Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course title
Manufacturing Technology- Part-2

Module-29
EDM part-2

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Hello and welcome to this manufacturing process technology part 2 module 29

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Manufacturing Process Technology II-Module 29

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We were talking about the EDM process electro discharge machining process and then we also wanted to find out the material removal rate and for that we looked at some parametric related to the process one of them being the depth of melting temperature up to which θ basically is either equal or greater than the melting temperature of the material where machining is being carried out and we also looked at a set of equations through which we could arrive at a formulation for this θ in terms of Z that is the depth at a particular radius a and we assumed a circular heat source and a constant heat flux boundary condition.

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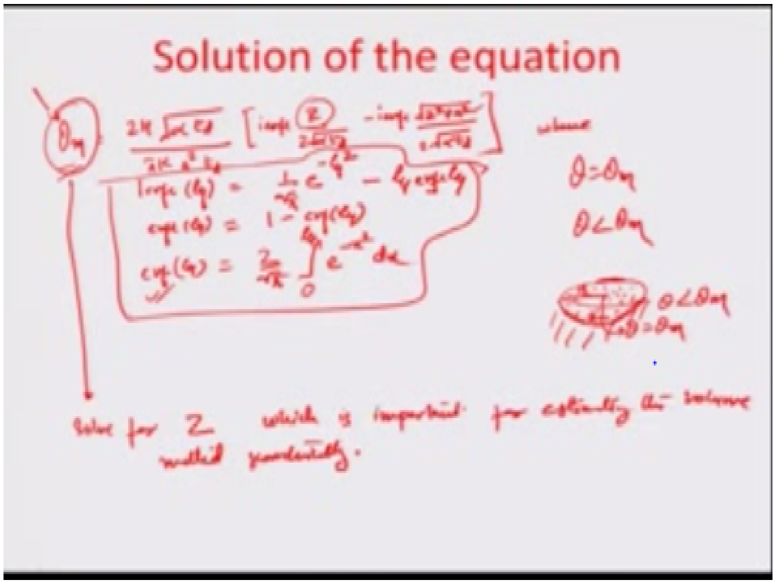

Solution of the equation

$$\theta_m = \frac{2H\sqrt{\alpha t_d}}{\pi K a^2 t_d}\left[\mathrm{ierfc}\frac{z}{2\sqrt{\alpha t_d}} - \mathrm{ierfc}\frac{\sqrt{z^2+a^2}}{2\sqrt{\alpha t_d}}\right]$$

where

$\mathrm{ierfc}(\eta) = \frac{1}{\sqrt{\pi}}e^{-\eta^2} - \eta\,\mathrm{erfc}(\eta)$

$\mathrm{erfc}(\eta) = 1 - \mathrm{erf}(\eta)$

$\mathrm{erf}(\eta) = \frac{2}{\sqrt{\pi}}\int_0^{\eta} e^{-x^2}\,dx$

$\theta = \theta_m$

$\theta < \theta_m$

Solve for Z which is important for estimating the volume melted quantitatively.

So basically we arrived at a formulation where we could write down θ melting as 2 H √ Td / π K^2TD do times of the third representation of the error function I RFC of Z the depth write this down little better manners e / 2 √ of α T minus the √IERFC / z^2+ a^2 / 2 √α TD and I also further mentioned that the way that you represent this IERFC off let us say some variable θ is 1 /$\sqrt{\pi}^{-2}$ of H minus of η ER FC η we are IERFC is actually equal to 1minus the error function of H and the error function of H is 2 by √π integral 0 to H e^{-x^2} DX.

So that is how you represent the different kinds of representations associated with this numerical integral which is the error function so having said that the you know solution is kind of clear in the sense that we try to find out this temperature boundary where the θ would be equal to θ M beyond which the θ would be less than θ M and if you look at really the crater and the way it is formulated.

We are really interested in the boundary where θ equal to θ M and beyond which there lies a zone or an area where θ is less than 3 time because that is still the solid portion whereas this cup which is formulated or the crater which is formulated has a liquid metal because temperature of this metal is either above or equal to the melting temperature of the material so this is in fact a solution of this boundary that we are looking at corresponding to θ equal to θ M and it depends on two factors one is of course a and other is Z.

