of the example problems we will take off later on in the MEMS area are really using EDM towards the micromachining.

You can also use metal spraying for developing the electrodes or press-forming operations for these electrode materials. Normally, you prefer the EDM electrode to have circulation of the fluid to be in the near vicinity, because as the circulation increases the material removal rate enhances, we have talked about this many times. Therefore, it is pertinent to mention that flow holes need to be designed within the electrode which will support this circulation and make it easier particularly considering the fact that the electrode workpiece gap is minimum in EDM operations. So, there are these holes which should be as large as possible for rough cuts and allow large flow rates at low pressures without much bending. So, that there does not occur any sort of depreciation or damage to the tool surface, and at the same time it allows for enough circulation in the EDM tank.

So, basic dielectric fluids which are used for EDM have the requirements of low viscosity of course, so that they can flow easily. They should have the absence of toxic vapors because otherwise the operator gets exposed chemically, they should be neutral without any ionicity. So, that even if they get decomposed there is no particular deposition which would take place on the electrodes or very minimalistic deposition which would take place at the electrodes should have the absence of inflaming tendency of these fluids it should not burn up or then it should be low cost. So, typically ordinary water and sometimes mineral oil are used mostly for EDM fluids, and what is also important is that the fluid that you are using should have a relatively higher dielectric constant. So, that it can support the respective potential difference between the tool and the workpiece, so that it can lead to a sparking condition.

So, with this, I think the EDM section is more or less covered. Now, we will start a very new and interesting topic of E-beam machining following this. So, in electron beam machining as you know it is a thermal process where a stream of electrons is impinged onto a work surface, and that is impinged at a very high velocity thereby transferring all the kinetic energy that these electrons have, or they possess on to the work surface. So, it is basically a sort of interaction of electrons with the matter which leads to the vibrational energy of the matter itself, and thus increasing the localized temperature to a level where the material, the atoms, the material would come off as atom in an atom-by-atom manner. So, depending on the intensity of the heat generated the material can melt or vaporize, and the process of heating by an electron beam can depend really on the intensity of the beam and can be used for various applications like may be annealing, may be welding or metal removal by delivering suitable heat content in every case.

So, just some facts and figures about the electron beam machining typically you have to have very high velocities of the electrons coming out from the source, and you know the kind of velocities that those electrons would have could range in several tens of thousands of kilometers per second, and if you apply a suitably high accelerating voltage of to the electrons. And so, if you look at facts and figures if an accelerating voltage of about 150 kilo volts is applied it can produce a fast electron as fast as about 228,478 kilometers per second which is very fast. And so, you can imagine that this kind of speeds imparted on to the electrons would lead to what kind of lattice vibrations as the electrons strike the material surface, and that is one of the principle reasons why things get molted or vaporized sometimes directly, because of the high amount of kinetic energy, and it is not one electrons it is a beam of electrons which is being focused on to a single spot where machining is to be done. So, typically if we look at again some of the values if an electron beam like this with about 228,478 kilometers per second velocity of individual electrons can be focused to a point which is about 10 to 200 micrometers in size, you can go up to delivering a power density as high as 6500 billion watts per millimeter square. So, this is how much you know energy can be delivered really in a very focused manner onto a surface.

Now, this kind of a power if applied to the lattice structure or the material as such can simply vaporize the material substantially. So, it just directly sublimates it goes into the vapor state, and if you raster the E-beam over the surface typically there is a tendency of the machining to be precisely controlled based on wherever the beam hits the material, and so as you can really super focus and narrow down the beam to a small spot the resolution at which you can do this increases. One of the reasons why E-beam is a preferred modality in most of the micromachining or nanomachining processes, because of the precision accuracy and the resolution limit of the system. These days E-beam lithography which is a very modern process, and we will be describing in some of the lectures later is essentially using the same principle of an accelerated beam super focused on to a small spot, and it creates enough damage to the photoresist material, and the resists are beam sensitive resists like may be PMMA for polymethyl methacrylate where such interactions would result in material coming off the surface or in a selective manner. So, you can actually imprint with this technique features as small as several tens of nanometers spaced by equal distances.

