Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Manufacturing Process Technology-Part-2

Module-40
Modelling of LBM processes

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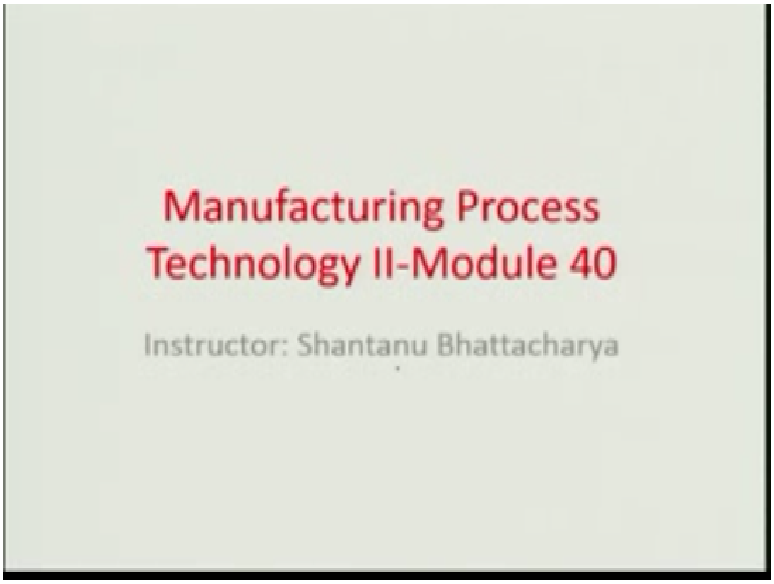

Manufacturing Process Technology II-Module 40

Instructor: Shantanu Bhattacharya

Hello and welcome to this manufacturing process technology part 2 module 40. There was a slight delay in the lectures, lecture modules, because of some logistic issues going to do sort of complete whatever was left over in the seventh week. And this particular week in the following one or two days, and probably by Wednesday we get everything posted. So thanks for bearing, I think you already have an immune in the chat platform from my TDTA's were briefed who had given you and shared the notes that I am going to do in the following few lectures.

So today we are going to just take off from the point we left earlier which was about laser machining and what we had discussed was really the minimum input power which was needed to melt the material on a laser machining surface which would be related to KθM/D where D is the spot diameter of the laser, K is the thermal conductivity and θm is the melting temperature of the particular work piece material.

So having calculated the minimum input power to melt the material, the next goal is that how the heat conduction would take place once the, let us say a deep and narrow hole is created or laser drilled into a sub state. So today we are going to look into that aspect and we are going to see what is going to be a sort of a steady state approximation in the way that a hole penetrates or a whole gets formulated by a laser beam falling on a sub state.

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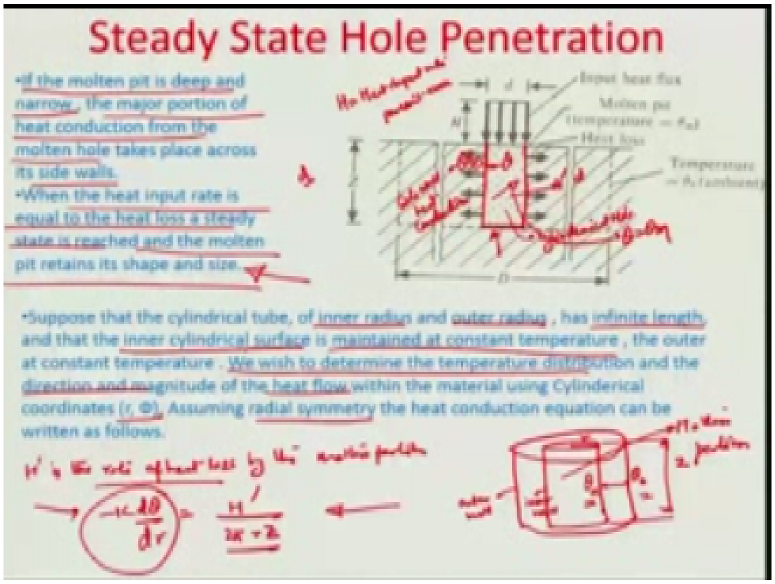

Steady State Hole Penetration

- If the molten pit is deep and narrow , the major portion of heat conduction from the molten hole takes place across its side walls.
- When the heat input rate is equal to the heat loss a steady state is reached and the molten pit retains its shape and size.

- Suppose that the cylindrical tube, of inner radius and outer radius , has infinite length, and that the inner cylindrical surface is maintained at constant temperature , the outer at constant temperature . We wish to determine the temperature distribution and the direction and magnitude of the heat flow within the material using Cylinderical coordinates (r, Φ). Assuming radial symmetry the heat conduction equation can be written as follows.