So Z basically gives you the maximum depth up to which you know the melting boundary extends and a is the radius which actually has been assumed at the very beginning when we assumed circular heat source and a constant heat flux boundary condition so you basically can solve for this Z value which is important for estimating the volume melted geometrically.

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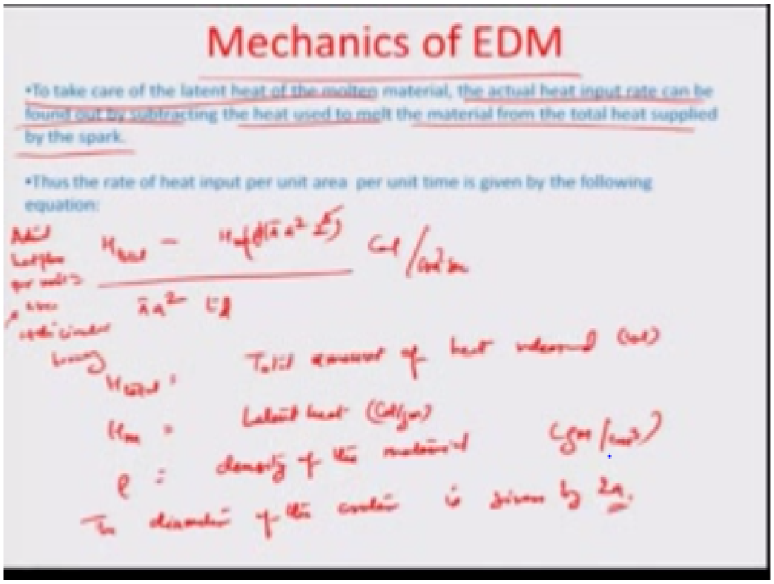

Mechanics of EDM

- To take care of the latent heat of the molten material, the actual heat input rate can be found out by subtracting the heat used to melt the material from the total heat supplied by the spark.
- Thus the rate of heat input per unit area per unit time is given by the following equation:

Actual heat flux per unit area at the circular boundary

$$\frac{H_{total} - H_m(\rho \pi a^2 Z)}{\pi a^2 t_d} \quad cal/cm^2 s$$

H_{total} : Total amount of heat released (cal)

H_m : Latent heat (cal/gm)

ρ : density of the material (gm/cm³)

The diameter of the crater is given by 2a.

So the mechanics of the EDM process is basically about the total amount of heat that is made to inflow from the circular boundary into this crater shape at area where melting is taking place obviously minus the amount of heat that goes into state conversion from solid to liquid and to take care of the latent heat of the molten material the actual heat input rate can be found out by subtracting the heat used to melt the material from the total heat supplied by the spark okay.

So actually if we look at that boundary we can actually apply a slight modification here where the total heat influx minus the latent heat of fusion times of the total mass you know which is $\pi a^2 Z$ the volume times density of the melt of the metal divided by the total area which is πa^2 divided by the spark discharge time so this is going to be the actual heat input rate per unit area so actual heat flux per unit area at the circular boundary.

So this can be expressed as calorie per centimeter second and etch total again each the total amount of heat released calories Hm is the latent heat in gram per calorie per gram the amount of it needed to melt or so do a state conversion of one gram of material row is basically the density of the material basically represented as gram per centimeter^3 and the diameter of the crater is given by 2a that is how you try to find out what is the actual heat flux parent area but the circular boundary.

So having said that we need to also empirically sort of estimate that how we can actually relate the diameter a2 things like operating power or the discharge time obviously if you may all recall that if supposing the power is more or the amount of time for which the spark discharges occur is occurring is more the a would not be fixed and will keep on expanding so circular region may you know increase because of additional heat flux which comes over and above the one which has been proposed okay.

So if supposing there is a increase in the power level of the DM system or increase in the past duration any of these would bring in additional heat energy and there would be I increase overall in the crater size in terms of diameter as well as the depth so in order to estimate it may be a numerical an empirical estimation of a may be needed with reference to both these quantities.

