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Course title
Manufacturing Technology- Part-2

Module-35

Mechanics of Electron Beam Machining Process

By
Prof. Shantanu Bhattacharya
Department of Mechanical Engineering,
IIT, Kanpur

Hello and welcome to this manufacturing process technology part 2 module 35

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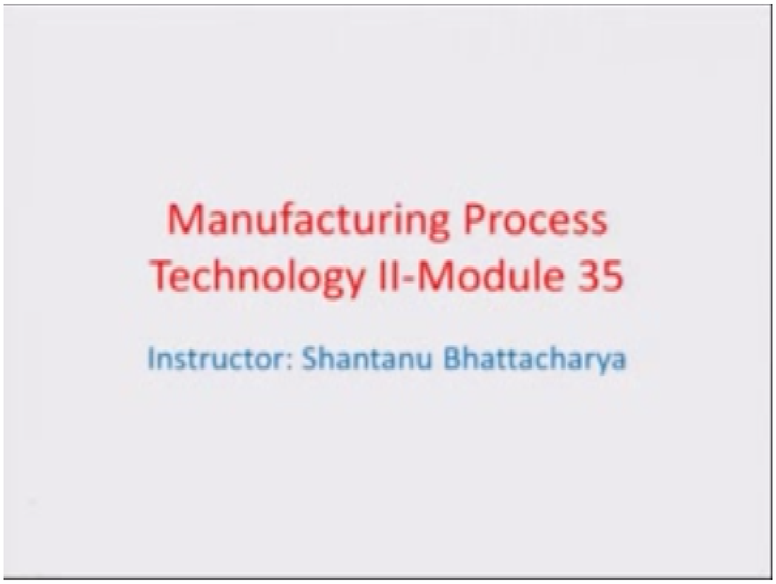

Manufacturing Process Technology II-Module 35

Instructor: Shantanu Bhattacharya

We were talking about EB machining in the last module and we also tried to guesstimate you know the power for a certain material removal rate and so there was a p equal to CQ relationship through which we got a ballpark value of the velocity at which scanning could happen of an EBM system if you want were to cut a slot on the surface of a metal substrate so let us look at a little bit of the mechanics which is involved or which is underlying of the EBM process really.

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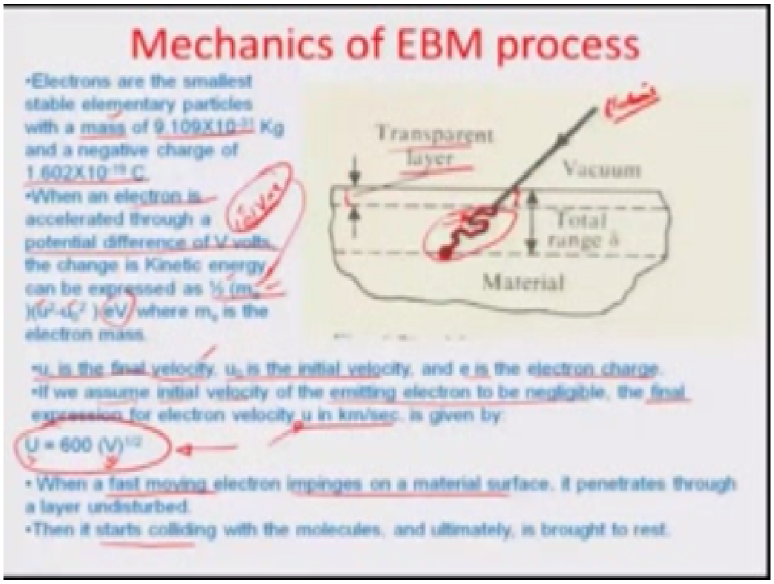

Mechanics of EBM process

- Electrons are the smallest stable elementary particles with a mass of 9.109×10^{-31} Kg and a negative charge of 1.602×10^{-19} C.
- When an electron is accelerated through a potential difference of V volts, the change is Kinetic energy can be expressed as $\frac{1}{2}(m_e)(u^2 - u_0^2) = eV$ where m_e is the electron mass.
- u is the final velocity, u_0 is the initial velocity, and e is the electron charge.
- If we assume initial velocity of the emitting electron to be negligible, the final expression for electron velocity u in km/sec. is given by

$U = 600 (V)^{1/2}$

- When a fast moving electron impinges on a material surface, it penetrates through a layer undisturbed.
- Then it starts colliding with the molecules, and ultimately, is brought to rest.