H' is the rate of heat loss by the molten pit

$$-K\frac{d\theta}{dr} = \frac{H'}{2\pi r}$$

So let us look at that, so if the molten pit is very deep and narrow as you can see here in this figure right about here, the major portion of the heat conduction from the molten hole takes place across its side walls. So these are the holes here represent, you know the side wall heat conduction which is happening from all directions assuming this to be a cylindrical hole.

So when the heat input rate is equal to the heat loss or steady state would be reached and the molten pit remains or retains its shape and size, because now whatever you are adding here as inhibit a portion of the material to hit a condition of θ = θm while the inflow and outflow are balanced now and there is a certain state of temperature in a state of equilibrium which is established so that the hole shape and size does not change anymore.

So let us suppose that, you know we balance or we try to represent this heat conduction problem in terms of a cylinder where that inner walls and outer walls maintained at two different temperatures. So let us say there is a concentric and newer cylinder which we are considering. And so, we have a situation where the cylinder is having an inner and outer radius and it is a cube that we are considering with a certain wall thickness around.

Further we assume that the cylinder has infinite length and that the inner cylindrical surface is maintained at a constant temperature which is equal to the melting temperature of the material. So you know that within this particular zone are shown by the dotted geometry, you have θ=θm or melting point of the material is reached in this particular zone. So the wall temperature as well is that θm okay.

And it is being the end at that constant temperature assuming that the hole has fully penetrated and occurred and θ is now equal to θm in that zone which we call the hole. The outer temperature of course is also a constant temperature, so we have the outer temperature as θO here constant temperature. And we wish to determine the temperature distribution and the directional magnitude of the heat flow within the material using cylindrical coordinates R and ϕ.

Further we assume radial symmetry and try to look at what would be the heat conduction equation between the inner wall and the outer wall so this is the inner wall of the tube and this the outer wall of the tube so if supposing h dash is the rate of heat loss by the molten position which is actually inside the cavity here this is the molten portion okay.

Just estimating something under real sense as in this doted region so we can write simply the 1 dimensional heat conduction equation as – k d θ/ dr okay = this h dash which is the rate of heat loss that means this is really the rate of heat flow outside the inner wall or going into the from the inner to the outer wall / unit area.

So the area of this wall if supposing we assume the total high here to be z and the radius of the concentric to be R you know so we have h dash by Π rz as the rate of heat loss per unit area which is actually equal to by the simple 4 years law – k dθ/ dr we have done this kind of problems earlier while discussing about the e beam machining as well as the laser the other EDM electro discharge machinating etc…

So if we wanted to solve this within the boundary is that have been motioned particularly the melting boundary and the normal temperature or the room temperature condition. We have – k times of integral θ m, to θ 0 d θ become equal to h dash by twice Π z times of integral let us assume the inner diameter to attain finally the value d and the outer dia can be something like D and this dr / r okay so that is how we can estimate the you know probably the h dash which is need for sending the hole dimension from certain size okay this could be 0 where this d really is the diameter of the melt zone.

So you can assume that as the hole as gone and formulated over a certain diameter in which the heat flux boundary condition exist for example in this case there is a heat flux boundary conation which exits in this particular diameter d which is actually the probably these for diameter of the laser right so there is a current pert area constant heat input rate so I can call h to be the heat input rate / unit area and this is constant assuming that the laser is uniformly supplying heat along it is hole diameter area in the real sense laser as a profile but we are assuming here for simplicity shake so that thermal model can be probably constructed.

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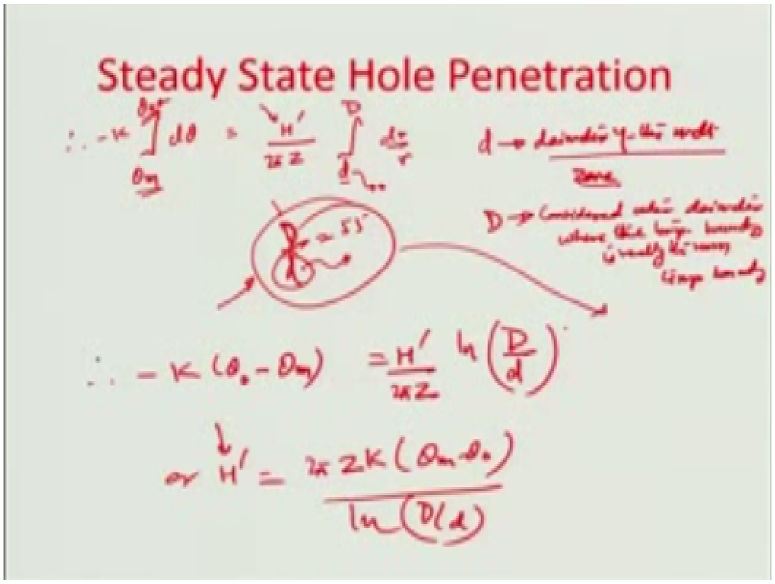