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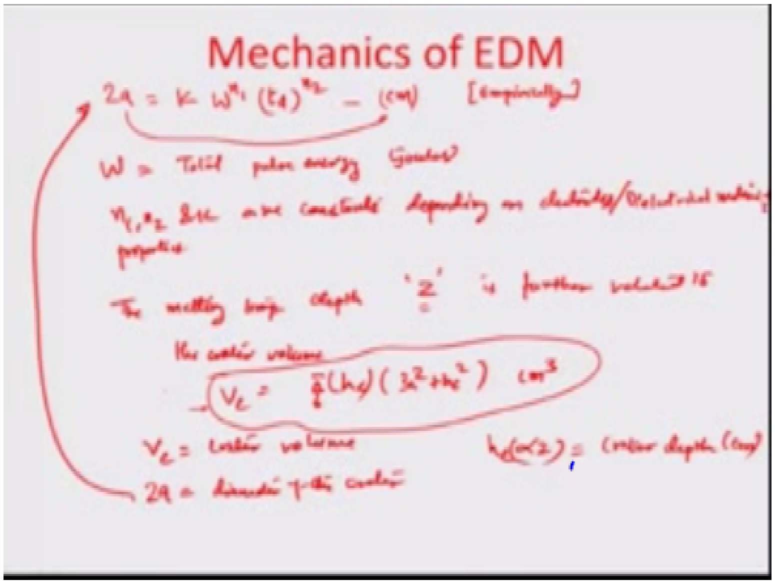

Mechanics of EDM

$2a = K W^{n_1} (t_d)^{n_2}$ — (cm) [empirically]

W = Total pulse energy (Joules)

n_1, n_2 & K are constants depending on electrode/[illegible] properties

The melting loop depth 'z' is further related to the crater volume

$V_c = \frac{\pi}{6}(h_c)(3a^2 + h_c^2)$ cm^3

V_c = crater volume

$h_c (\approx z)$ = crater depth (cm)

2a = diameter of the crater

So there is such an estimate which exists so to a can be given by some constant k times of w to the power of n 1 x of t d to the power of n 2 this is of course sort of an empirical formulation times of times of discharge time TD to the power of n to where the a is expressed in centimeters okay so the units here is centimeters for a and this is only an empirical relationship which is obtained experimentally.

So that one must understand so W is the total pulse energy in joules and all the three N 1and 2 and k are constants obviously depending on both the electrodes as well as dielectric materials properties so the way that the power law relates also is quite variable based on the material as well as material of the electrode as well as the material of the dielectric fluid so the melting temperature depth which we also recorded as z in the last step is further related to the crater volume to the greater volume in fact I am going to estimate the volume vc in terms of an expression at c which relates to the crater depth of the cat right whatever you may call times of 3a ^{2} + HC ^{2} centimeter ^{3} okay.

We c is the crater volume and obviously we know is the diameter twist the diameter of the crater centimeters obtained from this last step right here and HC is sort of you know proportional to Z you can call this the greater depth it is probably the maximum Z you know that is what the corresponding to θ equal to θ melting creator depth centimeters so that is how we can estimate what is the volume removal I am going to come to this formulation and try to prove it from first principle how this volume can be solved for.

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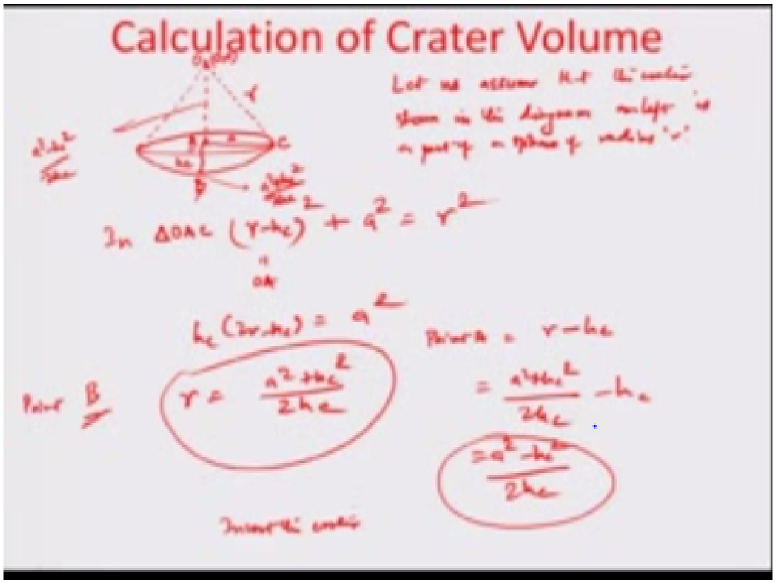

