Advanced Machining Processes
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Week - 8
Lecture – 20
Derivation of Functional characteristics of EBM, Power requirement in EBM, Mechanics of EBM process

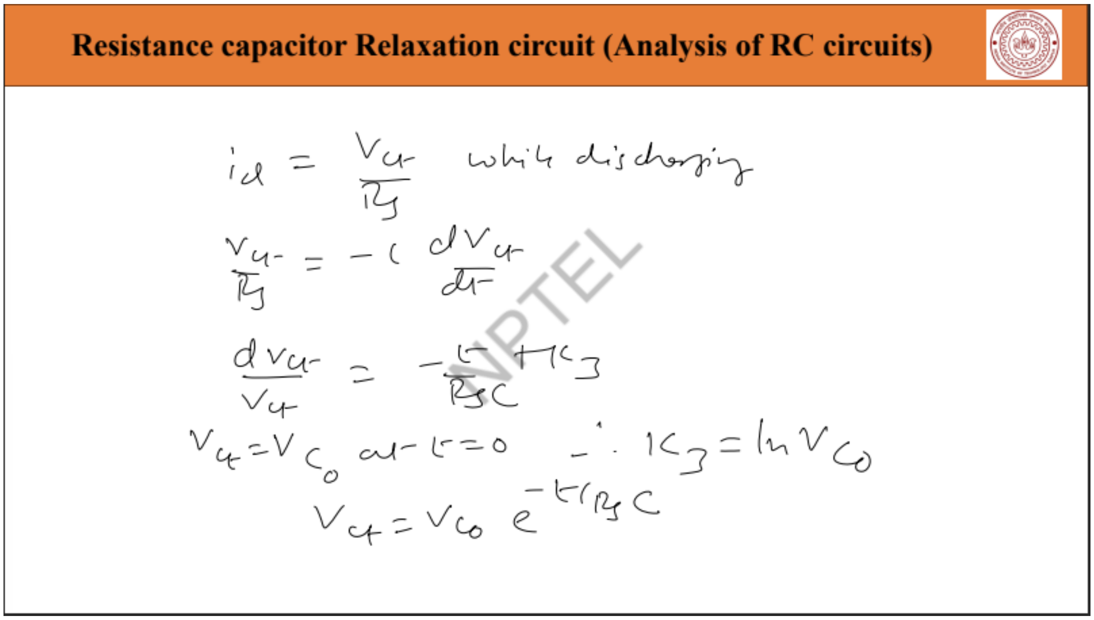
Hello, and welcome to this lecture of Microsystems Fabrication by Advanced Manufacturing Processes. You had the following things covered in your last lecture; one was the variation of melting temperature depth with crater volume in EDM processes. We also covered the role of cavitation in material removal particularly, because of the formation of plasma within the EDM there is a tendency of a low-pressure region to be created which actually drives away most of the material and is responsible for most of the material removal in the EDM process. We also considered the role of melting temperature in the MRR, material removal rate, and then we discussed some basic principles of EDM circuits. For example, the resistance, capacitance, relaxation circuit, the circuit was very briefly analyzed also mathematically as well. We also had the rotary impulse generator type circuit, and then we had this solid-state controlled pulse circuit, the three main circuits of EDM which and the various operation principles.

We also covered a detailed analysis, particularly of this resistance, capacitance, relaxation circuit, and just like to go through once more before starting. So, basically, this is the figure of the resistance, capacitance, capacitor, relaxation circuit as you can see here. There is one part of the circuit here which is the charging circuit, and similarly, the other part here given by the dotted line is the discharging part of the circuit. The idea is that there is an operating voltage which feeds the charging circuit, and there is a central capacitor which is the only electrical connection between the charging and the discharging side of both the circuits.

So, this actually is a R C network as can be seen with the variable resistor, and the capacitor charges in one cycle, and then discharges based on this gap potential which is there between the tool and the workpiece in the EDM tank, the electric discharge machining tank. So, we found out that using some R C modelling, R C circuit modelling that this Vc corresponding to the maximum power transfer is actually 72 percent of the operating voltage. So, the operating point of the capacitor or the capacitor voltage is only about 72 percent, and that corresponds to the maximum power. You can see here in this particular figure with respect to the time constant, you are actually plotting voltage, and you can see that corresponding to this point right here 72 percent of the operating voltage you have the maximum power, and simultaneously calculations were made doing that. Now, if we really want this power to be fully delivered on to the discharging part of the circuit, we should somehow be able to equate the breakdown voltage of the dielectric medium between the tool and the workpiece to this of the 72 percent of the V operating or Vo voltage of the charging part of the circuit.

So, therefore for maximum power delivery through the gap, the breakdown voltage should be equated to the supply voltage of the capacitor. In other words, V0 is tentatively equal to 0.72 Vo, Vb I am sorry the breakdown voltage Vb is equal to 72 percent of the operating voltage. So, current in the discharging circuit can also be evaluated by using the Ohm's law. If you just go back one slide and see what the discharging circuit is like you have really this part, this dotted part of the circuit as a discharging circuit.

So, you have an operational voltage 72 percent of the Vo or the charging voltage in the capacitor, and if you apply Ohm's law here in this particular circuit, the Id that is the current across the discharging circuit also can be written down as minus dQ by dt which is minus C Vct by dt. Vct is the temporal voltage of the central capacitor. If you apply the Ohm's law, the total current in the discharging circuit is nothing but this Vct by the total resistance cut. Take total resistance Rs which is this resistance of the discharging side. So, the Vct by Rs becomes equal to minus C Vct, dVct by dt, and so we try to integrate this in time and see what is the outcome.