Steady State Hole Penetration

$$\therefore -K\int_{\theta_m}^{\theta_0} d\theta = \frac{H'}{2\pi z}\int_{d}^{D} \frac{dr}{r}$$

d → diameter of the melt zone

D → considered outer diameter where the large boundary is really the many [illegible] boundary

$$\therefore -K(\theta_0-\theta_m) = \frac{H'}{2\pi z}\ln\left(\frac{D}{d}\right)$$

$$\text{or } H' = \frac{2\pi z K(\theta_m-\theta_0)}{\ln(D/d)}$$

So here you know d is the diameter of that melt zone and in the cabinetry is really the point where it goes back to normal θ0 so this is actually let say we consider outer diameter where we can bound the is really range of boundary, so normally d / d ratios is of about 55 are very normal you have in case of let say machine is steels and that sheets etc. So got it typically needs that between whole temperatures is raises to almost the melting temperature of steel or melting constant.

And above 55 times diameter zone where we can goes down all the weight temperature value okay, so I solve this equation now which I have constructed here so we are left with – k θ0 – θm because h dash / 2 π z times of the natural log of D/ d okay or in another words I can estimate the heat flux of the heat rate of out flow from cylindrical surface of the wheel cylinders to be twice πz see kinds of θm – θ0 / this ln upon d so as I already mentioned here that the D/ T normal sense.

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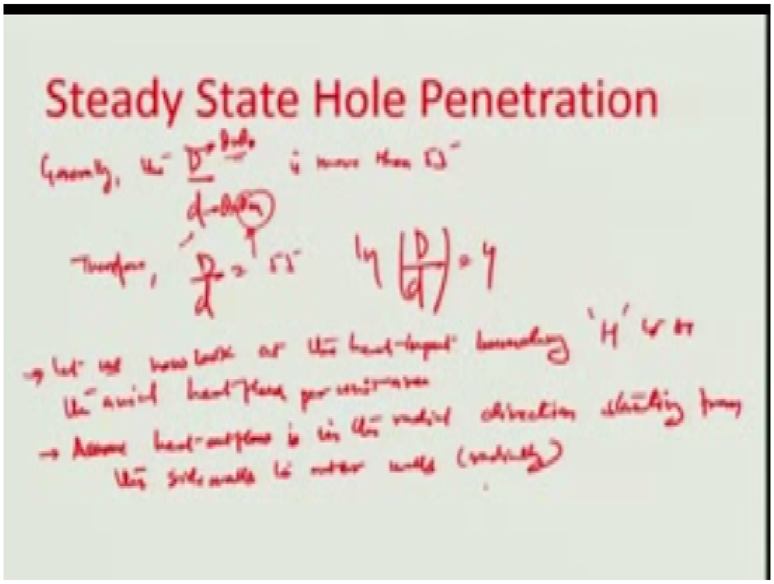

Steady State Hole Penetration

Generally, the $\frac{D^{\theta=\theta_0}}{d=\theta\theta_m}$ is more than 55

Therefore, $\frac{D}{d} = 55$ $\ln\left(\frac{D}{d}\right) = 4$

→ Let us now look at the heat-input boundary 'H' is the axial heat flux per unit area

→ Assume heat-outflow is in the radial direction starting from the side walls to outer walls (radially)

You know more than 55 so you write this down here so generally the D / d remember this is the diameter where θ = θ0 or room temperature this is the diameter we just corresponding to the melting point and we talked about steam is very, very high melting so by the time typically indicated from the θm value to and sharing the bits and the diameter gets increased multiple folds so generally D/ d in case of very high temperature we have considered of having this steel etc. You know attains a ratio which is more movement 65 so therefore if we really looked at D/ d is has to 55.

Or natural law of D/ d about 4 okay so let us now look at the heat input boundary which is actually on the top of the hold and we assume the H really to be the axial heat flux, per unit let say and further we know also assume here that our out heat out flow is in the radial direction starting from the side walls to outer walls and that to radial okay on the radial in other words we are not assuming that there is any.

