Mathematical Modelling of Manufacturing Processes
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Lecture – 19
Fusion Welding Processes-2

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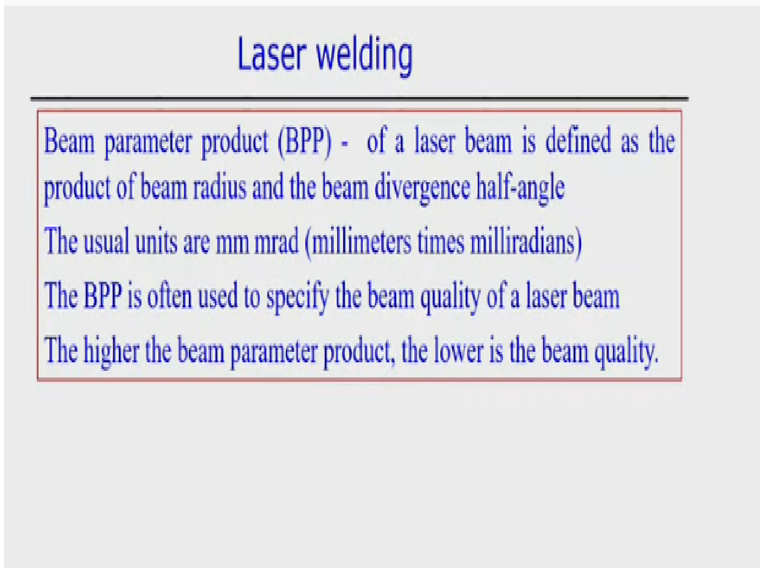

Beam product parameter which actually defined the quality of the laser beam and a measuring unit for beam parameter product that is in millimetre miilirad and that is millimetre times milliradians and this is often used to identify or to signify what is the quality of that laser beam. So apart from that this laser or link process there are two modes of heating normally use one is our conduction mode that we have already discussed conduction mode.

In conduction with the laser power intensity is around 10 to the power watt per centimetre square if it is more than that then we can see that keyhole mode laser welding process. So in conduction mode there is a the maximum temperature of the system is well below the vaporisation temperature of the material. What in keyhole mode laser welding process the power density is above 10 to the power 6 watt per centimetre square.

So this in this case there is a formation of the blind hole and the dynamic balance between the water pressure paper and the different driving forces mix during the processing of the laser when we try to produce a deep penetrated laser welding processes. So in this case definitively the maximum temperature of the system is above the vaporisation temperature of the material.

So here see if say creates kind of blind hole that is called the keyhole and of course vapour pressures is from the hot metal keeps the hole open during the welding process. But once there is a welding process over that means switch of the laser power then that cavity actually fails by the molten material.

So in this case some sort of loss of the materials also happens in the keyhole mode laser welding process but in the other way that it is possible to achieve the high depth penetration for a particular when you try to do the welding processes. But if you if you compare the efficiency or thermal efficiency or what does the amount of the energy absorbed in conduction mode and keyhole mode laser welding processes the absorption of the laser energy is more in case of the keyhole mode laser welding process.

Since that within the keyhole there is a multi-layer reflection the laser light occurs and that keyhole actually traps that maximum amount of the laser light energy. So the efficiency in this case is more as compared to the contextual laser welding process but in terms of the application area if we see that conductional laser welding processes when there is a thickness of the material or maybe very thin sheet.

We can apply the conduction mode laser welding process but if your other way if the sheet thickness is very high in this case the keyhole mode is more preferred to produce the full depth of penetration.