Resistance capacitor Relaxation circuit (Analysis of RC circuits)

$$i_d = \frac{V_{ct}}{R_s} \quad \text{while discharging}$$

$$\frac{V_{ct}}{R_s} = -C\frac{dV_{ct}}{dt}$$

$$\frac{dV_{ct}}{V_{ct}} = -\frac{t}{R_sC} + K_3$$

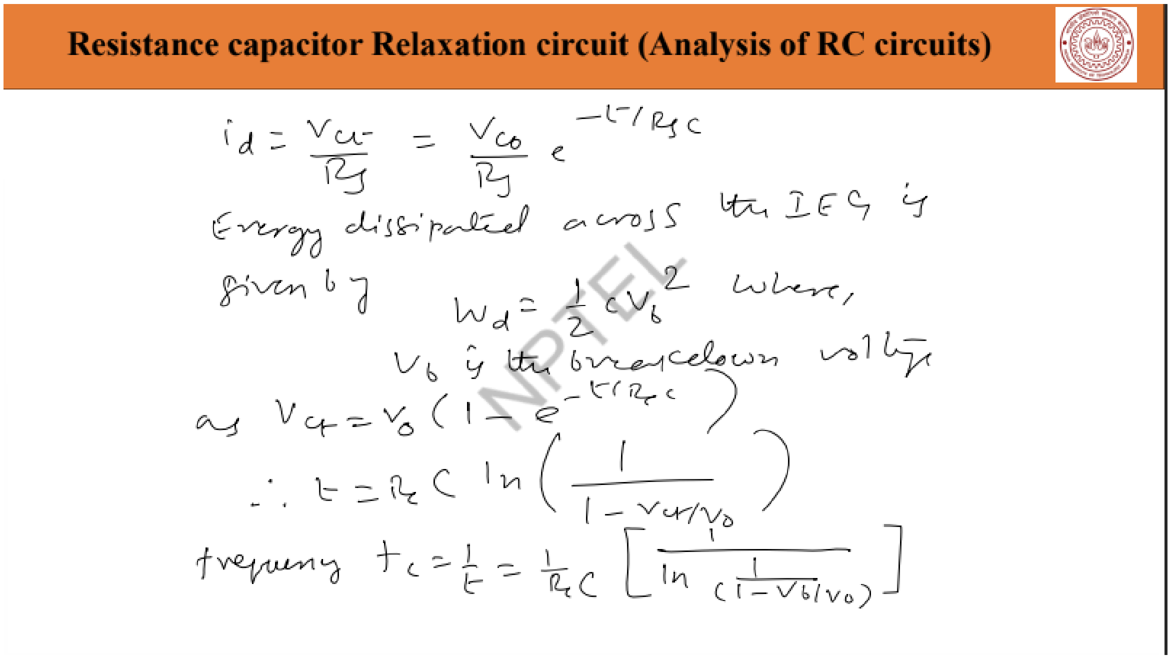
$$V_{ct} = V_{C_0} \text{ at } t = 0 \quad \therefore K_3 = \ln V_{C_0}$$

$$V_{ct} = V_{C_0}\, e^{-t/R_sC}$$

So, dVct by Vct is actually equal to minus of dt by Rs C, integrate both on time, we get natural log of Vct comes equal to minus t by Rs C plus integration constant, we call this K3. So, let us find out what this K3 is. So, at time t equal to 0, we already know Vct is actually equal to 72 percent of the output, the input voltage, the operating voltage. Now, we call this the VCo. So, this is corresponding to the value of Vc at time t equal to 0.

And so if you put this back into this equation here corresponding to t equal to 0, we get ln VCo is equal to K3. In other words, Vct can be written down as VCo e to the power of minus t by Rs C. Therefore, the relationship on the discharge side of the circuit is simplistically given by the charging voltage on the capacitor, central capacitor equals the charging voltage on the central capacitor at ab initio before the discharging process happen, times of exponential minus t by Rs times of C. C is the capacitor, the capacitance on the capacitor and Rs is the total resistance of the discharging circuit. So, as we know that you know Vct is already defined.

So, we can find out id again, which we initially defined as Vct by Rs, the resistance of the discharging circuit. In this case, we can write this down simplistically as VCo by Rs e to the power of minus t by Rs C. So, energy dissipated across the inter-electrode gap is given by half Cv square, and in this case, the V is corresponding to the breakdown voltage of the medium, we call it Vb. And so Wd the total amount of energy dissipated across the gap is half Cvb square, Vb is breakdown voltage. As Vct is equal to Vc0 1 minus e to the power of minus t by RcC, remember the charging part of the circuit where this equation had come.



Resistance capacitor Relaxation circuit (Analysis of RC circuits)

$$i_d = \frac{V_{ct}}{R_s} = \frac{V_{c0}}{R_s} e^{-t/R_s C}$$

Energy dissipated across the IEG is given by $W_d = \frac{1}{2} C V_b^2$ where,

V_b is the breakdown voltage

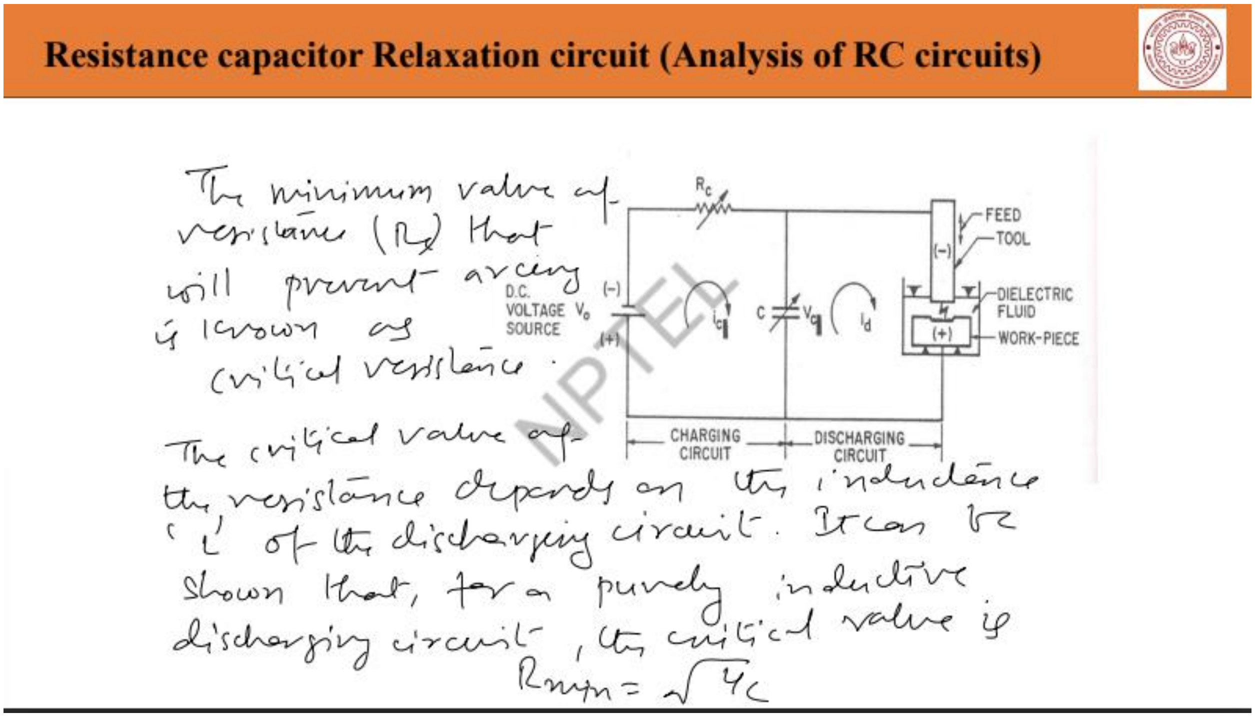
as $V_{ct} = V_0 \left(1 - e^{-t/R_c C}\right)$