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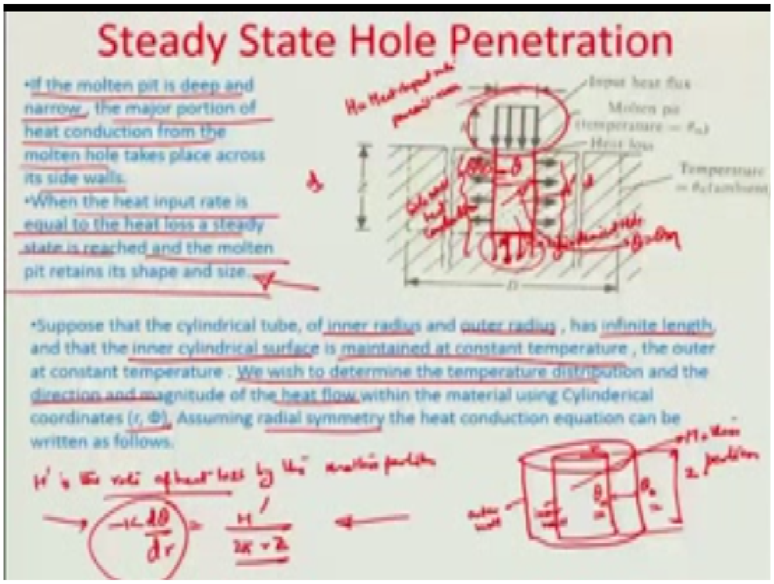

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H' is the rate of heat loss by the [illegible]

$$-K\frac{d\theta}{dr} = \frac{H'}{2\pi r z}$$

Kind of heat flow possible in this particular direction the axial direction in all the axial lead which is coming here is getting you know is going out from the side walls of the cylinder, so this is the condition what normally is dissipated particularly because this diameter that we are talking about are very small based on the spot size of the laser and it is probably worth to makes an assumption that it is early any flow in the axial direction and all the heat flow is mostly in the radial direction. Particularly in case of sued drilling and all this is mostly the case.

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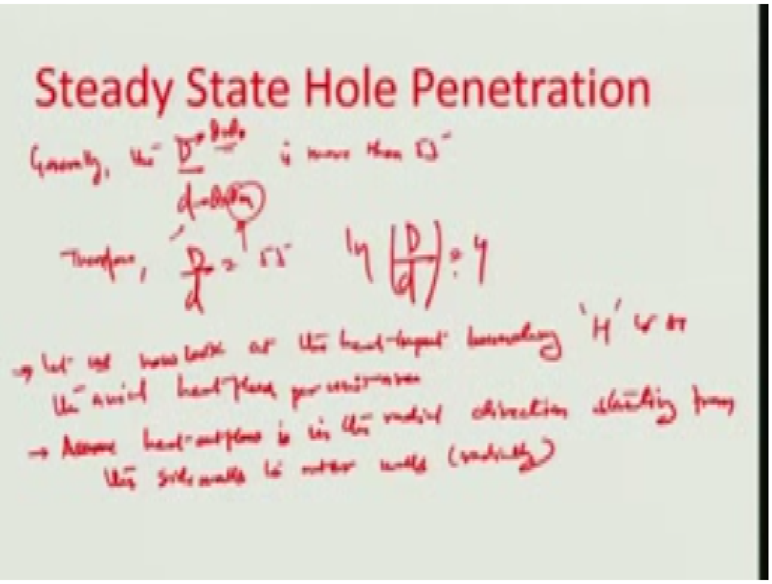

Steady State Hole Penetration

Generally, the $\frac{D^{hole}}{d^{beam}}$ is more than 55

Therefore, $\frac{D}{d} \approx 55$ $\ln\left(\frac{D}{d}\right) \approx 4$

→ Let us now look at the heat-input boundary 'H' & at the axial heat flux per unit area

→ Assume heat-outflow is in the radial direction starting from the side walls to outer walls (radially)

And therefore if we assumed that to happen in this particular case you know then we are left with and so we kind of assume here that at equilibrium condition and such a heat flux.

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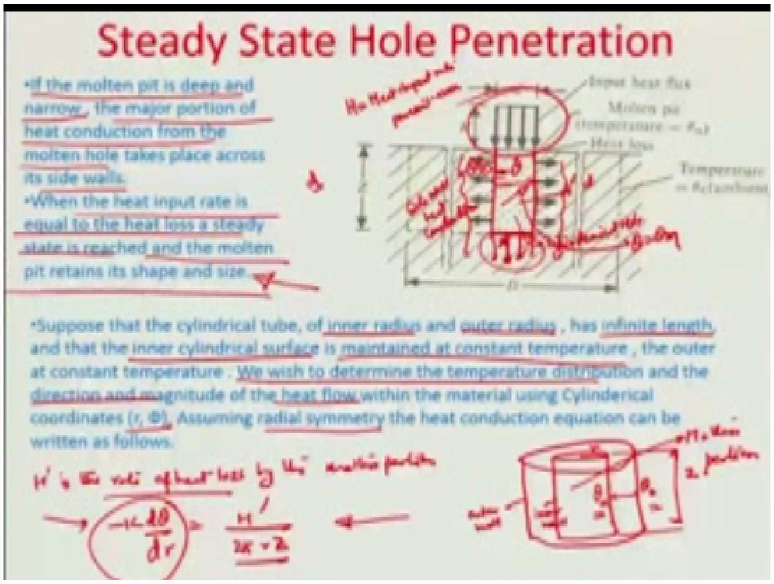

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H' is the rate of heat loss by the [illegible]

$$-K\frac{d\theta}{dr} = \frac{H'}{2\pi r}$$

Is existing on one side as an input to the system axially and another side the radial outflow from the system as you can see in this figure this is the input side you know axial inputs side and this is the radial output side so a equilibrium whatever heat comes in and goes out and there is some kind of a θ = θm or θ = θ melting solution which causes this whole to sort of a get formulated and they did it.