So as I already have illustrated the electrons are accelerated through a voltage and they have a very high overall velocity about probably close to that of light and this these electrons are actually falling on the material thus striking the lattice structure of the material and there is almost always that small layer of the material does not know if the electrons are so fast moving in nature so if the layer that is there is a shell layer that is there we does not even feel that there is a beam okay.

Which is hitting so you know if you look at some properties related to the masses of the electrons or the charge that they carry so you know that the mass of the electron is about 9.1×10^{-31} kg the charge is that the carries about 1.6×10^{-19} Coulomb and so the kinetic energy which would be obtained here is really half times of mass of the electron times of u^2 minus u_0^2 and this is electron volts where mV is the electron mass.

And obviously if electron is accelerated through a potential difference V volts the total amount of force that it experiences the total energy that it ultimately has is the charge on the electron times of the voltage times of the distance through which it is moving okay so for stress this product is the work done and that is actually equal to the kinetic energy half mV x $u^2 - u_0^2$ so if U were to be taken as the final velocity of the electron and u_0 was the initial velocity and is the electronic charge.

And if we assumed that prior to the emitting or just immediately after the emitting the electrons all had 0 electron velocities okay so or maybe very small electron velocities which are hardly comparable to the overall accelerated you know electron velocity that would result because of the perforated anode system you already here were of how the cup shape at tungsten filament creates the electron beams and focuses the electron beam into a perforated anode okay.

So the final expression that would come with plugging in all these values related to the electron mass the electron charge you know and the different let us say velocities which are taken into consideration and let us say the velocity use in kilometers per second further so this is given again with the relationship between the voltage that is there to accelerate the electron and the velocity in kilometers per second through a relationship be equal to 600 $v^{1/2.}$.

So this takes care of all the coefficients like the electron mass or charge which comes by this expression the total amount of work done equal to the kinetic energy okay and so when a fast-moving electron impinges material surface it should really penetrate through you know a transparent layer as I had illustrated earlier till the lattice starts detecting the electron and starts converting the momentum of the electron into kinetic energy okay.

So when the collision process starts to happen obviously that is going to be a temperature rise and so this curly path here is really representing the collision process which has happened below a few layers which have been crossed has a transparent layer by the high velocity or high moving electron and ultimately the electron is obviously brought to rest because all its energy has been transferred in terms of kinetic energy and the temperature of this particular layer has increased to the level so that it can start vaporizing.

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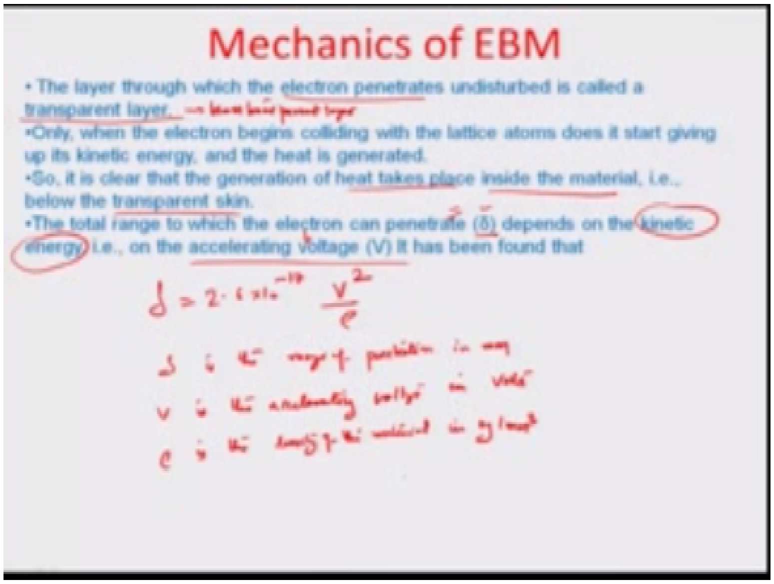

Mechanics of EBM

- The layer through which the electron penetrates undisturbed is called a transparent layer. → beam 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

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

δ is the range of penetration in mm

V is the accelerating voltage in volts

ρ is the density of the material in g/cm³

So the layer through which the electron penetrates again is called the beam transparent layer so this you must remember is a sort of a terminology so it is a beam transparent layer so it is basically as if the layer does not know that there is a EBM so the heat generation that would take place inside the material obviously below the transparent skin would result in you know an increase in the temperature to the melting point there would be your a vaporization point.