$$\therefore t = R_c C \ln\left(\frac{1}{1 - V_{ct}/V_0}\right)$$

frequency $f_c = \frac{1}{t} = \frac{1}{R_c C}\left[\frac{1}{\ln \frac{1}{(1 - V_b/V_0)}}\right]$

Therefore, we can say from this particular equation the time t can be computed as RcC natural log of 1 minus Vct by V0. And so, frequency of the discharging circuit is just the time inverse. And so therefore, the frequency is 1 by RcC 1 divided by this whole term ln 1 minus Vct by V0, where Vct is nothing, but the breakdown voltage Vb as we have already seen before in the last illustration. So, the minimum resistance Rc that will result in a control of the process without the formation of any arcing as such resistance for this particular circuit. And so, the critical value of resistance corresponding to the no arcing condition so typically depend on the inductance of the discharging circuit.

And supposing if the discharging circuit is purely inductive in nature, the critical resistance R minimum can be written down as the total amount of inductance of the discharging circuit per unit the capacitance, the central capacitance value C. And therefore, it is critical to have a resistance which is at least 30 times the R minimum value as shown here. So, 30 root L by C is the operating point for the resistance corresponding to no arcing condition. So, in a nutshell, we have kind of seen that the relaxation, the resistance-capacitance relaxation circuit is limited by the resistance of the charging side. And in most of the cases, it is around 30 times the root of L by C, L is the inductance of the discharging circuit and C is the capacitance, the central capacitance between the charging and discharging circuit.



Resistance capacitor Relaxation circuit (Analysis of RC circuits)

The minimum value of resistance (R_c) that will prevent arcing is known as critical resistance.

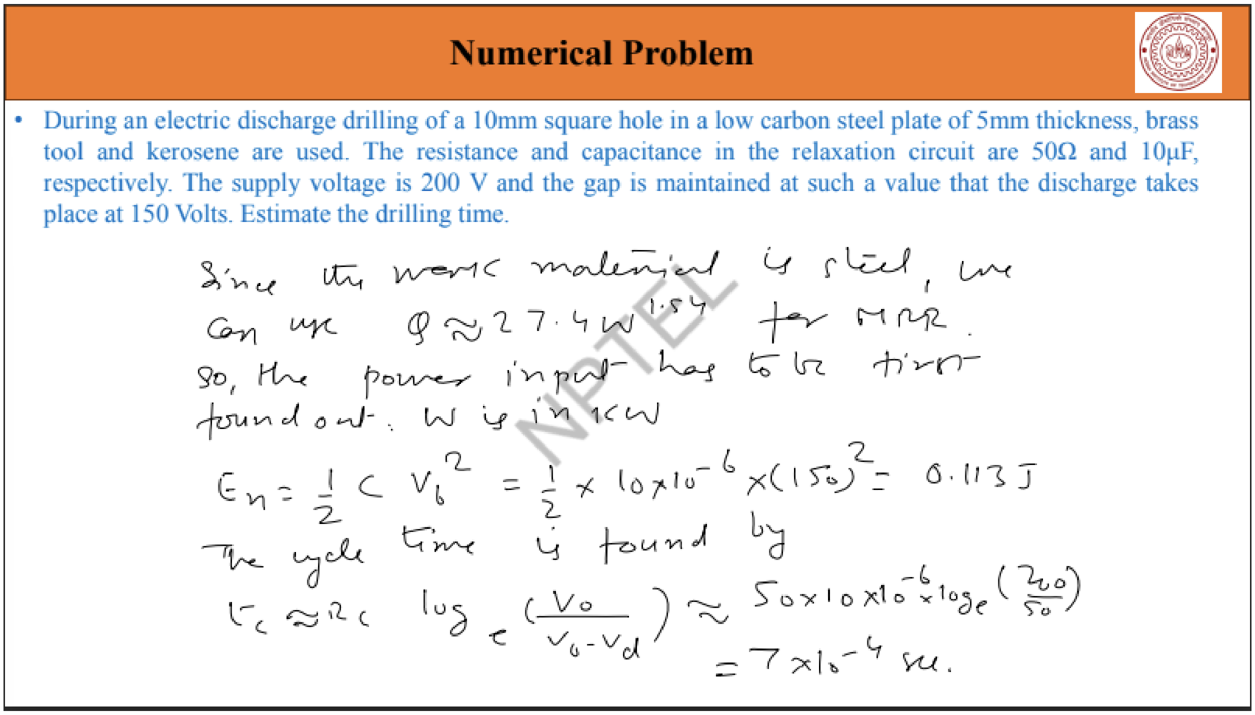
The critical value of the resistance depends on the inductance 'L' of the discharging circuit. It can be shown that, for a purely inductive discharging circuit, the critical value is

$$R_{min} = \sqrt{4/c}$$

So, in case of machining steels, there are certain conventions and there are certain correlational data which are followed by for estimating a real relationship between the material removal rate and the amount of power that is delivered onto the workpiece by the EDM system. And so, one such relationship which is very commonly used is mathematically Q equals 27.4 W to the power of 1.54, and this is purely empirical based on experiments. The various parameters that are used in the experiments here are Q is the removal rate, typically it is in millimeters per minute, millimeter cube per minute, volume per unit time of material removal, and W is the power delivered or the input power you can say on the relaxation side, the charging side of the circuit in kilowatts.