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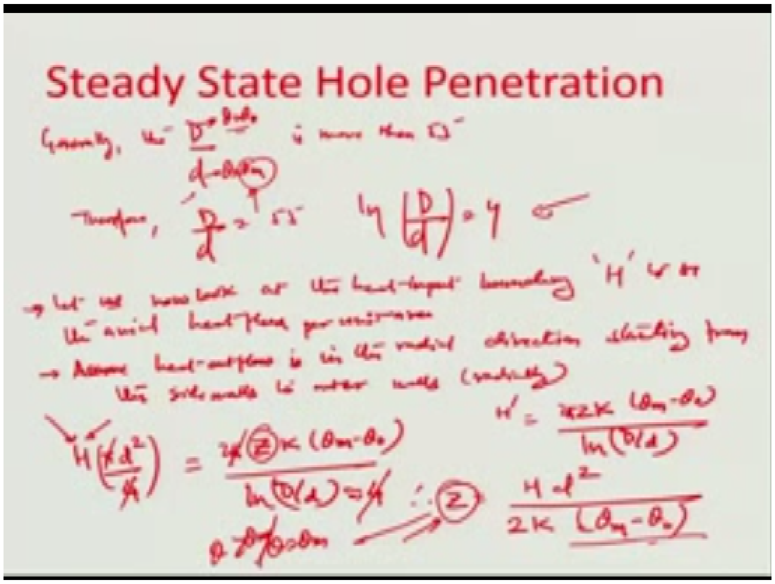

Steady State Hole Penetration

$$\ln\left(\frac{D}{d}\right) = 4$$

$$H' = \frac{2\pi z K(\theta_m - \theta_0)}{\ln(D/d)}$$

$$H\left(\frac{\pi d^2}{4}\right) = \frac{2\pi z K(\theta_m - \theta_0)}{\ln(D/d) = 4}$$

$$z = \frac{H d^2}{2K(\theta_m - \theta_0)}$$

So in that event we can equate the inflow the heat inflow and heat5 outflow and you do not have heat permit area permit time H is coming from the lasers spot on the top of the hole which its diameter is d^2 so the heat times heat per area times the area give she total quantum of heat which is coming per unit time and the total quantum of heat which is going out per unit time is again given by H ‘ which is adjust illustrated earlier.

And this H’ was earlier calculated in the last set of twice by zk times of θm – θ0/ natural log (D/d) so if we equate these two conditions we left with H times Πd^2 /4 = 2 Π zk(θm – θ0)/ Lm(D/d) okay. So in other words generally the condition that we arrive at is to sort of in this kind of equilibrium situation estimate what is going to be the value of z so value of z this again can be estimated as 4 from the last step right here the value of z becomes then equal to cancel out this Π/4 on both sides and we are left with z = the total heat in apparent area per unit time which is input to the system from the laser beam times of v^2 /2 times of the thermo conductivity k.

Of the material times of θ melting of the material – θ0 room temperature ,so basically that is how you can arrive at what is going to be the depth of the melting temperature or what is going to be really the z value upto θ = θm or θ > θ m okay, so that is how you calculate or you can estimate of with a steady state let us say hole penetration formulation that how much it will, how much that the laser will go up to if we assume equilibrium state of heat in flow equal to heat out flow.

Now the other goal that we have is that in such a case we also need to arrive at you know what is going to be the relation between the heat input that we are giving and the cutting speed, because ultimately the propose of a laser is to sort of not only create a certain depth of penetration but also keep creating it in the forward direction so that you can have the hole cutting process executed or the slot whatever you want to cut has to be executed.

So it is about also that velocity the rate at which you are scanning the laser given this hole time criteria or the depth of melting temperature criteria that we have arrived that in the last step. So let us look at that relationship so let us talk about the relationship between the heat input and the cutting speed okay.

