Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Manufacturing Process Technology-Part-2

Module-36
Functional Characteristics of EBM Process Edit Lesson

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Hello and welcome to this manufacturing process technology part 2 module 36.

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We were talking about UV machining and we were also talking about a numerical estimation through the Buckingham pi theorem of the beam matter interaction which would lead us to a sort of a, you know at least the governing power law with which we can relate the various parameters related to the process.

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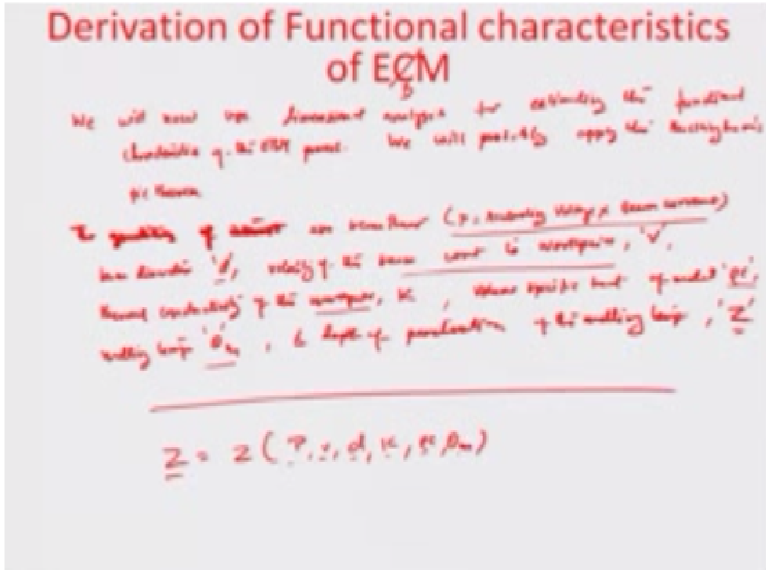

So in context of that we had actually figured out some quantities of interest, you know related to the functional characteristics of an EDM process. And here the main characteristics for the beam power which was a voltage current product, you know the accelerating voltage of the beam current product, the diameter of the beam D, the velocity of the beam with reference to, with respect to the work piece, also we were interested in the thermal conductivity of the work piece K, the volume specific heat of the material which was been removed, which is density and specific heat product.

And then we were also interested in the melting temperature and also the type of penetration Z of the melting temperature to happen. So with this we would like to now try to estimate some dimensional groups which are going to be, so non-dimensional groups. So our functional relationship finally would be that the Z, the type of melting temperature is really a function of all these different parameter, the P power, the velocity of scan, the diameter of the beam, the thermal conductivity K, the volume specific heat which is the density specific heat capacity product, ρc and the melting temperature θm.

So have been said that, let us try to express all these basic quantities, all these different quantities in terms of some basic dimensions like mass, length, time, temperature dimensions.

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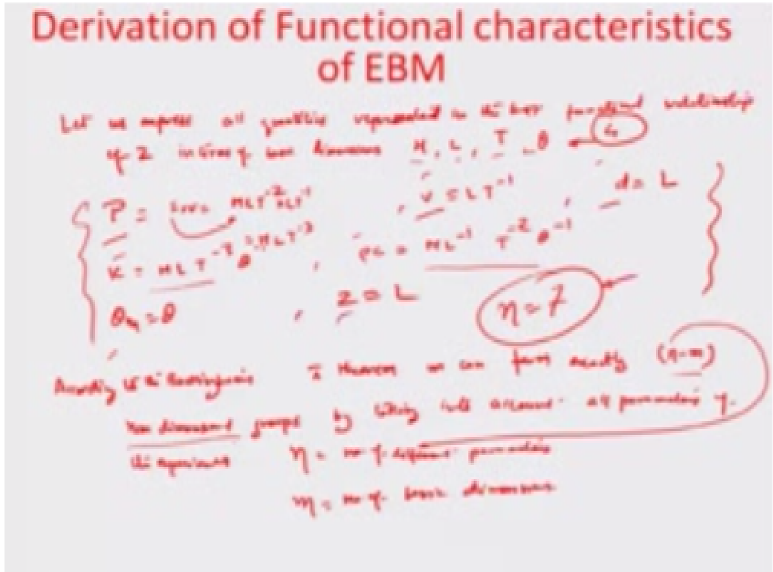

And let us look at what are the effectively the basic dimensions which come out of all this different parameters. So let us express now, so I am just applying Buckingham pi theorem here. So let us express all quantities represented in the last functional relationship of the depth of pitting to Z in terms of basic units, of basic dimensions. M is for mass, L is for length, t is time units, and θ is temperature units.