So, such relationships are very often used in EDM processes which would also help us to understand and design the RC circuits or the relaxation circuits for feeding an EDM tool. So, do a numerical problem based on that as illustrated here that in an electric discharge drilling process of a 10 mm square hole in a low carbon steel plate of thickness about 5 mm, the brass tool and kerosene are used as kerosene is the dielectric, brass is the tool. The resistance and capacitance of the relaxation circuit that have been designed are given as 50 ohms and 10 microfarad respectively, and it also indicating, or it is also indicated what the supply voltage is, the order of the supply voltage is about 200 volts, and you maintain a gap between the tool and the workpiece in a manner so that at 150 volts the breakdown happens. So, you can see here the breakdown takes place as 150 volts that is how you estimate the gap, and you have to estimate how much time is needed for drilling this hole.

So, one way of looking at it is that since the work material is steel here, we can use the equation that was talked about earlier for steel Q equal to 27.4 W to the power of 1.54 for MRR estimation, and the W of course, needs to be indicated in kilowatts that is the assumption that we made in the last empirical equation. And so therefore, we have to really calculate what is the energy being discharged, we already know that the energy being delivered by the capacitor C, the breakdown side is given by half C Vb square, where VB is the breakdown voltage. And this breakdown voltage has already been illustrated here in this example as 150 volts, for the capacitance of 10 microfarads, this becomes equal to half times of 10 into 10 to the power of minus 6 times of square of 150 is 0.113 joule.



Numerical Problem

- During an electric discharge drilling of a 10mm square hole in a low carbon steel plate of 5mm thickness, brass tool and kerosene are used. The resistance and capacitance in the relaxation circuit are 50Ω and 10μF, respectively. The supply voltage is 200 V and the gap is maintained at such a value that the discharge takes place at 150 Volts. Estimate the drilling time.

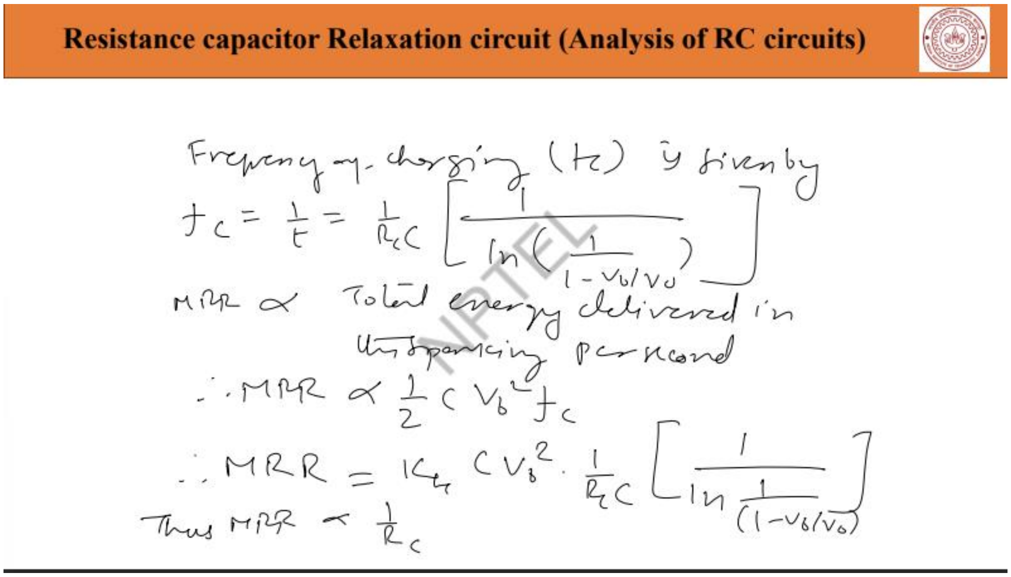
Since the work material is steel, we can use $Q \approx 27.4 W^{1.54}$ for MRR. So, the power input has to be first found out. W is in kW

$$E_n = \frac{1}{2} C V_b^2 = \frac{1}{2} \times 10\times10^{-6} \times (150)^2 = 0.113\ J$$

The cycle time is found by

$$t_c \approx RC \log_e \left(\frac{V_0}{V_0 - V_d}\right) \approx 50\times10\times10^{-6} \times \log_e\left(\frac{200}{50}\right)$$
$$= 7\times10^{-4}\ \text{sec.}$$

And the cycle time in this case is found by Tc, and the equation that was discussed earlier is R c times of c log of V0 by V0 minus Vd, Vd is the discharge voltage, this is log to the base e. So, this becomes equal to 50 times of 10 into 10 to the power of minus 6 the capacitance times of log to the base e of the operating voltage, which is taken as 200 volts in this example, divided by Vd minus Vo which is about 50 volts in this particular case. So, this corresponds to a time of about 7 10 to the power of minus 4 seconds. So, once this time is known, we should be able to find out how much power is being delivered as the average power input is W equals 0.113 joules the energy that has been discharged by the ED machine divided by 7 10 to the power of minus 4 seconds, and this power is in kilowatts.