So, that is the resolution at which you can write owing to the fast and the small spot size and scanning speed respectively. So, if we look at some of the dimensions of features that E-beam is suitable to use. So, typically EBM has been used for drilling of fine holes, cutting narrow slots, holes as small as 25 to 125 microns in diameter and this limit has, I think further gone down depending on modern technology that is being increasingly used to super focus the beam. It can also be used for drilling thicknesses up to about 1.25 millimeters. So, really high aspect ratio features and structures can be drilled in metals using this technique. So, the narrow slot which can be cut by E-beam has a width tens of microns, this I think we have discussed before, and an electron beam can be maneuvered by typically magnetic deflection coils making the machining of complex contours easy. So, it all becomes a matter of programming the topology of a surface on the beam direction, and direction can be controlled by suitably varying magnetic field in space. So, you have a lot more flexibility to raster the beam on complex shapes and features which as well may not be the case in some of the conventional machining where metal-to-metal contact is needed. So, one has to however be careful of one small factor that these electron beams are high energy, and so typically they should not come in direct collision with air molecules which might create ionization, and lot of undesirable effects which might change the resolution greatly.

Schematic view of the e-beam machine

- The figure below shows the basic schematic view of the electron beam machine.
- The electrons are emitted from the cathode (a hot tungsten filament), the beam is shaped by the grid cup, and the electrons are accelerated due to a large potential difference between the cathode and the anode.
- The beam is focussed with the help of the electromagnetic lenses.
- The deflecting coils are used to control the beam movement in any required manner.
- In case of drilling holes the hole diameter depends on the beam diameter and the energy density.

- When the diameter of the required hole is larger than the beam diameter, the beam is deflected in a circular path with proper radius.
- Most holes drilled with e-beam are characterized by a small crater on the beam incident side of the work.

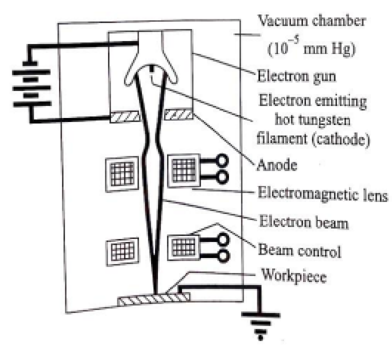


Fig. Schematic view of electron beam machine.

So, typically the only limitation that the E-beam system has to offer is that these are done in high vacuum columns, and the workpiece size has to be limited because of the associated complexity of creating vacuum to the level of almost no air, I mean probably 10 to the power of minus 6 or minus 7 torr pressure, where minimum amount of air is permissible. So, typically you do these in vacuum columns which limits the size, and the process becomes unsuitable for large workpieces. And if you look at the way that the different applications can be grouped as a lot of power density delivered to the surface with respect to the hot spot diameter, you can see that for the E-beam machining typically the combination has the largest size, meaning thereby that it works for a lot of hot spot diameters with a wide-ranging power density in watt per millimeter square. The other machining processes are quite limited as you can see here electric discharge, laser beam, in fact welding arc, gas flame so on so forth. The E-beam by and large has the largest range of the different values of power density and hot spot diameters.

It is obvious that the electron beam is, therefore, one of the most preferred thermal processes for all kind of machining activities in comparison to some of these other form where associated sparks or high-power optical beams are being used. So, this typically shows the layout, schematic layout of a beam column which generates the electron beam. And as you can see here the beam-column has several parts, it is typically stored in a vacuum chamber which has a 10 to the power of minus 5 or minus 6-millimetre mercury vacuum level. There is an electron gun which operates on the principle of thermionization meaning thereby that this gun is heated on its surface there is a filament, and this is also the cathode which is electron rich. You can see the way this power supply is positioned making this the negative electrode.

And so, there are huge amount of electrons which are existing in this particular region here of the electrode. There is a hot tungsten filament which heats this cathode so that it starts thermionising the material and electrons come off by virtue of thermionic emissions of the surface. And then there is a driving anode here which is also perforated in nature. So, this is perforated anode, and the idea is that as in most of the beam-columns even used for scanning electron or tunnelling microscopy processes. The electrons thus generated out of this cathode are pumped through the voltage which exists between this anode and the cathode.