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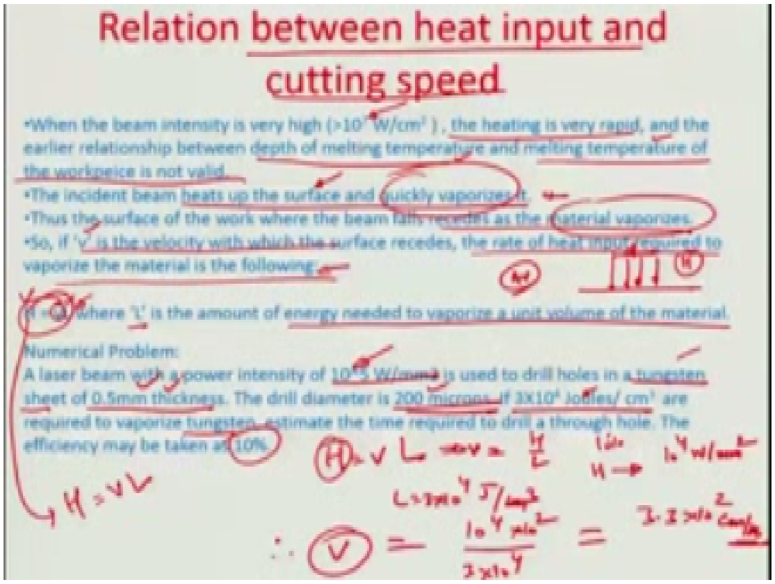

Relation between heat input and cutting speed

- When the beam intensity is very high (>10^7 W/cm^2), the heating is very rapid, and the earlier relationship between depth of melting temperature and melting temperature of the workpeice is not valid.
- The incident beam heats up the surface and quickly vaporizes it.
- Thus the surface of the work where the beam falls recedes as the material vaporizes.
- So, if 'v' is the velocity with which the surface recedes, the rate of heat input required to vaporize the material is the following:

$H = vL$ where 'L' is the amount of energy needed to vaporize a unit volume of the material.

Numerical Problem:

A laser beam with a power intensity of 10^5 W/mm^2 is used to drill holes in a tungsten sheet of 0.5mm thickness. The drill diameter is 200 microns. If $3X10^4$ Joules/ cm^3 are required to vaporize tungsten, estimate the time required to drill a through hole. The efficiency may be taken at 10%.

$H = vL$

$H = vL \Rightarrow v = \frac{H}{L}$

$H \rightarrow 10^4$ W/mm^2

$L = 3\times10^4$ J/mm^3

$\therefore v = \frac{10^4 \times 10^{-2}}{3\times10^4} = 3.3\times10^{-2}$

And you know particularly I would like to mention here that when the beam intensity is very high may be let us say of the order of about 10^7 W/cm^2 it is a very, very high beam flux that is you know permit area which is heat flux which is coming as a function because of the lasing action on the surface, and so the heating also is very rapid okay, and the earlier relationship between the depth of melting temperature and the melting temperature is no longer valid, okay.

So in the earlier relationship we had assumed that we have a steady state condition where the heat flow inside the zone of melting is exactly equal to the heat out flow. In this particular condition we are probably not giving it time enough for the equilibrium condition to arrive. So in that event the incident beam sort of heat sent to the surface to its vaporization point it evaporates the material quickly and you know the surface of the work where the beam falls suddenly recedes an the material is taken it to its vaporization temperature.

And in that event if we assume v to be the velocity to which the surface kind of recedes because of the beam matter interaction and the rate of heat input required to vaporize the material can be given by this following equation here where let us say if l where the amount of energy which was needed to vaporize a unit volume of the material we are that we talking about a case where you know we have the heat flux that means the heat per unit area equals to let us say you know the velocity at which this recession is happening on the surface times of the l value.

Let us understand it little more closely so when we are talking about a torque material through the heat input is happening we have already seen earlier that the laser surface interaction you have a certain diameter basic diameters d over which the heat input is happening and this is the heat flux so you have the H as per unit area how much heat is going to be in, so if that you multiply with velocity so area velocity product is really the volume wrote of evaporation of the volume rate of recession of the surface.

And so you can easily say that the heat flux you know per unit area equals the rate at which you know the surface receives that is the velocity times the amount that is needed to vaporized a unique volume okay. So I will exponent volume how much energy easily, so let us look at this problem little closely we have laser beam with the intensity of let us say about 10^5 watt per mm^2 or 10^7 watt per cm^2 is use to drill the whole in a tungsten sheet and thickness of the sheet as been provided to be 0.5 mm.

The drill diameter is about 200microsn so that is what is going to be the whole diameter and further we have the l values for this particular material tungsten has 3 x 10^4 joule per cm^3, can this required to vaporize this amount of l or this amount of energy is needed to vaporize a unit volume of the tungsten material. So we want to estimate the time require to drill a through whole obviously the diameters is 200miocron and the thickness is also provided so the amount of volume to be taken out to this machines, machining is known.