Resistance capacitor Relaxation circuit (Analysis of RC circuits)

Frequency of charging (f_c) is given by

$$f_c = \frac{1}{t} = \frac{1}{R_c C}\left[\frac{1}{\ln\left(\frac{1}{1-V_b/V_0}\right)}\right]$$

MRR $\propto$ Total energy delivered in the sparking per second

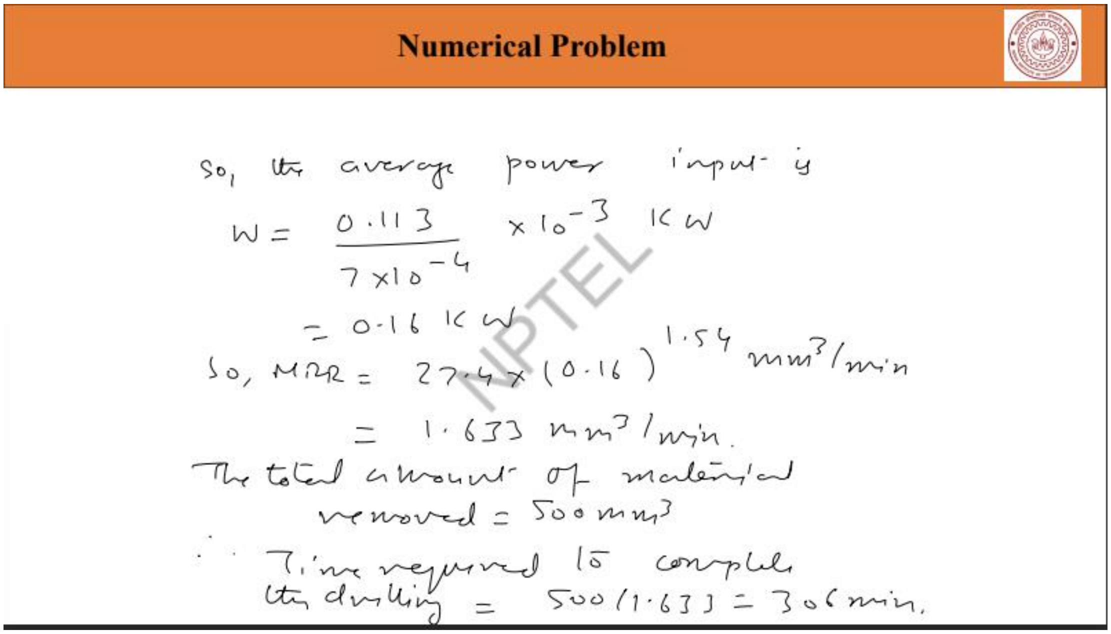
$$\therefore \text{MRR} \propto \frac{1}{2} C V_b^2 f_c$$

$$\therefore \text{MRR} = K_4 \, C V_b^2 \cdot \frac{1}{R_c C}\left[\frac{1}{\ln \frac{1}{(1-V_b/V_0)}}\right]$$

Thus MRR $\propto \frac{1}{R_c}$

So, it is basically 10 to the power of minus 3 kilowatts, which makes it 0.16 kilowatts. And using the equation that we had discussed about mild steel particularly, MRR can be represented as 27.4 times of this value of W in kilo watts to the power of 1.54 in millimeter cube per minute.

So, this is an estimation of what would be the material removal rate. This in our case comes out to be equal to 1.633-millimeter cube per minute. We also know by virtue of the question that the total amount of material that needs to be removed is calculated as about 500-millimetre cube. This can be geometrically done.



Numerical Problem

So, the average power input is

$$W = \frac{0.113}{7 \times 10^{-4}} \times 10^{-3} \text{ KW}$$

$$= 0.16 \text{ KW}$$

$$\text{So, MRR} = 27.4 \times (0.16)^{1.54} \text{ mm}^3/\text{min}$$

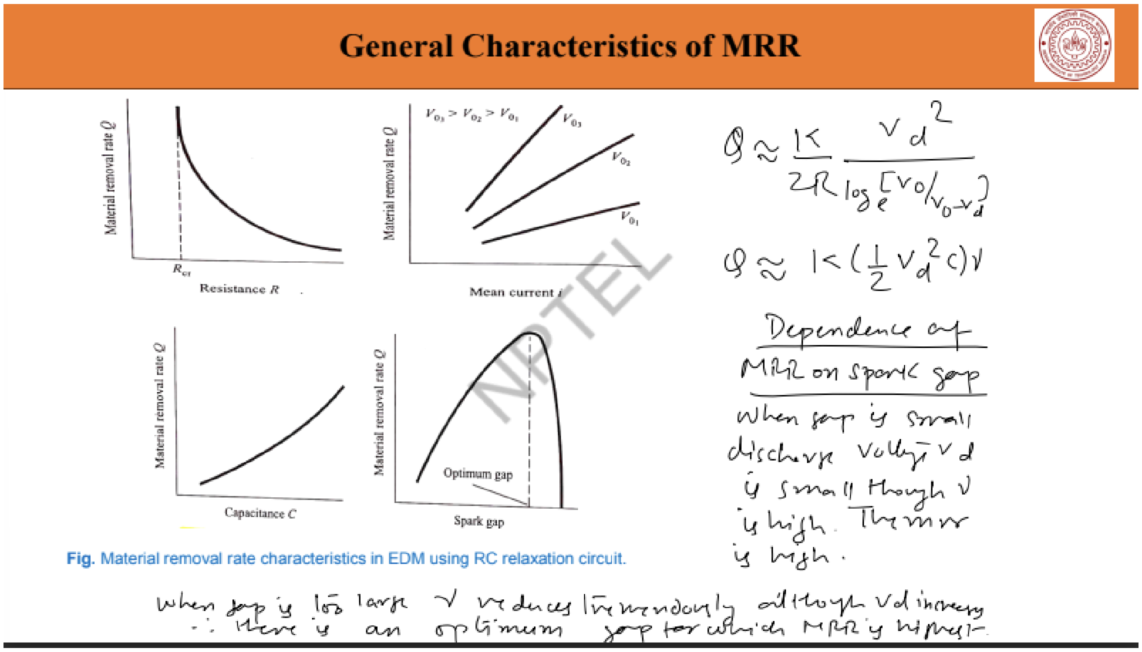
$$= 1.633 \text{ mm}^3/\text{min.}$$

The total amount of material removed = 500 mm^3

∴ Time required to complete the drilling = 500/1.633 = 306 min.