So, the potential difference existing here is responsible for imparting kinetic energy onto the thermionically emitted electrons. And as they go into space, they also get squeezed because of the shape of the emitter here, and in a way, they are further squeezed by using electromagnetic lenses. And there are two set of lenses, one for focusing as you can see here, and the other set of lens for rastering the beam whereby just varying the magnetic field you can do beam control on the workpiece. A workpiece is typically grounded so that it is by virtue of its state of electrostatic potential also captures maximum electrons which are generated by the beam setup. So, the grid-shaped cup here is very important for focusing the primary focusing of the beam which occurs in this particular region which ensures that this beam kind of gets into the narrow gap of electromagnetic lens as shown here, EM lens.

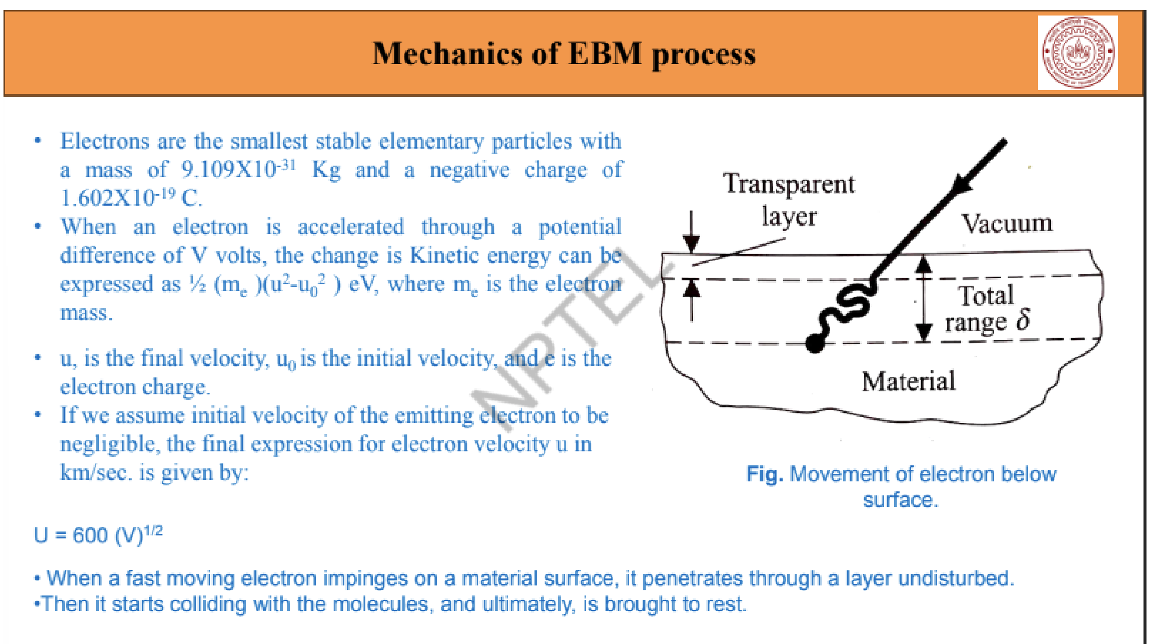
So, when the diameter of the required hole is larger than the beam diameter typically you can take the beam around in a circular path by changing the beam control, and this will result in a much wider area of rastering and scanning on the surface resulting in machining. So, most holes drilled with E-beam are though characterized by small crater on the beam incident side of the workpiece. So, that is how a E-beam system operates and generates the beam. Some characteristics typical of the E-beam processes are the drill holes that are mostly achieved by using E-beam machining processes have a short taper of 2 to 4 degrees, and particularly this is so when the sheet thickness is more than 0.1 millimeters, and the taper in this process comes by the fact that again the same principle that as the beam hits the surface and goes below or ploughs below the surface there is still a tendency because the surface is in ground potential of the electrons to get deflected and captured by the walls.

And therefore, as long as the drilling process is continuing and the material comes off in a from you know in this cavity which is being formulated, the sides of the cavity are thereby also equally exposed, and that results in some kind of continuous removal on the sides, and they are more exposed in comparison to the bottom, the very bottom, and so therefore, the slight taper. So, some ideas about the performance characteristics of these drilling holes can be obtained from this table here. For example, if the material that you are machining is a tungsten workpiece, the sheet thickness may be about let us say about 250 microns, hole diameter of 25 microns need to be created. So, typical parameters of operation include drilling time of less than about 1 second, accelerating voltage of 140 kilovolts, and a beam current of 50 microamperes. If it is a stainless steel, the material is stainless steel you have a 2.5-millimetre workpiece thickness with the hole diameter of 125 microns, the drilling time is about 10 times more, about 10 seconds, and that is using an accelerating voltage of same order 140 and a beam current which is double about 100 microamps. Similarly, for stainless steel the thickness changes to 1-millimetre hole diameter 125, and the drilling time is still less here, less than 1 second, using similar beam parameters 140-kilo volt accelerating voltages, and 100 beam current, 100 micro amp beam current. So, in a way, this workpiece thickness defines a lot of machining time as can be seen here. Some other materials are, for example, aluminum, alumina, and quartz, and their respective times have been mentioned here in this particular table. So, that is how you are placed as far as the E-beam process parameters go.