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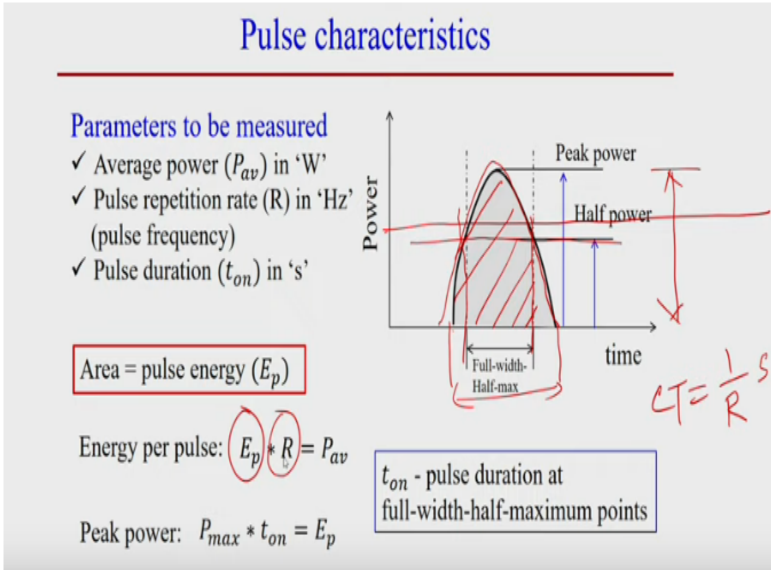

So apart from that different modes of the laser welding process so sometimes we use that pulse mode of laser welding process. So pulse mode also available in the welding process and even for the plasma articling cooling process but how we characterize the pulse basically what way we define the pulse parameters. So in this case if you see from this figure this indicates that pulse energy so over which the pulse on any remaining time the pulse if off but what are the characteristic parameters in this case.

One is the average power second is the pulse repetition rate or you can say the pulse frequency and of course the pulse duration or actually characterize the pulse mode of laser welding process. So in this case that definitely the average power is equivalent to the continuous mode of laser welding process that means over the duration of the welding process it maintains the average power but if you look into the pulse in pulse welding process the energy is applied within the pulse on time.

So here if you see that suppose this is the peak power in pulse laser welding process and the surface typically kind of goes in distribution most of the cases but it is a temporal distribution that means in distributed over the time span and in this case then how to defend the pulse on time. So we just simply take the half power position and the corresponding to this half power this is the duration of the pulse on.

So t on is a pulse duration at full width half maximum, maximum point so what and this area actually represents the energy of the pulse. We can estimate mathematically that area the presentation of the pulse energy and the pulse energy per pulse can be a link with this the average power. So average actually exist over a continuous mode that means it is a kind of continuous supply of the power.

So that energy pulse energy*pulse r is the pulse repetition rate and of course the cycle time can be estimated at 1/R or maybe 1/F that in sums of the pulse frequency and often we measure in terms of the second. So pulse energy into the R that actually represent the average power and other cases the peak power can be estimated that if you know the pulse energy. So that peak power*the duration that actually equivalent to the pulse energy.

From that point we can estimate what is that maximum power in case of pulse welding involved. So most of the cases actually by looking into the different pulse parameters we estimate that what is the average power and based on the average power we do the further calculation in case of the pulse welding process and which our is very much equivalent to the continuous mode of laser welding process.

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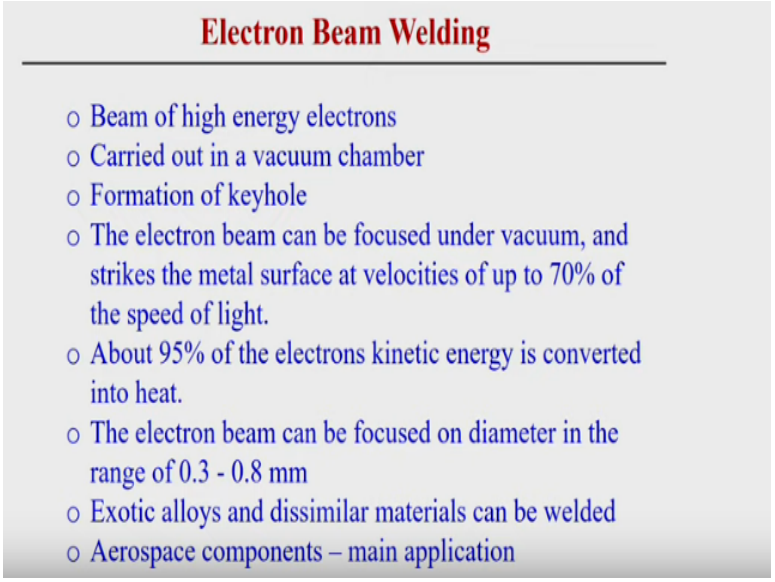

Now we come to that point the electron beam welding process. So electron beam welding process is a flow of electrons and definitely it is carried out under the vacuum and it creates also the keyhole like laser welding process but the electron is focused or speed of the electron metal the velocities of the electron is as much as 70% of the velocity of the light. So in this case since it produce the keyhole and its conducts under the vacuum then most of the kinetic energy of the electrons is actually converted to the heat.