The dimensions of the hole, the thickness of the sheet etcetera are all provided in the question. And so therefore, the time required to complete this machining operation comes out to be equal to 500 by 1.633 that is 306 minutes. So, you can estimate the rate of an EDM process, particularly the rate of material removal and realize that in about 306 minutes you can actually just be able to drill a very small hole on a thickness of the sheet which is about 5 millimeters. So, in comparison to any conventional process, this process, of course, is a slow process, but then EDM has an advantage that you can work using some of the alloys where probably conventional machining may not be that helpful.

In this particular case as you see there is a low-carbon steel plate which is being drilled, which sometimes is very challenging in the conventional machining when it comes to tool designing etcetera for the particular surface. Also, this is of course, a regular topology, but then if the topology is very complex, correct profile matching of the conventional machining side on a CNC or some other setup becomes absolutely complex. And so EDM can work as a very good tool in those illustrations although the time of machining may be a little higher rate of material removal may be slower. So, let us now look at some of the other important aspects, some of the machining trends with the different parameters that we have discussed so far. So, here in this particular slide, we are illustrating the variation of the material removal rate Q with respect to different parameters like the resistance of the charging circuit, the mean current I, in this particular instance it is the capacitance C of the relaxation circuit, and then of course, the variation of MRR with respect to the spark gap.



General Characteristics of MRR

Fig. Material removal rate characteristics in EDM using RC relaxation circuit.

$$Q \approx \frac{K}{2R} \frac{V_d^2}{\log_e [V_0/V_0-V_d]}$$

$$Q \approx K\left(\frac{1}{2}V_d^2 C\right)\nu$$

Dependence of MRR on spark gap

When gap is small discharge voltage V_d is small though ν is high. The mrr is high.

When gap is too large ν reduces tremendously although V_d increases ∴ there is an optimum gap for which MRR is highest.

So, as we already know the equation for material removal rate had been earlier defined as to be proportional to this term Vd square divided by log to the base e V0 by V0 minus Vd, and Q was found as K times of half Vd square C times of nu, where nu is the frequency of generation of the spark half C Vd square is the total amount of discharge energy that is needed by the EDM process, and of course, Q is proportional to this both these terms together. So, if we look at the various aspects in these two equations we will have different trends. For example, as you can see it is an inverse variation of resistance. So, with an increase in resistance, the MRR goes down obviously from this equation, and as we already discussed before that the relaxation circuit is supposed to have a minimum critical resistance particularly as far as the discharge gap is concerned, because if supposing the resistance is very small there may be a arcing instead of sparking, and it may be a continuous phenomenon arcing instead of sparking which is not really conducive to the EDM process. So, it starts at a minimum value of resistance, the critical resistance which needs to be necessarily maintained in the inter-electrode gap, so that a successful EDM operation can be carried out.

One of the reasons why if you look at this trend here, the range of resistance really starts RCR onwards or critical resistance onwards, and as the resistance increases material removal rate goes down. Similar kind of trend can be discussed for the capacitance, here for example, in this equation 2, let us call this equation 1, this as equation 2, the Q is proportional to capacitance, so pretty much it should vary linearly. However, in an actual experimental setup, the material removal rate is found to very close to linear, not exactly linear with respect to the capacitance. Let us look at the variation of material removal rate with respect to mean current I, as can be found in this graph here. If you can see that there are different operating voltages of V03, V02, and V01 with an interrelationship mentioned at the top left corner of the graph here, the operating voltage V03 is the highest followed by V02 followed by V01.

And as is obvious Vd or discharge voltage is actually equal to 72 percent of the operating voltage which for maximum power transfer, which we had actually calculated and in detail shown earlier. And so, therefore, if the V operating is more the discharge voltage also subsequently rises, actually it is a cause and effect, which is the cause and which is the effect. So, basically, discharge voltage is the independent parameter, which is dependent on various parameters, various properties of the gap, the dielectric of the gap, dielectric constant of the gap or the gap itself. And therefore, Vd is really that point of voltage which starts the discharge. And so, the Vo has to be set in accordance with this Vd.

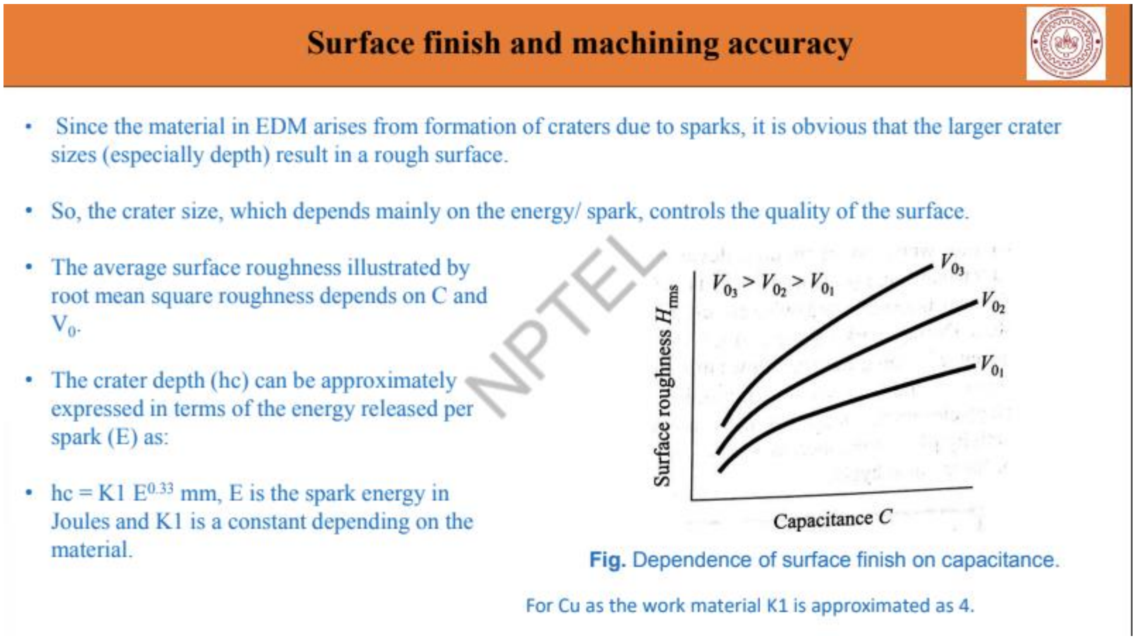
And therefore, if Vo is higher, it automatically means that we are operating at a higher gap discharge voltage Vd, and Vd being proportional to Q means that higher V operating meaning thereby higher V discharge would have a higher machining rate or material removal rate in comparison to a lower operating voltage Vo1. Thus, this different range. So, the V thus characteristics of different V operating on different straight lines from 1 to 3 as can be seen in this particular graph. One more important point is that as the mean current increases it automatically means that the discharge voltage also is increasing because it is really a function of the gap resistance. And therefore, with an increase in mean current as you can see the material removal rate is also increasing.