And typically there is going to be beams platter mostly because you know if there is a skin layer which is there on the top and there is some kind of a super heat that is given to the metal vapor that has been created in a small cavity or a pocket beneath the skin layer the skin layer would open up with a with an impact okay and so that can create what that can lead to some beams patterning.

So the total range to which the electron can penetrate let us say Δ in this case you know would really depend on few things like kinetic energy for example of the electron so higher is the velocity of the electron the thicker would be the penetration depth of the electron to the particular material surface and this further would depend on the accelerating voltage because the kinetic energy high means that the voltage through which electron has been accelerated is also quite high.

So the total penetration depth in this case which is also including the beam transparent layer so you can see here as the total range okay so it is a beam transparent layer may be Δ dash plus Δ double dash the total layer in which collision start to happen where Δ'and Δ" is equal to the total range of penetration or depth of penetration.

So that Δ is empirically related again to both the accelerating voltage as well as the density of the material which is being machined and in this case the empirical relation is $(2.6\text{x}10^{17})^2$ V okay the accelerating voltage is square divided by material density ρ so Δ is the range of you can say penetration and this is express 10 mmV is the accelerating voltage in volts and obviously ρ is the density of the material in kg /$\text{mm}^{3.}$

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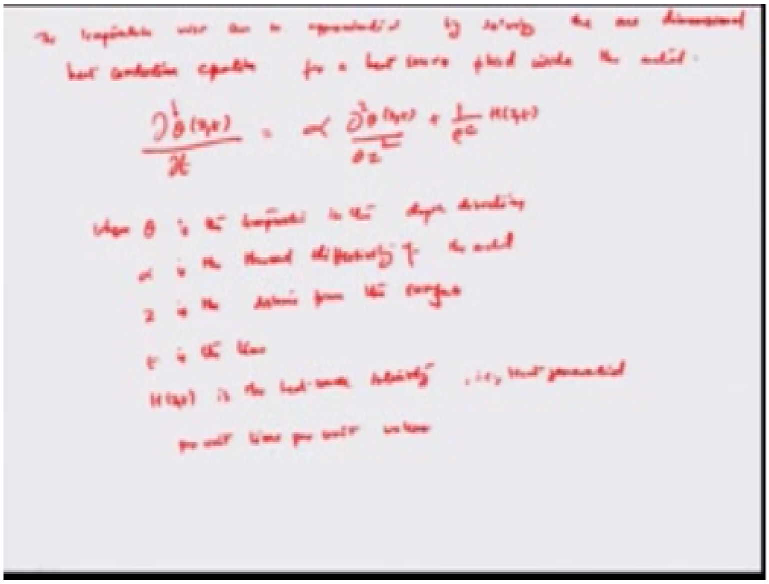

Let us look at a numerical design of this estimation of the Δ to get a ballpark idea of what is going to be the range of penetration depth in maybe while doing a normal you know even machining on steel okay so we designed this problem from a real experiment that during drilling of holes in steel work piece by EBM electron beam machining and accelerating voltage150 kV is used you have to determine the electron range of penetration.

So let us first look at what is the density of Steel so the density of Steel is about $76\text{x}10^{-7}$ kg/mm^3 and penetration depth therefore can be given by the expression $2.6\text{x}10^{-17}$ times of 150 kilo volts which is being used for the EB machining in this case so square of that okay divided by the density which is $76\text{x}10^{-7}$ and this can be reported in terms of millimeters then so this becomes about 77μ.

So you can already think of the extent up to which an EBM can penetrate its 400 μ which is close to the diameter of a human hair so this much is the kind of penetration depth that would happen if the EBM were to strike on a surface obviously as the process is in you know happening continuously as a function of time the extent up to which the delinquent could be a through-hole as more and more heat is added and more and more you know layers are disturbed within the surface.