So in this case the efficiency is relatively higher. So electron beam can be focused into a very small area here you can see that around 03 to 08 millimetre and definitely different dissimilar combination of materials as well as very typical materials or rarely used materials we normally use the electron beam welding process.

But the main difficulties of this process is that this process is very costly process and the welding cost is very high using the electron beam welding process but in other way we can expect very good quality of the welding joint because it performs under the vacuum. So there is no question of contamination of the weld pool during the processing. So that is the one advantage and that is why this process is mainly used in aerospace components and very specific to dissimilar combination of the materials.

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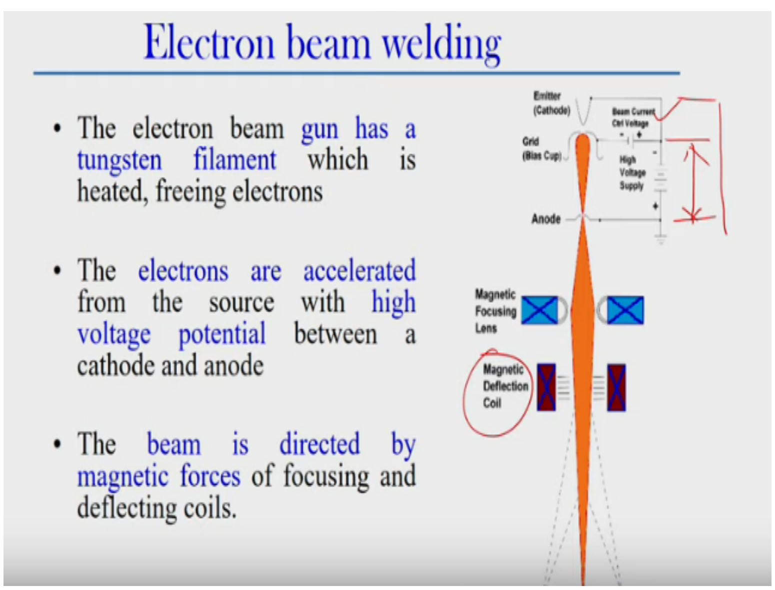

So we see that how he looked at me and happens now it is a kind of schematic figure of the electron beam welding process. So there is a tungsten filament first start with the tungsten filament with application of some kind of the voltage here. So tungsten filament actually emits the electrons or freeing the electrons when it cross the ionized potential of a particular material but here we use the tungsten.

So once it frees the electrons then there is a acceleration of the flow of the electrons happens by application of the potential difference or by application of the voltage the electrodes has been accelerated. So therefore after acceleration of the electron then this is passes through the magnetic focusing lens.

So magnetic focusing lens in this case the electron beams actually focused in the particular area which is different from the optical focus in case of laser welding process. But here we use the magnetic focusing lens and then magnetic deflection coil. So this deflection coil actually deflected the flow of the electron at a particular position whenever there is a CPC that in this there is a two socket.

So that between the cathode and anode there is a voltage supply but one part of the voltage is used to just image the electrons from the tungsten electrode and second part of the voltage potential difference is utilized to accelerate the electrons. So this is typically or very schematically we can represent the working principle of the electron beam welding process.