So for example, if you look at power, power is nothing but, you know its force velocity products, so you have MMT-2S the basic unit for force, mass acceleration product, times of the velocity L t-1. So therefore, this basic representation of power would be in terms of MLT-3. Similarly, velocity V is LT-1, diameter again is the length unit, so you have L and the dimensional representation of thermal conductivity K is given by MLT-3 θ-1, and just wanted to make sure that these things do not interfere.

So – 1 and then we have the volume specific heat ρc product which is $Ml^{-1} T^{-2} \theta^{-1}$ and θm is again θ z basically z = l okay so these are the basic representation all these different parameters that we have pointed out in the last step in terms of basic digestions that is the mass length time and temperature digestions I am not going into details of each and every one of these because these are very elementary how you where right at them.

And let us now see what the Buckingham Π theorem has to say so according to the Buckingham Π theorem we could we can form exactly n – m non dimensional groups by taking into account all parameters of the experiment okay so in this particular case there are about 7 different parameters as you can see here so n is the number of okay so let me just comment about nm here so n is the number of different parameters and m is the number of basic dimensions where all these parameters are being represented.

So you have 7 different parameters here power velocity diameter of beam thermal conductivity the specific heat volume specific heat capacity and temperature θ and z being the depth pf melting temperature so there are about 7 different basic parameters related to the experimental process and you are representing them in terms of 4 basic dimensions you know that is the mass length time and interpreted dimensions so you can exactly have 3 groups here right so n – m non dimensional groups can be taken into account or can be formulated okay so let us now look at.

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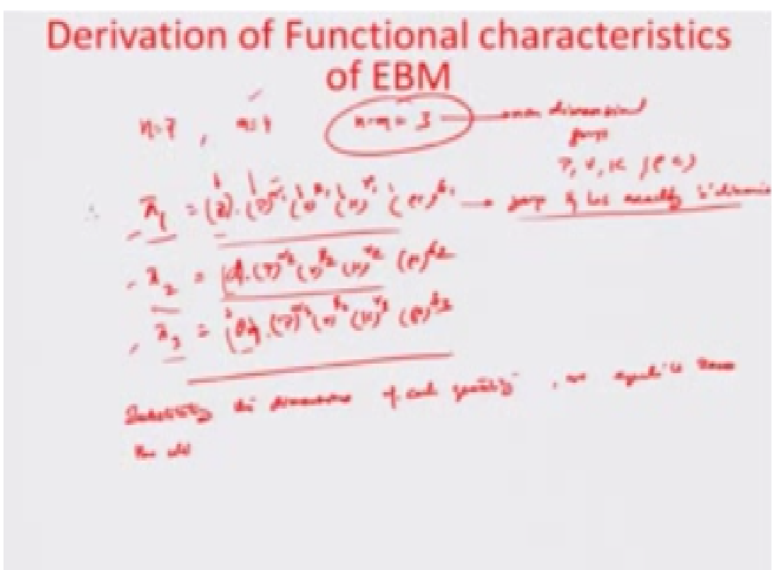

In our case n = 7 number of parameters m = 4 so you have n – m = 3 so you have 3 non dimensional groups and the idea is that all these groups have formulated they should be able to represent themselves in terms of one and other so that ultimately we can get at least a power law relationship between the basic dimensions so here for example if we where to introduced 3 different groups let us say we try to formulate you know group Π_1 which is again non dimensional and we will some see how to do or how to make it dimensional.

So let us assume these groups to be linearly related in one case to the depth of melting temperature z another case may be to the beam diameter and 3rd in to the depth of all the or to the melting temperature of the material okay so in one case let us assume a non dimensional group Π^1 being formulate by the other different parameter which are mostly involved a part from the Z, d and θm so apart from, these 3 parameters the other parameters which are involved in all the analyses are the power p the velocity of the beam v in thermal conductivity k and the volume here specific heat capacity ∂c.