But for one such strike or one such penetration of the electron beam material an extent of two about 77 to 80 μ is the only kind of penetration depth which is covered you know in the process of doing this EB machining so let us now look at little different aspect about EB machining and that is about trying to estimate what is going to be the temperature rise and trying to estimate what is going to be the depth of penetration through a heat conduction formulation.

And again just as I did in the EDM process in this process also i would typically look at only the governing equations and maybe the boundary conditions and then try to evaluate the solutions of those equations using the boundary condition so that should get an estimate of what is going to be the maximum temperature or the maximum depth of melting temperature or in this case vaporization temperature which may happen.

So let us estimate that from first principles let us say the temperature rise can be approximated by solving the one-dimensional this is only a simplistic model heat conduction equation for a heat source placed inside the metal okay you know that in this case you know it is not a surface driven heat flow but actually the heat pocket that has been generated as within the material in this particular case.

In EDM of course we looked at only a you know a heat flow which starts from the surface in words and because of a spark coming and hitting the surface and disturbing you know layers from the surface layer on words in this case the heat pocket is below the transparent layer you have to remember that okay so placed inside the metal so if you look at a one dimensional heat conduction problem this way so you have ∂θ as a function of Z which is the depth okay.

And time T / ∂Tθ is temperature here okay is equal to the thermal diffusivity α or the material times of ∂l2 ZT by ∂ T 2 of ∂ I am sorry ∂Z2 +1 /ρ times of C times of the heat source and center intensity which is also a function of depth Z and the time T HZT okay. so here the various terms mean θ is the temperature in the depth direction from the heat pocket okay α is the thermal diffusivity α is the thermal dense diffusivity of the material metal and z of course is the distance from the surface t is a time and HZT is the heat source intensity you can say that it is the heat generated per unit time per unit volume so that is at zt.

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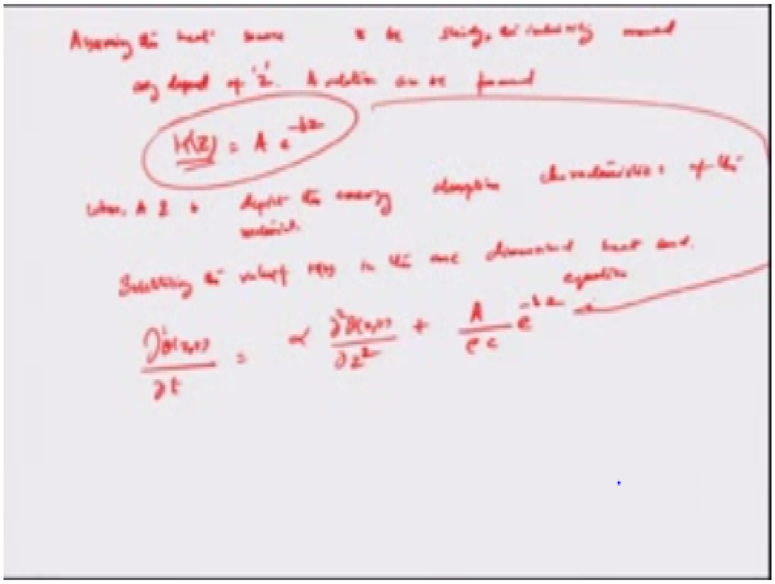

$$H(z) = A e^{-bz}$$

$$\frac{\partial\theta(z,t)}{\partial t} = \alpha \frac{\partial^2\theta(z,t)}{\partial z^2} + \frac{A}{\rho c} e^{-bz}$$

So if we assume the heat source to be a steady heat source you know the intensity would only depend on the depth from the surface and not time right so you know you can you can actually have a relationship a relation can be framed where HZ the heat as a function of distance from the surface $Z=AE^{-pz}$ okay A and B are sort of the energy absorption characteristics of the material so where I can say a and the small Tom be here depict the energy absorption characteristics of the material.

So if I just wanted to substitute this value back into the governing equation that I had earlier you know salt so substituting or earlier lade outlet so substituting the value of Hz in the one dimensional heat conduction equation we get this Dθ as a function of Z and T by DT okay so the variation of temperature is with respect to time would be α times the second differential of the temperature with respect to space is at T that is square plus a by ρC^{-vz}.