So once this electrons image and then it image the kinetic energy to the thermal energy and it is impact on the work piece and on this work piece there may be the formation kind of the keyhole.
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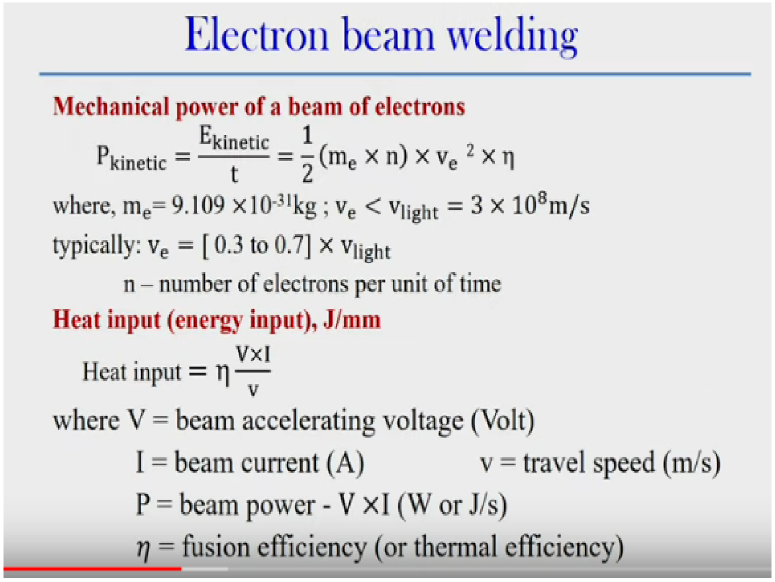

So typical or but simple calculation we can it can be done in electron beam welding process we will see the mechanical power of the beam of electrons can be estimated like that, that kinetic energy is the estimated that e kinetic/time which is equivalent to half of the mass, mass of the electrons or n number of number of electrons and the mass and then this is the velocity of the electron and of course that this is the efficiency.

So in this case mass of the electrons is given order of 10 to the power-31 kg and velocity of the electron is less than that of velocity of light and normally the velocity of the electron varies ng depending upon the potential difference it can be 0.3 to 0.7 that means 30% to 70% of the velocity of the light and in actual represents the number of electrons per unit time. So these are the typical estimation of the kinetic energy of mechanical power of the beam of electrons. But how to estimate the heat input in electron beam welding process.

Here you can estimate the heat input like that efficiency*voltage*current voltage mean here the accelerating voltage is more important in electron beam welding process and I is the beam current v is the travel speed means at which velocity the electron beam moves to perform the welding of a particular material.

So it is a travel speed P so then power divided by travel speed that actually indicates the energy input per unit length. So directly you can estimate the beam power or by just noting the potential difference and current and fusion efficiency or thermal efficiency if we look into take into account then actually heat input to the substantial material can be estimated using this expression.

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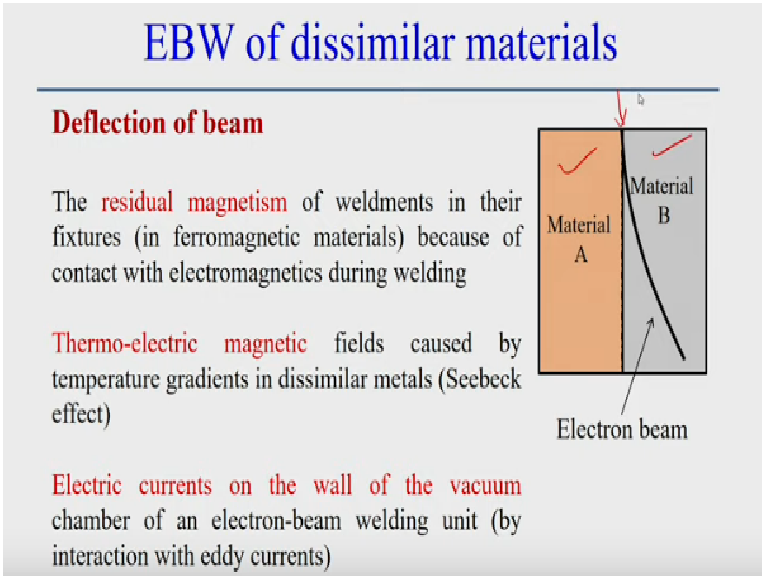

One of the critical or maybe a difficulty in electron beam welding process when you try to specifically join the dissimilar combination of the materials for example suppose material A and material B we want to join and there is a passage of the flow of the electron beam from the top surface at the interface between these two materials. What happens in this case? Since the thermo physical properties of material A and material B are different and of course there is a flow of the electron beam actually representation is the flow of the electron within this material.

So magnetic field actually disturbs the passage of the electron beam. So some sort of the magnetic field creation indicates that there may be the possibility of deflection of the electron beam either any one side of the material. So it is very difficult in this case to exactly focus at the interface of the two materials. So what are the possible reason for that? There may be one maybe the residual magnetism of the weldments and in their fixtures.