So these are the basics three dimensions where there are linearization of the power of these with respect to the non dimensional groups and let us assume that we have a coefficient or we define a coefficient α β and γ where you know the substrates changes between α1 β1 γ1α2β2γ2 and α3 β3 γ3 between the three non dimensional.

Groups here so the first one has a linear power of z times of $V^{\alpha 1} V^{\beta 1} K^{\gamma 1} \partial c^{\Delta 1}$ okay such a that the group 51 has exactly the c row dimensions, so I am just trying to linearization in terms of one of the parameters okay and I am trying to make groups for all these you know three different parameters where the whole linearly into each group you know the zd and θm which they go linearly, into each of this non dimensional groups and the other 4 parameters which are left over and apart from the parameters which are linear in this 3 non dimensional groups are.

To be raised to certain powers so there ultimately the group has a 02 dimensions similarly in the case of the second equation we have $P^{\alpha 2} V^{\beta 2} K^{\gamma 2} \partial^{c}$ Δ2 and the third case which goes linear and θm we have a $P^{\alpha 3} V^{\beta 3} K^{\gamma 3} \partial^{C}$ of Δ3 and that is how the working m by theorem is applied, so we need now to calculate everything in terms of basic dimensions remember basic dimensions are four that is mass length time and θ and try to find out what are the values related to α1 β1 γ1 ∂1 and similarly.

In all the and all the equation is α2 β2 γ2 ∂2 and α3 β3 γ3 and ∂3 so substituting the dimensions of each quantity, we equate to 0 the ultimate exponent of with basic dimensions by already mention that πi is r non dimensional groups are non dimensional numbers okay, so let us look at what happens to individually these equations okay, so we have for example in the first case.

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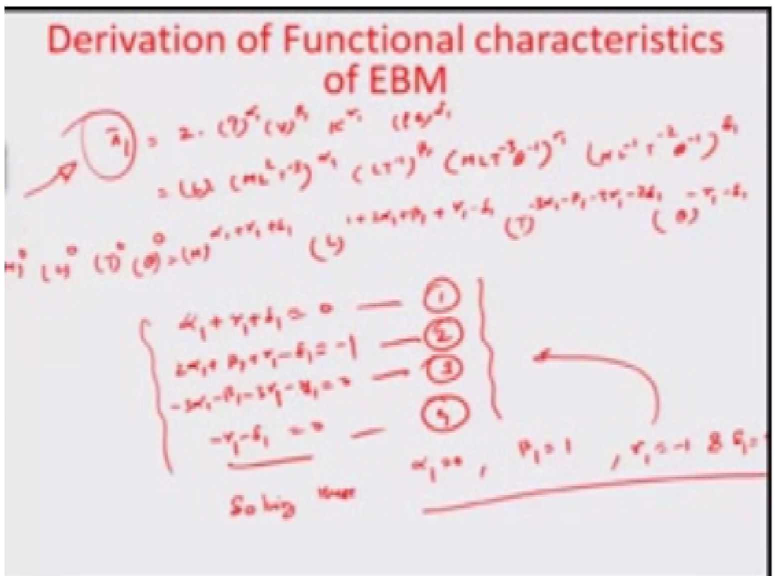

By one case we have z times of $T^{\alpha 1}$ $V^{\beta 1}$ $K^{\gamma 1}$ ∂^{C} of $\partial 1$ this comes as dimension l times of dimension for power which is m l 2T – 3 is borrowed from earlier to power α1 + one dimensions of velocity LT – 1 to the power of β1 + that of thermal conductivity which is mLT – 3 θ – 1 to the of γ1 times of this ∂C the volume specific heat capacity was represented in terms of dimensions. I am sorry $(ML^{-1} t^{-2} \theta^{-1})^{\delta 1}$ so if I word to symbol all the different basic dimensions together in this algebraically we will be getting you know $M^{-\alpha 1 + \gamma 1 + \delta 1}$ okay. We get $L^{1 + 2 \alpha 1 + ß 1 + \gamma 1 \pm \delta 1}$ because this ML^{-1} in this particular case the last groups case.

So –δ1 and then we have time units T to the power of -3 α1 – ß1 – 3 γ1 – 2 δ1 and then temperature units which are –(γ1) and – δ1 and so all of these are equal to M^0 L^0 T^0 and θ^0

remember the group the whole group has such has basic dimensions 0 it is a dimensionless group that we are talking about, so we are left with four linear equations here where $\alpha 1 + \gamma 1 + \delta 1$ is 0 and $2\ \alpha 1 + ß1 + \gamma 1 - \delta 1$ becomes equal to -1.