Calculation of Crater Volume

Let us assume that the crater shown in the diagram on left is a part of a sphere of radius 'r'

In ΔOAC $(r-h_c)^2 + a^2 = r^2$

$\overset{=}{OA}$

$h_c(2r-h_c) = a^2$

Point B $\boxed{r = \frac{a^2+h_c^2}{2h_c}}$

Point A $= r - h_c$

$= \frac{a^2+h_c^2}{2h_c} - h_c$

$\boxed{= \frac{a^2-h_c^2}{2h_c}}$

Invert the crater

So let us assume that let us say if we are talking about a small crater of this size or total diameter let us say a and total height at c okay so let us call this point at the center a capital A this capital B and we further extend this all the way to the geometrical center of the point where we call it oh ok so I just want to exchange this all the way to this point here geometrical center where we call it oh let us project the radii on both sides as radii are and let us assume that the crater shown in the diagram on left is a part of a sphere of radius R okay.

So I can simply apply let us call this point C so I can simply apply the Pythagoras theorem in triangle OAC and say that r minus HC which happens to be o a okay 2 plus square of a brings us to square of R okay so if I solve this expression here we get at c times of 2 r minus at c equals a ^{2} or in other words r becomes equal to a ^{2} plus at c ^{2} by 2 at c so if I assumed this to be equal to 0 let us say 00 or the origin the point B would really be at you know a corresponding value of radius equal to a ^{2} plus at C ^{2} by 2 at c.

And similarly the point a just as the point B has been found out from the earlier step is nothing but R minus HC so basically it is a ^{2} plus at C ^{2} by 2 at C minus at c in other words a ^{2} minus at C^2 by 2 at c so what we are trying to do here is to sort of find out you know what is going to be the Creator volume based on the variation of this crater from the point at all the way to the point B where we already know that a is at least a ^{2} minus HC ^{2} by 2HC away from the point oh okay.

So let us write this down a ^{2} minus c ^{2} by 2 at C ^{2} at c and we also know further that the point are you know the point B is at a distance a ^{2} by hc ^{2} / 2HC from the point 0 so let us now invert the crater and try to do the element a analysis of the crater.

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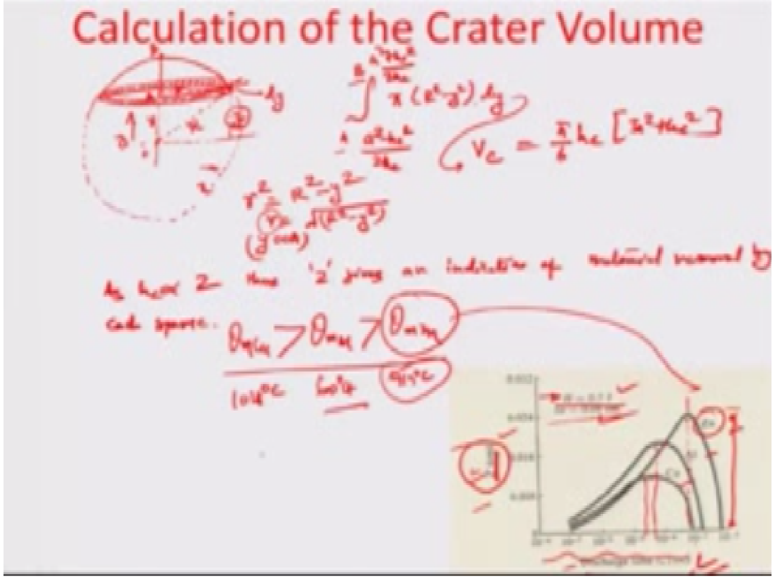

Calculation of the Crater Volume

$V_c = \frac{\pi}{6} h_c [3a^2 + h_c^2]$

So I am just going to make the crater upside down okay just for convenience of representation and nothing else let me just do this in a little better manner so here is the crater and then if we really project it brings us to a overall you know spherical shape or diameter represented by a center here and the dotted line so this Center is really the oh and there are two points obviously one of them is the point A and the other is a point B this is the Point C and we are trying to map you know this point.