Some other characteristics of E-beams while cutting a slot, the machining speed should intuitively depend on the rate of material removal that you need, and also this corresponds to nothing but the cross-section that you want to actually machine, or cross-section of the slot that you want to cut or remove on the material. So, the sides of a slot in a sheet with thickness up to 0.1 millimeter are almost parallel, a taper of about 1 to 2 degrees is observed in a slot cut in a thicker plate. Smaller amount of beam splatter occurs on the beam incident side in the workpiece, and some of these values are represented here in the table. You can see that corresponding to about 175 microns thickness and, slot width of about 100 microns, you can get a cutting speed of about 50 millimeters per minute with an accelerating voltage of 130 kV, and an average beam current of 50 microamperes.

And this changes as you go between stainless steel tungsten, brass, alumina, brass being a softer material you can see that the same kind of cutting speed can be obtained for slightly higher thickness of the workpiece with similar accelerating voltages, and average beam current which is intuitively quite feasible. So, if we talk about the power requirement in a E-beam, the requirement is found to be approximately proportional to the rate of material removal. So, if Q is the material removal, then this power needed is proportional to Q, and the constant of proportionality C has been mentioned here in terms of power in watts per minute material removal rate in millimeter cube per minute C. So, for tungsten to iron to titanium to aluminum you can see these different values of C as reported in this table. Now, let us do a quick problem to have an idea of the numerical values of the various power requirements which are increasingly felt in E-beam.

So, let us say we want to cut a 150-micron wide slot which is about on a 1 mm thick tungsten sheet using an electron beam with 5-kilowatt power. So, determine the cutting speed in this particular case, let us see how the cutting speed can be found. So, let the speed of cutting we assume to be V millimeters per minute, then the rate of material removal required is given by Q equal to 150 by 1000 times of 1 V millimeter cube per minute. We know that the slot is about 0.15 mm wide and about 1 mm thick. So, this volume is coming from that cross-section times of the rastering speed of the beam per minute time gives you how many mm cube per minute you want to remove. And so, P in this case can be represented as C tungsten times of Q which is 12 times of 150 by 1000 volts and P is given to be 5000 watts and V comes out to be equal to 5000 by 12 into 0.15 millimeter per minute that is 2778 millimeter per minute of 4.6 centimeter per second which is quite an appreciable velocity. So, this is the velocity at which the beam should raster on the surface for creating a cut about 150 microns wide and 1 mm thick.



So, this speed though is much less than actual speed and one of the reasons why the actual speed is more is that there is a huge amount of thermal dissipation from the cutting zone to the areas adjoined to it. And so, that factor is not being accounted for in this particular simplistic mode of P equal to C Q material removal rate. So, let us now understand a little bit of the mechanics of how what are the events the sequence of events in which the material starts getting ablated from the surface as being hit upon by an E-beam. So, some of facts and figures that probably we all realize are that the electrons really are the sort of very stable small elementary particles with charges in the range of 1.602 into10 to the power of minus coulomb minus 19 coulomb. It contains negative charge and the amount of mass that it has is typically 9.109 into 10 to the power of minus 31 kg. Now, such an electron is accelerated through a potential difference let us say V volts. The change in kinetic energy can be expressed as half into electron mass 9.1 into10 to the power minus 31 times of u square minus u 0 square and this is in eV electron volts where me is the electron mass.