And $-3\ \alpha 1 - ß1 - 3\ \gamma 1 - 2\ \delta 1 = 0$, $-\gamma 1 - \delta 1 = 0$ so these are set of four equations linear equations with four variables which can be easily solved and we are left with so solving these we are left with $\alpha 1 = 0$, $ß1 = 1$, $\gamma 1$ is -1 and $\delta\ 1 = 1$ you could actually substitute this back and put or may be solve using gauss elimination or just normal substitution method and could actually be able to get the different values of $\alpha 1$, ß1,$\gamma 1$ and $\delta 1$.

So if where to put all these values back into the $\Pi 1$ which was initially assumed to be a non dimensional growth the $\Pi 1$ this would come out to be.

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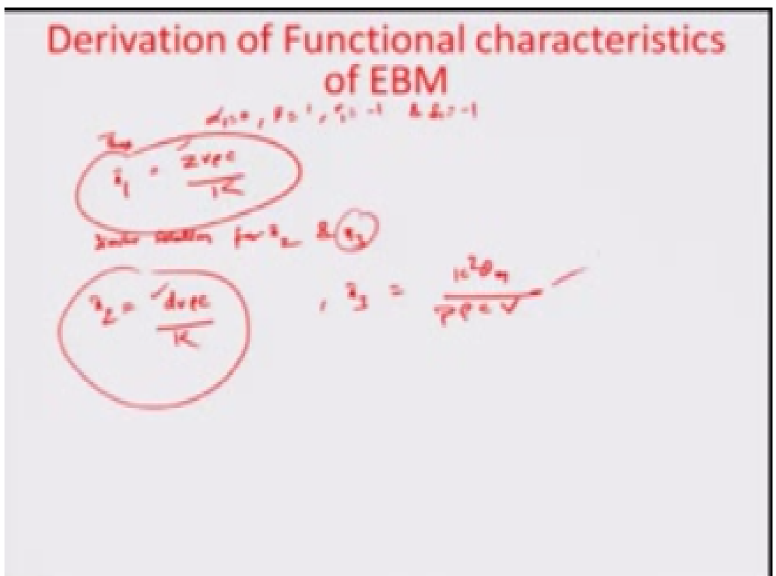

Z v ρ c k with the value of $\alpha 1 = 0$, ß= 1,$\gamma 1 = -1$ and $\delta 1 = -1$ we do similar solutions for $\Pi 2$ and Π 3 groups and in case I am not going into details of the calculation here you are welcome to do it yourself in the same manner that I did for $\Pi 1$ okay, so $\Pi 2$ becomes = dv ρc/k and $\Pi 3$ becomes equal to in this case k^2 θm/ρcv times of power so these are the three groups that are being formulated obviously you can think of the similarity between Π 1 and Π.

Because both of them had linear dimension in length one was indicating the depth of pending temperature z another was indicating the diameter of the beam both are length of dimensions and length dimensions were going linearly so obviously the other portion of the group would be similar in terms of their αβγ and Δ values for π3 it is a slightly different because we are now talking about temperature as a basic variant which goes linearly into the π3 and therefore k2θm/ρp(ρc) volume specific heat tomes of the velocity at which the beam can be rastered, okay. So that is how all the three coefficients π1, π2 and π3 are related.

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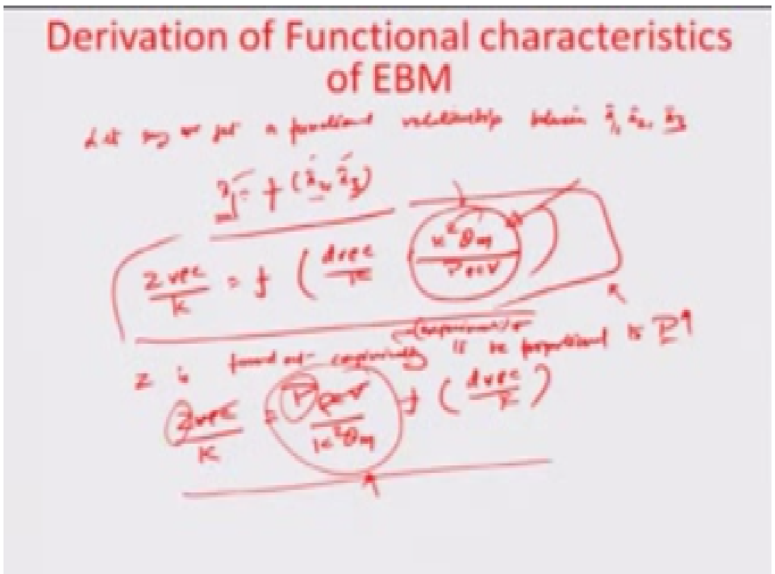