So let us assume that the total radius of the sphere here in this case is capital R okay and further we are assuming a certain value of y here in the y co-ordinate side okay so this is the y co-ordinate this is the x co-ordinate where we want to estimate the size of an annular or a ring ok so we first of all want to draw a ring here which is just parallel to this crater here so you have a ring here where we are trying to estimate okay and this ring has a thickness dy okay.

So you have a thickness here d Y and this ring is so small that you know you can consider it to be mostly like a an incremental ring you know and in the dy is very insignificant okay and typically although the dy is really along an angle but we can consider that the angle is not very matter able because we are having a very thin section here so having said that now the total volume that would come of the crater would really be the total area of this particular ring here and the area can again be obtained by looking at this radius of the annular small are let us say radius small R^2 obviously can be represented as the capital R^2 minus the ^{2} of Y okay.

Where y is the distance OA as I had earlier pointed out here along the Y direction so R small R or the radius of this annular is√R^2 minus y^2 so in this event the total volume would be obtained by looking at the area of this annular which are the volume of this annular which actually which actually can be represented as a cylinder of the radius R^2 minus y^2 so we have pi times of ^{2} of this radius of the annular r^2 minus y^2 times of height dy.

Where the Y really varies as you know from the point A to the point B and I had already expressed to the point A to B having you know a distance a^2 minus H^2 by 2 at c and be having a distance a^2 plus at C^2 by 2 at c so by solving this integral x solution of this integral you would actually arrive at the total volume of this crater VC so that is how the volume of the crater is represented as π by 6 at c times of three ^{2} plus HC^2 I am not going to do the detailed solution here.

Because I understand that you know I be able to take care of this integral you could just substitute the values of a and B in order to find out what is going to be the total volume of the crater so as HC is proportional to Z thus the Z value gives an indication of material removal by each spark and the figure below shows the theoretical Z values here for example and the Z value is plotted as a function of spark discharge time and you can always see that as the discharge time is increased the total amount of melting temperature depth.

Which is this Z maximum is also higher and higher for a certain pulse energy and for a certain diameter that we are trying to assume however it is also to be noted here that points with higher melting point may have this so it is indicated that you know the all these things that Z value the discharge time as well as the melting point that they are kind of related so if you look at the different melting points of this three material zinc aluminum copper.

So the melting temperature of copper let us say θ m copper is highest you know and then is for aluminum and then is for zinc and so this is the lowest melting point melting temperature and you can see here that the extent to which for a certain amount of spark power and for a fixed diameter in this particular case of melting temperatures egos is maximum if the θ is minimum okay θ melting is minimum zinc for example melts at 419 ° C visible copper which is at about close 2028°C or aluminum which is about 619 or 60 and about 600 plus.

Let us say so you can see that there is a parity in the way that Z is being estimated here with respect to the discharge time and also important is the fact that you know the discharge time but say if we look at as more you know in case of zinc this is really the point from which the Z value starts falling down that means there must have been the power switch off where the Z value has peaked beyond which the melt pool getting formulated in the distance getting small bigger between the electrodes would enable the electric field to go down from the breakdown field of the medium and the spark would extinguish.

So these are really the points where these park such park extinguishes beyond which the Z plot goes down okay and so you can see that for zinc this time duration of this park is also a little higher in comparison to aluminum or copper so that is about how the variation happens with different materials of different melting temperatures.