So, typically we already have discussed this before that the amount of velocity is that the electrons hit upon is huge it is in the range of about hundreds of thousands of kilometers per second with which the electrons start moving because of this accelerating potential and the thermionic effect. So, it has been increasingly found that as the electron goes very near to the surface of a material there is you know not the material is not able to register an immediate effect on the electron striking because, by virtue of the electron size being very small, there is always the formation of something called a beam transparent layer on the top of the surface. So, the actual kinetic energy deliverance of the electron beam happens within some particular depth from the surface and this area is actually called the affected zone in the E-beam process E-beam machining process. And this beam transparent layer is you can think of it as a layer which you know the electron velocity through which goes undetected particularly because it is so fast, and it is very rapidly moving and very small the layer is not able to get excited the vibrations are not able to really get started the moment the electron passes through them. So, therefore, when a fast-moving electron impinges on a material it penetrates through a layer undisturbed before it starts colliding with the molecules ultimately brought to rest.

So, what essentially you are doing is that this half mv square energy is being transferred onto wherever the electron is finally, hitting upon and wherever the electron is finally, coming to rest. So, if you assume the initial velocity of the emitting electron to be negligible the final expression of the electron velocity in kilometers per second can be expressed by this term here where it is 600 times V to the power of half where V is basically the potential difference across which the electron is being moved and this is a really a beam parameter. So, if it is a 150 KVA kilo volt through which it moves then this v corresponds to 150,000 value. So, it is a very high value and that is how u is determined for the electrons in kilometers per second. So, electron finally, after the beam transparent layer is crossed over collides with lattice atoms and imparts vibrations onto these atoms due to which there is an increase in the thermal energy because of random lattice vibrations occurring in a certain region.

So, this however happens beneath the skin or the upper portion of the also called the beam transparent layer. So, there is always a skin which is developed in the machining zone below which the whole thermal energy is generated by conversion from kinetic to thermal. So, the total range to which such an electron can penetrate if you call that delta. So, it typically depends on what is the kinetic energy, what is the accelerating voltage etc. And empirically it has been really found that the delta, the beam penetration depth can be related to the voltage by the equation 2.6 into 10 to the power of minus 17 square of V by P rho, where this delta is the penetration range in millimeters, V is the volt, so voltage. So, this is accelerating voltage and rho is the density of the material. So, that is how you can correlate. So, it really varies as the square of the accelerating voltage V.

Mechanics of EBM process

- The layer through which the electron penetrates undisturbed is called a transparent layer.
- Only, when the electron begins colliding with the lattice atoms does it start giving up its kinetic energy, and the heat is generated.
- So, it is clear that the generation of heat takes place inside the material, i.e., below the transparent skin.
- The total range to which the electron can penetrate (δ) depends on the kinetic energy, i.e., on the accelerating voltage (V) It has been found that

$$\delta = 2.6 \times 10^{-17} \frac{V^2}{\rho},$$

where δ is the range in mm, V is the accelerating voltage in volts & ρ is the density of the material.

So, let us look at a problem example here. So, during drilling of holes in a steel workpiece by EBM we have hit upon an accelerating voltage of 100 K, 50 KV. So, we determine what is the range of depth just to give you an idea of the value of this transparent layer how small it is.

Problem

During drilling of holes in a steel workpiece by EBM, an accelerating voltage of 150kV is used. Determine the electron range.

Ans $\rho_{steel} = 76 \times 10^{-7}$ kg/mm^3

$$\therefore \delta = 2.6 \times 10^{-17} \frac{(150 \times 10^3)}{76 \times 10^{-7}} \text{ mm} = 77 \mu m$$

So, let us look at the density of steel here, density of steel is equal to 76 10 to the power of minus 7 Kg per millimeter cube, and delta by that equation becomes 2.6   10 to the power of minus 17 times the square of V which is 150 times 10 to the power 3   150 volts kilo volts square of that times divided by 76 into 10 to the power of minus 7. So, this only comes, and this is in mm millimeters, this comes out to be about 77 microns.

So, that is how small this skin is, the skin which is not affected as the electron beam goes.   So, transparent layer is about close to 10s of microns which is formulated by an accelerating voltage of 150 KV. Of course, if the accelerating voltage is changed then this delta value will increase further, and depending on what the accelerating voltages can be it can go up to probably 1000 KV or so, this can go up to about 100 microns 100 to 150 microns. So, that is how much this penetration depth can go up to. So, in the interest of time, we have to close today's lecture, but then in the next lecture, I would like to talk about the thermal modelling part associated with the E-beam and try to develop an analysis of how this local temperature rise would lead to melting of the materials and try to relate them to the material properties for getting a good understanding of the machining processes. Thank you.