So this is what the value of H set comes out to be it is no longer time dependent because we assume that to be a steady heat source so the function of time it does not change only changes with said you can the depth from the melting temperature so now let us also further assume some boundaries.

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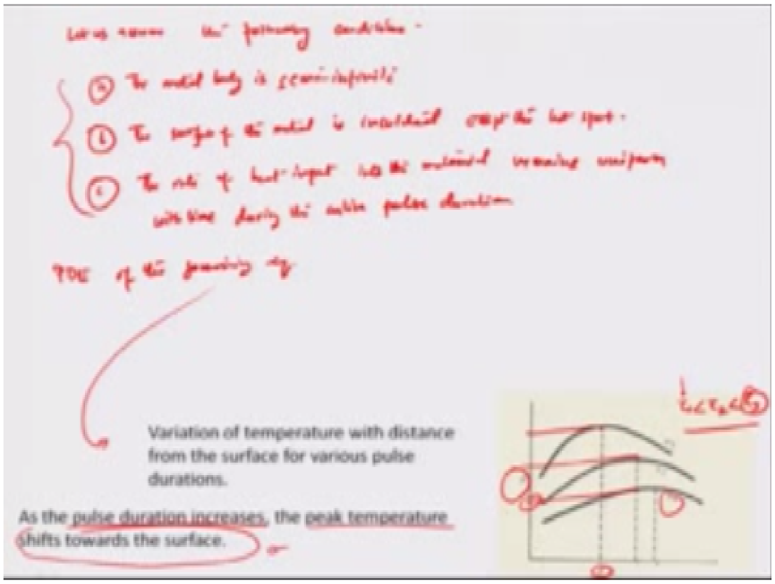

Variation of temperature with distance from the surface for various pulse durations.

As the pulse duration increases, the peak temperature shifts towards the surface.

So we assume the following conditions one is that the metal body is semi infinite that we are looking at so the metal body is semi in finite okay we can also assume that the surface of the metal is insulated except the hot spot and we can further assume that the rate of heat input remains uniform with time particularly during the duration of the EBM pulse okay so the rate of heat input into the material okay that remains uniform with time during the entire pulse duration.

So with these three conditions if we were to solve the pd of the governing equation we will get these you know trends of the variation of temperature with respect to Z and as you can see here that four different pulse durations for example t1 is probably lower in comparison to t2 in comparison to t3 is the highest duration of the pulse the values of maximum temperatures are also different okay.

So for a lower duration EBM a low radiation EBM pulse the temperature arrived at is quite obviously lower in comparison to offer a higher duration EBM pulse and also the very fact that you know if the time duration of the EBM pulses more and you have the maximum temperature the maximum hot spot which reaches within the material at a lower value of beam depth in comparison to that of lower value of pulse.

Because obviously it is a conduction process and you can think of it that the material is conducting out in outwardly manner from the vapor pocket which has been formulated and of you know there is there is going to be if supposing the duration of the EBM is more than probably you know the heat conduction time also is given to it is very, very high in comparison to a single small pulse of the EBM.

So you can think of it in this manner that as the pulse duration increases there is going to be homogenous a shin of the of the temperature within the material and the very fact that there is a boundary outside you know facing the atmosphere where most of the heat reduction would actually happen from the vapor pocket it would seem for a higher pulse duration that the peak temperature sort of should shift towards the surface.

So the various Z values which are reported from the surface or the vapor fact pocket which has been formulated for a higher duration pulse would be nearer to the to the surface because it has enough relaxation time I guess between the pulse on pulse of durations for the heat to be properly distributed okay so that the depth would not be much of an issue there but if it is a sudden impact process of a shorter duration then the EBM transparent layer would obviously be thicker and it would have very less time to relax and conduct the heat and outwardly manner as if you are localizing the heat in the vapor pocket which has been created at a few layers deep within the surface.

So that is the reason why you know the temperature would kind of the maximum temperature of the peak temperature would kind of be nearer to the surface for a higher duration EBM or higher pulse duration and a lower pulse duration so these are some of the learning is that we have from the solution for temperature as a function of Z and T remember in this case it is quite different from the case of a spark machining process where it was a surface inward driven phenomena here it is a vapor pocket out were driven phenomena.