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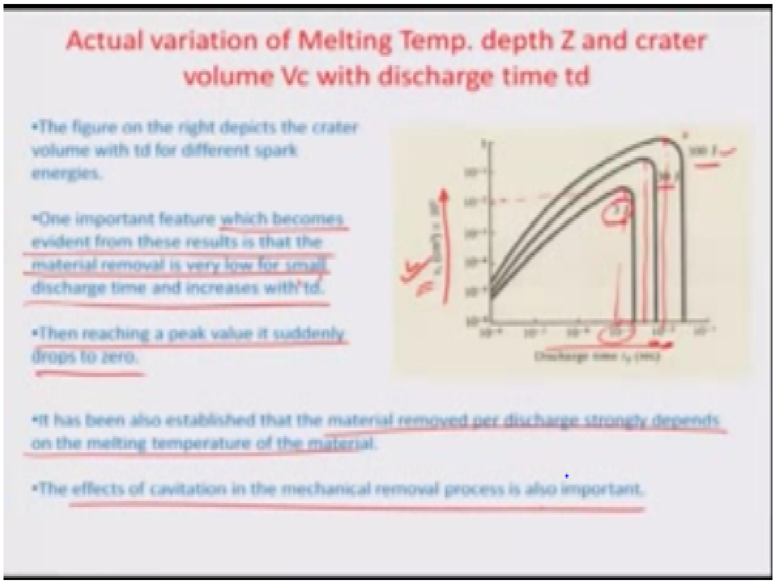

Actual variation of Melting Temp. depth Z and crater volume Vc with discharge time td

- The figure on the right depicts the crater volume with td for different spark energies.
- One important feature which becomes evident from these results is that the material removal is very low for small discharge time and increases with td.
- Then reaching a peak value it suddenly drops to zero.
- It has been also established that the material removed per discharge strongly depends on the melting temperature of the material.
- The effects of cavitation in the mechanical removal process is also important.

The actual variation of the volume of the crater or the material removed with respect to the discharge time is also shown in this figure right here and you can see that as the pulse the spark power is increased from 3 joule 2 30 joules 2 300 joules the crater volume that is formulated as 1000 so many 1000 centimeter $^{\text{cube}}$s is certainly more obviously this is the switch of time beyond which there is a change in the volume where it comes down and obviously the discharge time also as you can c is different.

So for a 10 to the power of minus to discharge time at a power of about 300 joules you could go and produce a greater volume which is close to 10 to the power of 3 centimeter cube okay or if the power is changed by a factor of 100 to three joules and the discharge time is changed again by two orders to about 10 to the power of three you could see that this removal rate can come again all the way down to about 10centimeter cube which is about a 100thof what happened in 300 joules.

So there is a parity with discharge time of the you know the total volume which is removed and also is a parity between the volume and the power so you have estimates which relates the Z or the melting temperature depth as a function of the material you have a steam eights which relate the volume total volume remove the volume of the crater as a function of the power that is being used in the discharge time.

So the one important feature which becomes evident from these results is that the material removal is very low for small discharge time and increases with TD okay when reaching a peak value is suddenly drops to zero that is another important thing so it has also been established that the material removed but the star strongly depends on the melting temperature of the material and the effects of cavitations in the mechanical removal process is also very important.

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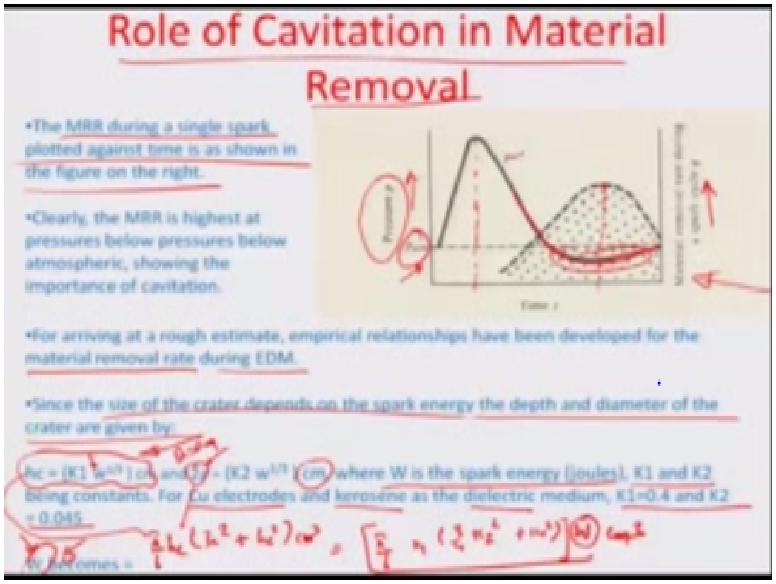

Role of Cavitation in Material Removal

- The MRR during a single spark plotted against time is as shown in the figure on the right.
- Clearly, the MRR is highest at pressures below pressures below atmospheric, showing the importance of cavitation.