The other important factor in this characteristics is how the material removal rate varies with the spark gap. And if you may recall this equation number 2, there are 2 components of this equation. One is this half Vd square C component which is the spark energy, and the other is nu which is the spark frequency. And when it comes to optimizing the energy versus frequency the following things may be thought of in a physical way in the EDM machine. So, as the gap the internal electrode gap is lesser, you need lesser amount of discharge voltage, because the gap is very small.

The electric field which is causative of the electrical breakdown is dependent on Vd by internal electrode distance d, and d being small Vd can also be reasonably small for the discharge to occur or the breakdown field to reach. However, if the distance is small there is a tendency of the spark frequency to increase, and although the Vd is smaller at a lower electrode distance or lower spark gap as you may better call it, the frequency is extremely high. On the other hand, if the electrode gap increases you need a higher discharge voltage Vd to cause the electrical field breakdown, and because the spark has to travel through all this distance which is now higher in comparison to what was before, the spark frequency suitably reduces. So, it is essentially an interplay between these components as shown here, the spark energy and the spark frequency.

So, let us call it 1 and 2 respectively. And the reason why this material removal rate with respect to the spark gap is like a plateauing curve as illustrated in this particular diagram here, is that on the left portion of the optimum gap that means on this particular portion the frequency dominates, because of lower gap, and on the right side of the optimum gap the Vd increases, because of increased gap, and the energy dominates the frequency term. And so, because it is an interplay sometimes the frequency is higher, and it increases the material removal rate because it is dominating, and in the other hand if the energy may not be that, you know the rate of increase of energy may not be that high in comparison to the frequency it leads to the fall down of the material removal rate as shown by these set of arrows on the right side of the optimum spark gap. So, essentially, we can summarize all these by saying that when the spark gap is small, discharge voltage is also small, though the frequency is high resulting in a high MRR. When the gap is too large the frequency nu reduces tremendously, although discharge voltage Vd increases. Therefore, there is an optimum gap for which MRR is the highest.
So, we have more or less discussed about the general characteristics of how the machining rate or the material removal rate in an EDM process would vary with several process parameters. The other important issue is about how surface finish and machining accuracy can be dependent on some of these parameters like for example, the capacitance or the operating voltage. And for doing that let us just see some of the important aspects to be considered in this particular slide.
So, as you know since the material in EDM arises from formation, material removal in EDM arises from formation of the craters due to sparks, essentially it is obvious that larger crater sizes, especially the crater depth result in rough surfaces. So, as we talked before about thermal energy and the way the depth of melting temperature reaches on a crater, if the depth of melting

temperature is higher the roughness would go up and vice versa for obvious reasons because you will have a deeper crater and a crater-by-crater removal of the material over the whole surface.



Surface finish and machining accuracy

- Since the material in EDM arises from formation of craters due to sparks, it is obvious that the larger crater sizes (especially depth) result in a rough surface.
- So, the crater size, which depends mainly on the energy/ spark, controls the quality of the surface.
- The average surface roughness illustrated by root mean square roughness depends on C and V_0.
- The crater depth (hc) can be approximately expressed in terms of the energy released per spark (E) as:
- hc = K1 $E^{0.33}$ mm, E is the spark energy in Joules and K1 is a constant depending on the material.

Fig. Dependence of surface finish on capacitance.

For Cu as the work material K1 is approximated as 4.

So, the crater size if we really look at mathematically and we have done this earlier, this mainly depends on the spark energy. And if you are releasing this energy as a packet with a high intensity, obviously the crater will be deeper and vice versa if the energy delivered is smaller and probably the frequency is larger, then the crater would have a lower depth. And obviously, from an engineering standpoint intuitively one can think that higher energy deliverance corresponds to a rough surface, and a lower energy deliverance corresponds to a smooth surface as far as machining quality is concerned. So, it controls the quality of the surface. So, the average roughness is illustrated by root mean square roughness, and this mainly depends on two important aspects, one is the capacitance, and another is the operating voltage.

I think we have already mentioned this N number of times before that the q r, the q the material removal rate is really proportional to the half C Vd square and the frequency. And so, as one can see here easily if C is more the material removal is more meaning thereby that half C Vd square is essentially that energy packet that we are talking about during one EDM exposure or one EDM spark. So, if half C Vd square is more it automatically means that the energy density which is being delivered onto the material is much higher, and the crater size would be greater in nature. And if this is lesser meaning thereby that you have a lower operating voltage on which you are operating the half C Vd square would again in a way depend on that lower operating voltage, and the surface roughness would be lesser, or surface would be smoother. So, here, for example, V o3 is a higher operating voltage greater than V o2 greater than V o1.