We assume coupling efficiency of about 10% so on the above 10^4 watt per mm^2 is felt you know as a usable power on the surface and we are already have here of the relationship h = vl h ^{2} x area heat flux or heat rate you can say at which the laser sends in energy in to the work surface so obviously the velocity at which the surface received from the equal to h / l, l being = 3 10^4 joule

per cm^3 and typically we have a 10% coupling so our h this felt by the surface is really is about 10^4 watts per mm$^{2.}$
And therefore we can say that V becomes equal to 10 4 watt per mm2 and if I wanted to convert that in to watt per cm2 this multiplied by 102 so this is watt per cm2 times 1/ l and the l happens to be about 300 or 3 x 10 4 joules per cm3. So 3 104 so overall then the velocity at which the surface would received is about 3.3102 cm per second and we are already aware that we need to cut a point 5mm thickness of the sheet.

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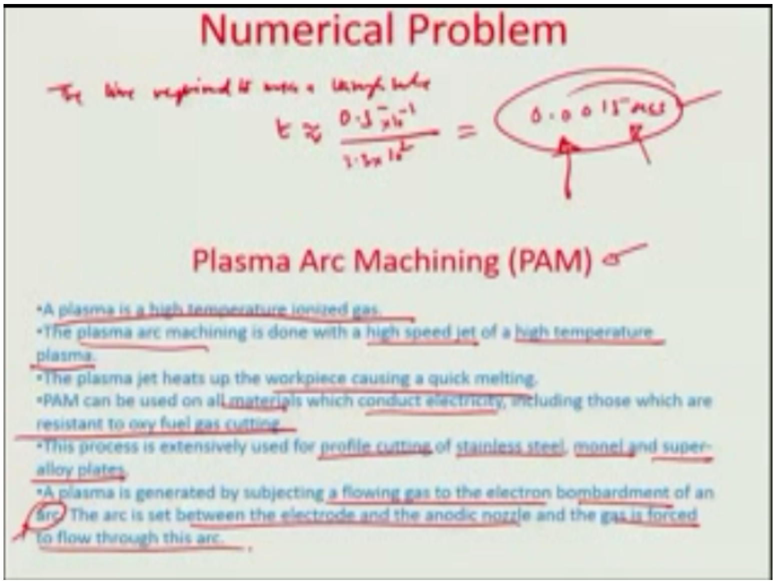

Numerical Problem

The time required to make a through hole

$$t \approx \frac{0.5\times10^{-1}}{3.3\times10^{2}} = 0.0015\ \text{secs}$$

Plasma Arc Machining (PAM)

- A plasma is a high temperature ionized gas.
- The plasma arc machining is done with a high speed jet of a high temperature plasma.
- The plasma jet heats up the workpiece causing a quick melting.
- PAM can be used on all materials which conduct electricity, including those which are resistant to oxy fuel gas cutting.
- This process is extensively used for profile cutting of stainless steel, monel and super-alloy plates.
- A plasma is generated by subjecting a flowing gas to the electron bombardment of an arc. The arc is set between the electrode and the anodic nozzle and the gas is forced to flow through this arc.

So in order to make a through hole the time required would be equal to 0.5 mm times 1/3.3102 the parameter of velocity that we found cm per second and this becomes equal to because it is 0.5 mm thickness so we have this in to – 1 so 0.05 cm thickness the t value becomes 0.0015 seconds. So a thickness of sheet equal to about 500micrron about 0.5mm can be through drilled using this particular laser system for less than about 0.0015 second. So it is very, very small amount of time that laser melting would really need for the machining to take place and that is why laser machining is consider to be a high yield or a fast process of machining.

The other machining means also and I just wanted to illustrate just the basic definitions of this plasma machining process, so as we all are we are a plasma is really a high temperature ionized gas and basically this plus mark machining is done with the high speed jet of high temperature plasma and plasma jet kind of heats up the work piece and cause quick melting and this kind of machining can be probably used and all materials particularly once which conduct electricity.

And they can formulate and electrode and result in formulation of plasma and they can also be particularly applicable to those materials which are resistance to the oxygen based fuel gas conventional cutting technique okay, so this process sis extensively used for various operation like profile cutting of the stainless steel monel and super alloy plates so on and so forth. So we have already seen details about how would plasma is generated by subjecting the fuel gas to electron bombardment and this bombardment can come to an arc.

Ao normally as we have earlier seen all our micro fabrication section that there is an arc which is settled just to create enough mount of irons and electrons and then there is a either a source waves energy which is given in terms of a magnetic field or you know change of the direction of motion of the irons or electrons.