- For arriving at a rough estimate, empirical relationships have been developed for the material removal rate during EDM.
- Since the size of the crater depends on the spark energy the depth and diameter of the crater are given by:

$h_c = (K1\ W^{1/3})$ cm and $D_c = (K2\ W^{1/3})$ cm where W is the spark energy (joules), K1 and K2 being constants. For Cu electrodes and kerosene as the dielectric medium, K1=0.4 and K2 = 0.045

V_c becomes =

Let us also look at the timing of the maximum material removal rate cavitations obviously plays a big role in material removal for already EDM processes if I look at the MRR during a single spark plotted against time it is reflected here this right side y axis indicates the material removal rate during a spark cycle q as a function of time and the left side indicates the pressure with respect to time as this parking happens obviously you can look at this plot and see that the maximum material removal rate is sort of time shifted with respect to the maximum pressure.

This is obvious because you know the pressure that is there mostly on the work piece in EDM is because of the electron pressure and there is a certain time duration at which the electron wave which is coming to hit the surface of the work piece has the maximum impact or the maximum momentum transfer which could be considered to be the point of the maximum pressure so here the pressure is much above the atmospheric pressure at such an instance of time and it is because of this compression shock wave that melting happens you know and the material gets completely molten upto the depth of melting temperature.

However that is not really a good time for the material to get remove because the pressure is still on and then once the alternate compression which is there the rare affection which is there comes in and the electron has been or the electron momentum has been completely sort of absorbed you can think of it that you know the EDM which is over and above the work piece has a higher inertial component in comparison to the electron and there would be a time delay for the medium to come and fill up that zone.

You know which has just been voided because of the sudden absorption of the electron at the anode remember is a cathode anode remember is a electron zinc so okay so all the electrons suddenly moving out in the region close to the anode may create a cavitations effect where they're the where maybe there is a case where the pressure even goes down below the atmospheric pressure you can see the pressure plot here that at the time where such a thing has happened.

In such an event has taken place the pressure actually goes below even the atmosphere pressure although the old fluid is maintained at an atmospheric pressure over the idiom is an open process open to the atmosphere but there is always a tendency of this inertial lag between the EDM and the fast moving electrons which may create a sort of a cavitations negative pressure differential with respect to the atmospheric pressure.

And so this is really the point where the material would be the most removed because of the pressure is lower than atmospheric pressure there is a tendency of the of the material to get pulled out into that pressure void or you know pressure differential so you can see that the plot of the material removal versus of these spark cycle happens at an instance of time maximizes and an instance of time when such a capitation effect is being felt okay.

And the electron wave has completely eliminated and there is a pressure less than atmospheric pressure in near the work piece where the material needs to be diffused within the liquid dielectric so that shows that how critical you know this process is process the EDM processes in terms of its material removal on the overall pressure that the electron would exert over the D work piece surface.

So material removal otherwise is a very complex you know thing to be estimated during an EDM because of all such integrate issues but there can be always an average rate estimation which may not really be a real time rate installation and since the size of the crater depends on the spark energy the depth and the diameter of the crater are given by again to empirical relationships here.

At c for example the total critter depth where the θ can reach up to θ M is given by K 1 w to the power of 1 by 3where w is the pulse power in joules this HC is represented in centimeters and 2a or the total diameter also there is an another empirical estimate which estimates this to BK 2 w to the power of1 by 3 centimeters w is the spark energy in joules and k1 and k2 are constants.