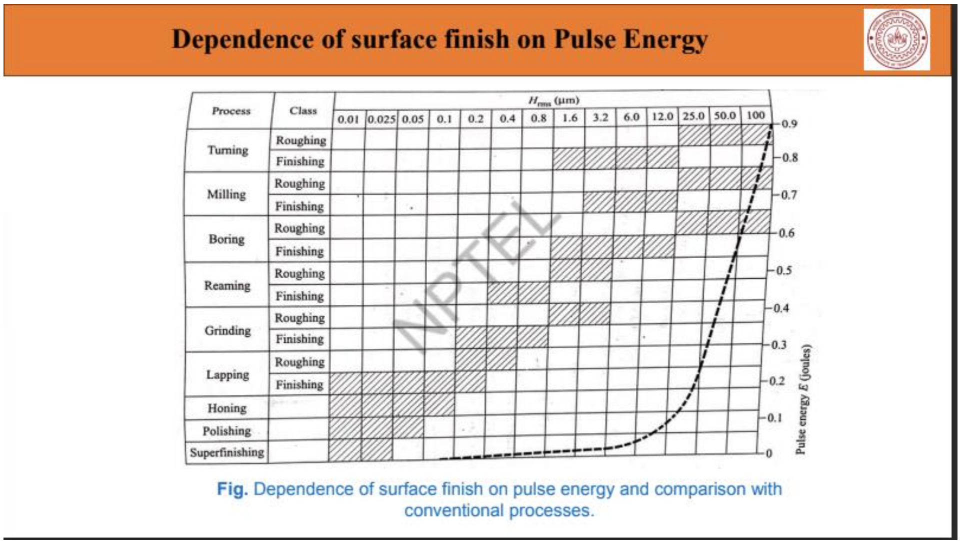
You can see all the surface roughness trends vary with capacitance as high roughness on the higher voltage operating voltage characteristic, and a lower roughness on the lower operating voltage characteristic. And the variation is more or less proportional although there are certain parts towards the very beginning where the trend is not that linear because probably there is still not a completely established charging discharging precedence or relationship between both the circuitry's both the circuits, and that is how the average surface roughness HRMS varies with respect to capacitance. Also, you can think of it as by looking at that if you may recall earlier, we had talked about the crater depth hc which can be expressed in terms of spark energy released, and we arrived upon a formulation where this crater depth was empirically determined in terms of K1 times of spark energy E to the power of 0.33 millimeters. So, if half C Vd square is more obviously, e is more and hc is more.

So, there is also from a mathematical standpoint some relationship between the crater depth and the spark energy. So, copper when used as a work material experimentally yields this K1 value to be approximately 4, and you can accordingly find out an estimate what is the surface roughness HRMS based on the material properties, and the energy deliverance on to the material. The other important aspect, therefore, is that if I really take e to be half C Vd square and try to formulate this empirical relationship it results into this expression 0.78 K e to C to the power of 0.33 Vd to the power of 0.66 K is again that constant of proportionality which in case of copper was 4 observed to have value 4. And thus, the relationship how the hc varies with respect to capacitance, and also Vd the discharge voltage which is again somehow a function, and closely related to the operating voltage characteristic.

So, the dependence of surface energy on pulse energy E, and the comparison of surface finish with that obtained by conventional processes are now quite well studied. Lot of research has gone in this area, and lot of studies have been made in determining a suitable relationship between the rate of material removal, and the quality of the surface finish. However, these are all empirical in nature, and very dependable kind of relationship has not really emerged so far between the surface finish, and the spark energy.

It works well in case of combinations of different materials. So, in particularly case of steels, you have a very well-defined relationship, how Hrms is related to the material removal rate, although it is quite empirical in nature. But then there is an equation Hrms equal to 1.11 Q to the power of 0.384, where Hrms is the surface roughness the average surface the rms root mean square roughness in microns, and Q is in millimeter cube per minute.

Generally, one more aspect that we have illustrated before is that if there is a force circulation of dielectric in an EDM tank, it results in smoothening of the surface by lot of diffusive forces interplayed by the moving dielectric over the surface. So, it carries away the melt, distributes the temperature, and so therefore, overall, there is a surface smoothness which comes because of higher circulation rate. So, let us look now at the more dependable relationship between surface finish, and pulse energy as illustrated in this process here. And you can see the spark energy on the right y-axis here in joules for the various operations like electro-discharge turning, electro-discharge milling, boring, reaming, grinding, lapping, honing, polishing, and super finishing. And you can see that there are two different regimes of roughnesses for each, one of them is the roughing regime where there is a rough-cut finishing which has a lower value of roughness smoother surface, and this describes the Hrms in microns.



Dependence of surface finish on Pulse Energy

Process	Class	H_{rms} (μm)													
		0.01	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.0	12.0	25.0	50.0	100
Turning	Roughing												▨	▨	▨
	Finishing								▨	▨	▨	▨			
Milling	Roughing												▨	▨	▨
	Finishing									▨	▨	▨			
Boring	Roughing												▨	▨	▨
	Finishing								▨	▨	▨	▨			
Reaming	Roughing								▨	▨					
	Finishing						▨	▨							
Grinding	Roughing								▨	▨					
	Finishing					▨	▨	▨							
Lapping	Roughing					▨	▨								
	Finishing	▨	▨	▨	▨	▨									
Honing		▨	▨	▨	▨										
Polishing		▨	▨	▨											
Superfinishing		▨	▨												

Fig. Dependence of surface finish on pulse energy and comparison with conventional processes.

So, for example, corresponding to a pulse energy of 0.1 joule, you can get an average roughness of around close to 0.01 microns when you talk about electro-discharge polishing processes, and as I has about 0.05 microns. So, this is the operating range of the roughness for 0.1 joule energy. The other side if you talk about turning operations, so in turning you can get a rough range of roughness varying from 25 to 100 microns, whereas corresponding to a really high pulse energy of 0.9 joules, and then if the pulse energy is slightly reduced, you have a finish turning, finish electro discharge turning operation where the roughness varies from 1.6 to 12 microns, the rms root mean square roughness. So, that is how you can read this particular figure, this is an ensemble of the different electro-discharge processes with respect to the roughing, and finishing roughnesses, and pulse energy. So, let us close this lecture in the interest of time by all this analysis about roughness and energy.

In the next lecture, we will start from slightly newer topic of E-beam machining. Thank you.