And let us say now you know assuming again further along the way, let us say we get a functional relationship between π1π2 and π3 as π1 is a function of let us say π2 and π3, now this could be either way it could be π2 as a function of π1 π3 or π3 is a function of π1 π2 the only thing which would happen here is that we have to somehow be able to correlate only on the dimension front that it should be consistent.

So you have π1 whish is a non-dimensional number as a function of two more non-dimensional number so dimensionally there absolutely consistent and there is no question in this particular presumption and π1 already was a group which was having ρ sorry z vρc/k and this would be a function of ρ2 which is a group d vρck and π3 which is a gorpu k^2θm/ρρcv okay, so that is how the functional relationship would actually exist and now we try to see what we have in terms of experimental or empirical information from the experiments.

And we have that you know z is found out empirically to be proportional so this empirical happens from experiments so obviously so you can say that this knowledge is brought from all experiments to be proportional to, so this is more from a regression analysis point of view proportional to the power p okay, so as the p increase the depth of melting temperature z also increases. So therefore, if we had this kind of a relationship which is linear in power we may as well have to reward back the presumption here which says that this was inverse the z was inversely proportional to the power.

So we can actually write the relationship here as $z\rho vc/k$ equals this $\rho vc/k^2\theta m$ and a function of let us say $Dv\rho c/k$ it is no harm because again this group is absolutely 0 dimensional so if it is even the inverse of this group or you know the group directly both of them have no dimensions and the dimensional consistent in this equation still holds even if it is the inverse okay, but here we are getting though closeness to the empirical estimation determine from the experiment which says z is proportional to the power and that is something that will be important here for you know the prediction of this whole formulation. So therefore, we have now if I just wanted to cancel a few terms here we will having over left with a new.

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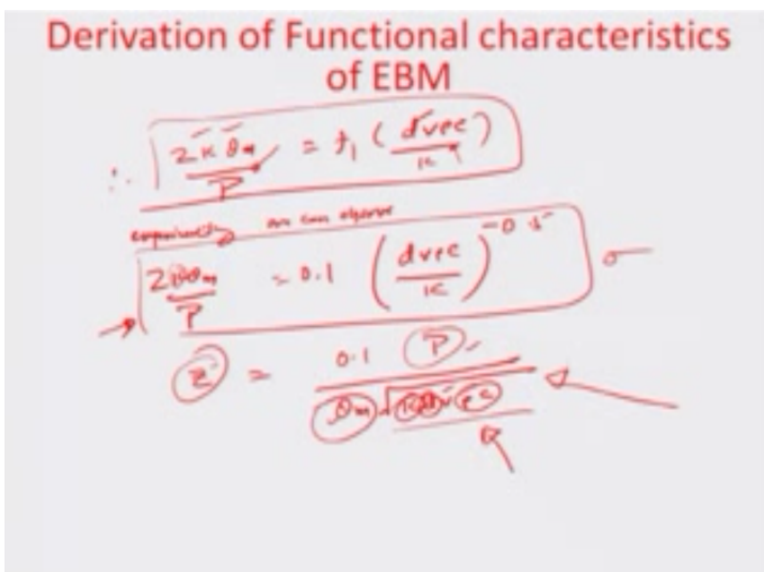

Relationship z k θm / p is a function of zv ρ c / k okay and now you can actually have a predetermined experiment, so experimentally one can absorb that the actual z k θ m / p is nothing but 0.1 times of $(dv\, \rho\, c / k)^{-0.5}$ so this is a completely regression experiment imperial relationship that you may say and what essentially it brings us to that we are maintaining dimensional consistency to our ivied of final formulation which we are now empirically investigating with there the relationship between you know the parameter which has been formulated here and the parameter which has been formulated here.