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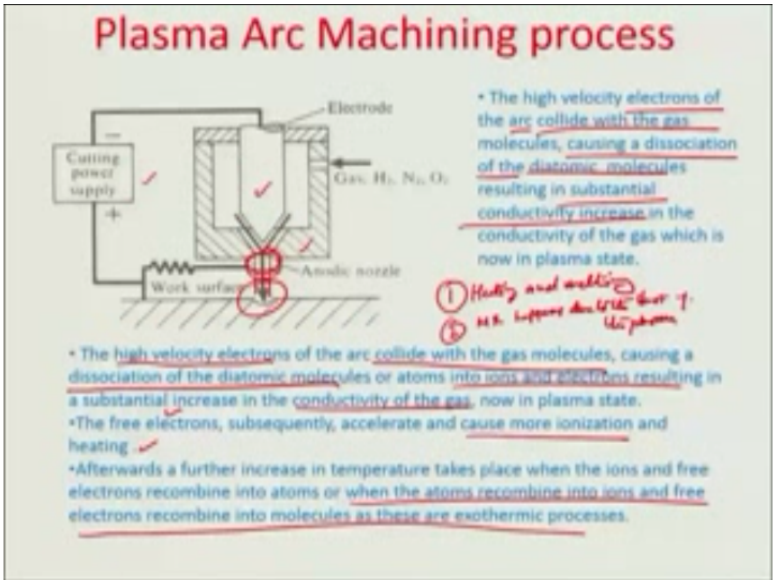

Plasma Arc Machining process

- The high velocity electrons of the arc collide with the gas molecules, causing a dissociation of the diatomic molecules resulting in substantial conductivity increase in the conductivity of the gas which is now in plasma state.

① Heating and melting
② M.R. happens due to the heat of the plasma

- The high velocity electrons of the arc collide with the gas molecules, causing a dissociation of the diatomic molecules or atoms into ions and electrons resulting in a substantial increase in the conductivity of the gas, now in plasma state.
- The free electrons, subsequently, accelerate and cause more ionization and heating
- Afterwards a further increase in temperature takes place when the ions and free electrons recombine into atoms or when the atoms recombine into ions and free electrons recombine into molecules as these are exothermic processes.

So that the sustaining of the plasma happens once formulated so this arc is said between the electrode and the anode nozzle in this particular case on the gas is forced to flow through this arc and here is where the details of this schematic plasma machining process can be seen so you have a cutting power supply and one of the electrodes and there is a gas which is sent between this electrode and anode nozzle.

And there is a highly organized state of plasma created between this two electrodes which is again forced out of this chamber and creates so the high velocity electrons the gas an arc is typically set up in order to accurate this, this plasma okay it cause dissociation of the molecules you have already seen how diatomic molecules can be disassociated earlier in your micro fabrication module.

And this substantially increases the conductivity of the gas comes into plasma state and obviously get high velocity electrons which colloid with further gas molecules causes disassociation of the diatomic molecules so happens the electrons and this results in substantial increase in the gas conductivity because of plasma represents of lots of winds and electrons that charges.

So in free electrons again with further accelerate themselves in cause more organization which kind of give you heating effect of this plasma and so at the end of the day the anode nozzle there comes out increase in temperature plasma state because of free electrons and irons okay and theses irons or free electrons now recombined somewhere in the part so that they can give out heat released.

So here obviously because of this recombination there is excessively high temperature it is highly in thermal the process which happen close to the working substrate so the challenge here is really how to take this plasma state all the close to the surface therefore the recombination takes place so that you can get a high temperature where zone of a machining or the work piece is kept so this is sort of accomplished by changing in shapes and size and sourcing out the plasma up to this nozzle.

At a certain velocity you know the form of jet and principally the mechanics of the material removal again is based on heating and melting and also removal of the molten metal by blasting action of the plasma the gas is short at the certain velocity so there is some plastic action so

MRR the material removal MR happens due to the blast of the plasma so I think now I would kind of covered of all the basic nontraditional processes.

And this brings us to the end of one section of this module in the next few lectures I would focus more on metal forming and may be on or two process models about some forming causes and back closes manufacturing technology process technology part two so thank you very much for being with us and I would like to start the formal section from the next module onwards thank you.

Acknowledgement

Ministry of Human Resources & Development

Prof. Satyaki Roy
Co – ordinator, NPTEL IIT Kanpur

NPTEL Team
Sanjay Pal
Ashish Singh
Badal Pradhan
Tapobrata Das
Ram Chandra
Dilip Tripathi
Manoj Shrivastava
Padam Shukla
Sanjay Mishra
Shubham Rawat
Shikha Gupta
K.K Mishra
Aradhana Singh
Sweta
Ashutosh Gairola
Dilip Katiyar
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Hari Ram
Bhadra Rao
Puneet Kumar Bajpai
Lalty Dutta
Ajay Kanaujia
Shivendra Kumar Tiwari

an IIT Kanpur Production