So for copper electrodes for example in kerosene is a dielectric medium k 1 k 2as an estimated to be 0 point for and 0.045 and if we apply the VC formula here which says VC equal to πby 6 HC times of 3 a ^{2} plus at C ^{2} centimeter^{3} I can simply apply or substitute the values of SC and a from these two empirical empirically arrived at relationships to find overall you know power dependence on the total volume rate of removal and this power dependence can be represented as π /6 times of k 13 x 4 k 2 ^{2} plus k1 ^{2} times of w centimeter $^{\text{cube}}$ okay.

So you can say that this constant right here which has been developed you know is a sort of proportionality between the Vc that is the material volume of the greater volume that has been formulated and the pulse power the spark power or spark energy in joules I am sorry not power but energy in joules which has-been applied onto the material surface so there are some empirical estimations again where you can talk about what is the relationship between the you know the material removal rate and the melting point of the material obviously.

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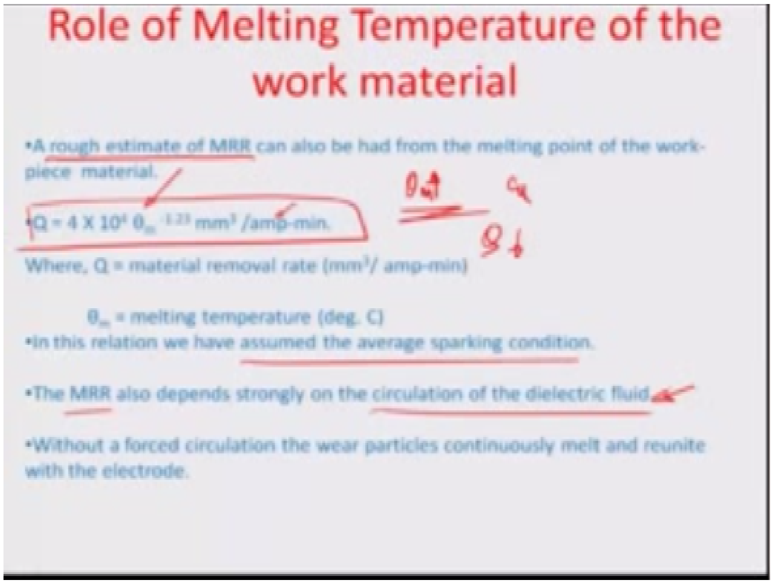

Role of Melting Temperature of the work material

- A rough estimate of MRR can also be had from the melting point of the work-piece material.
- $Q = 4 \times 10^4\, \theta_m^{-1.23}$ mm^3/amp-min.

Where, Q = material removal rate (mm^3/ amp-min)

θ_m = melting temperature (deg. C)

- In this relation we have assumed the average sparking condition.
- The MRR also depends strongly on the circulation of the dielectric fluid.
- Without a forced circulation the wear particles continuously melt and reunite with the electrode.

$\theta_m \uparrow$

$Q \downarrow$

If the melting point is higher then there is a possibility that the material removal rate may be smaller so rough estimate in case of you know MRR has also been empirically found out as q equal to 4 10 to the power of 4 θ m to the power of minus 1.2 3 millimeter $^{\text{cube}}$ per ampere minute 10 per minute is basically units for charge flown into the system and so you could say that if the θ m for a material is higher let us say in the copper example earlier we had taken three time to be higher material removal rate okay.

Obviously falls down because the ηm $^{-1.23}$ and we in this relation have assumed sort of average sparking condition also this is not a snapshot of really what happens with the onset of this park and the dying down of the spark it is actually only an average removal rate also if we circulate the dielectric fluid there may be a better MRR because of this circulation obviously because now you are trying to give very less relaxation time between once spark.

And the next set is very obvious that if supposing there is an establishment of a spark column there is always a tendency of this column to retain itself you know and these conducting characteristics unless the dielectric fluid comes and washes the column away so in this particular example or in this particular case if there is for circulation such relaxation time is changed and then the spark is in able to formulate more quickly or the spark frequency can be then taken up much easily.

So I think i will sort of stop here for this particular module and in the next module we will try to work out some more factors related to some circuits some power sources which would be feeding the EDM process and letting the material removal to occur so up till then goodbye and thank you.

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