So such a relationship existence so therefore we can say that actually this z value comes out to be 0.1 times the power value / θm times of √ kd v ρ c okay. So you can just sort of you know because there is a k term here you bring the k this is $k^{0.5}$ so this √ kvdvρc comes through that method and so z is inversely proportional to the melting temperature which is a very good to go assumption obviously if the melting point is higher the amount of conduct the penetration of the beam would be lower and so is the power is the power is higher the depth of penetration z is again higher.

So from the to the empirical relationship you can already absorb the power of this technique that we could arrive at an actual formulation using a non-dimensional analysis where all these different parameters the velocity the volume heat capacity the conductivity of the material the beam diameter the depth of melting temperature z the melting temperature itself θ m power cold all be correlated to arrive at some you know ball park relationship which would be more accurate in process related to EBM machining.

Let us just look at the same experiment that we had conducted earlier numerically an arrived at some velocity in that case it was I think about 4.6cm /s that are derived at in probably one of the modules where we were talking about the velocity of scan you know of a particular EBM, in this case the velocity actually obtain through this empirical analysis is much semi empirical analysis much higher as you will see.

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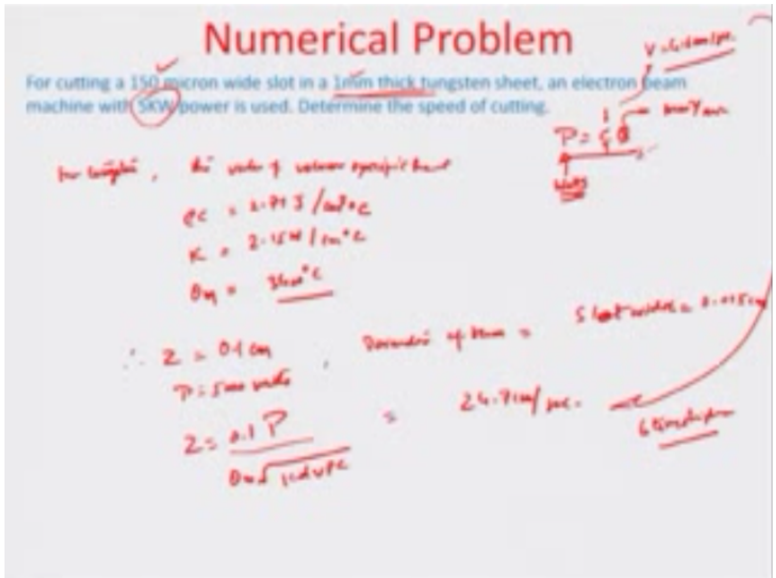

So let us go back to the earlier problem were from the guess estimate relationship between power and material removal rate remember power was in watts and this cube value was taken to be millimeter cube per minute and this C value is were all estimate empirically we had for a 150 micron wide slot of 1mm thick tungsten sheet.

And with the electron machining beam machining carried out at 5 kilo watt power we had a speed estimate of about close to 4.6cm per second okay by this relationship this estimate relationship be equal to C^3 let us look at our new formulated relationship here and for tungsten for example the value of volume specific heat can be estimated ρ_c to be 2.71 Joule per cm^3 degree Celsius the thermal conductivity K for the tungsten can again be estimated a 2.15 watts per cm degree Celsius.

The melting temperature ζm for tungsten temperature is about very high $34100^{\circ}C$ and we get that you know the so the Z value therefore in this case is 1 mm because beam has to penetrate through the thickness of the tungsten sheet 0.1cms and the diameter of the beam obviously should be equal to the slot width equals slot width and in this case the beam diameter for that to happen should be about 150 microns about 0.015cms power of course 5 kilo watts so 5000 watts.

And you know the velocity arrived at therefore from the relationship Z is equal to 0.1P/ θm root over $Kdv\rho_c$ is around 24.7cms per seconds so it is about 6 times higher as you can see 6 times higher then what was the predicted by the guess estimate you know with reference C values. So this is more appropriate expression that you know that actually leaves to prediction of the cutting speed or cutting velocity of an EBM system.

So I think I will stop to close on this module here and you know in the next few modules we will discuss about little bit about you know the effects of EBM's on the various materials and then probably start an another topic of interest which is the laser beam machining system so with this I will close this particular module thank you and thank you being with me bye, bye.

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