So the two are completely different in terms of the basic physics in the mechanism that goes in for doing the machining operation so I had earlier talked a little bit about you know how the scanning velocity can be affected as a function of power and we had generated a very first estimate or a guesstimate of the power versus MRR let us now look at a little alternate way of arriving.

At this through semi experimental means and we will perform some dimension and analysis based on the parameters which we think are important for this whole beam material interaction process and through the dimensional analysis will probably arrive at some governing equation where we could actually correlate all these parameters together where there could be the velocity of scan there could be the melting temperature of the material there could be the thermal conductivity of substrate there could be the beam evaluated so on so forth so that we have a nice estimate of a more appropriate estimate of the of the scan speeds of the beam.

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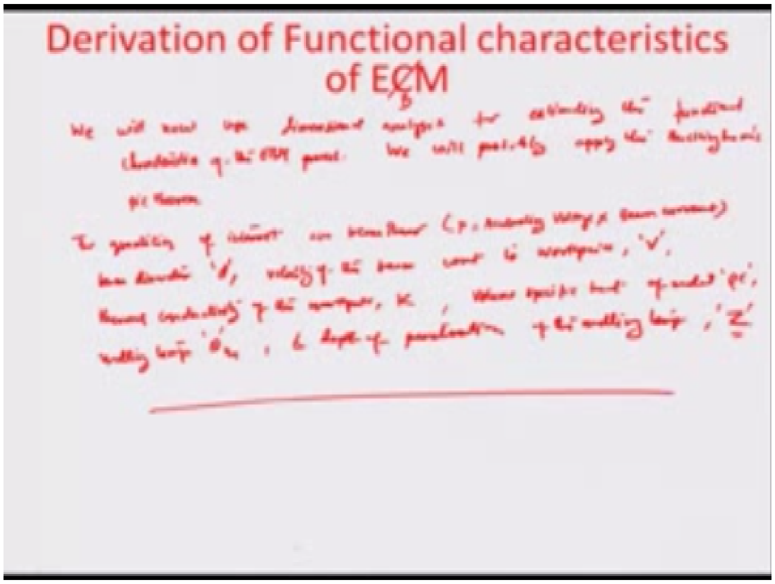

Derivation of Functional characteristics of E~~C~~BM

So let us actually look at such process this is EBM sorry a BBM so we will use we will now use dimensional analysis for estimating the functional characteristics of the Embraces and we will probably apply the Buckingham pie theorem here but before doing this we probably try and have a look at what are going to be the most important parameters for a process of B matter interaction in the EBM machining case.

So the quantities of interest are obviously EBM power again so you could have the power as a accelerating voltage EBM current product so accelerating voltage into EBM current that is what mean power is going to be you have a EBM diameter D you have velocity of the EBM with respect to the work piece I will call this V will also have another important property which is very much related which is thermal conductivity of the work piece itself of the work piece this is the value K obviously the volume specific heat of the metal.

So volume specific heat of metal which is ρC in this case the melting temperature we call this θ melting okay and depth of penetration of the melting temperature which is going to be Z so you have to understand here that we are talking about you know from the vapor pocket what is going to be the depth on words which would lead to the formulation of the melting zone so the temperature estimation would be done in a manner.

So that t equal to t melting you know so to include a zone behind aside or beside the or around the vapor pocket which would create a melt pool you know because of the zone conducting heat in an outwardly manner from the wake of paper pocket which has been formulated within a few layers of depth of the of the material so these are in general all the parameters which are associated with the EBM matter interaction in this particular process and what we are going to do probably in the next module is to sort of create some groups some non-dimensional groups which are going to be important for the Buckingham PI analysis Buckingham analysis.

So that we are arriving or we are able to arrive at dimensionally consistent relationships between these various parameters and then later on we can also have some empirical you know experimental empirical relationship to correlate to the to the relationship formulated by dimensional analysis so that we can get an appropriate expression for the beam power versus EBM depth so with this I would like to end up this particular module and in the next body you will we will probably do further analysis on this EBM power to depth thank you and good bye you

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