Basically fixture for ferromagnetic materials they actually interact with the electromagnetics during the welding process. So that can deflect the electron beam secondary reason maybe the thermo electric magnetic field merely caused by the seebeck effect and that seebeck effect is mainly driven by that some temperature gradient for the dissimilar materials.

If temperature gradient exists at the juncture of the discipline materials in that case the thermo electric magnetic field is actually created and that influence the flow of the electron beam. Third reason may be there maybe the of the electric currents or art on the wall of the vacuum chamber. So that actually influence created magnetic field electron beam welding and finally there is a interaction of the eddy currents and contribute may contribute to the deflection of the electron beam or maybe creates the difficulty to exactly focus at the interface of the electron beam.

So these are the possible three reasons that we generally observed for welding of the dissimilar materials using the electron beam welding process. So look into that at what side? The electron beam gets deflected.

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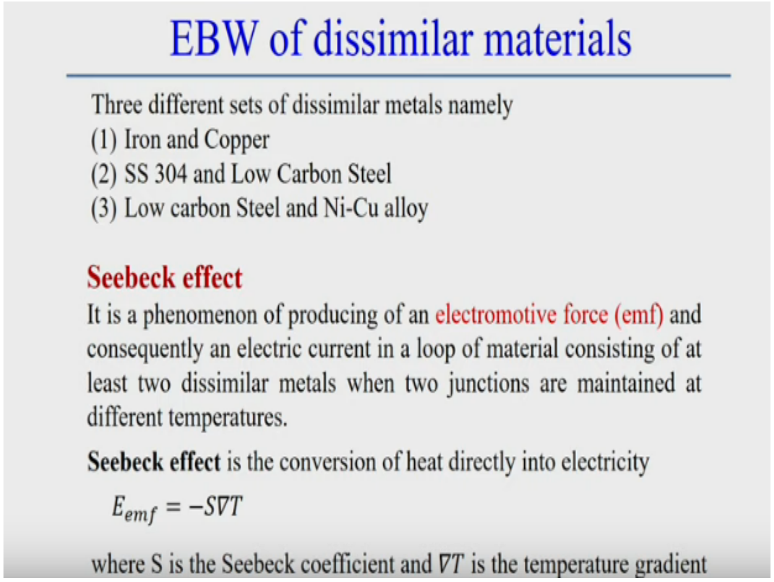

We considered the three different combination of the dissimilar materials welding ay be first we considered iron and copper then stainless steel 304 and low carbon steel combination or low carbon steel and nickel and copper alloy. These three combination we can see that in which direction the beams gets deflected.

But before that just idea about the see beck effect is a kind of phenomena that actually produce the electromotive force emf generates and the electric current flow in a loop of material consisting of at least two dissimilar materials and at that junction there must be some sort of temperature gradient exist. So that temperature gradients creates the electromotive force and that see beck effect can be represented using this equation.

So that is the -S*delta T, delta T is the temperature gradient and S is the coefficient that is called the see beck coefficient. So we can estimate roughly what is the electromotive force creates during the joining of the dissimilar materials.

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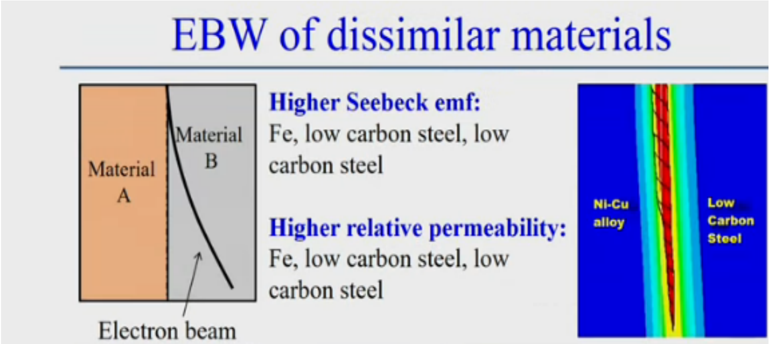

Sl No	Metals	Deflection angle (degree)	Deflected direction
1	Fe and Cu	2.86	Fe
2	SS304 and Low carbon steel	2.50	Low carbon steel
3	Low carbon steel and Ni-Cu alloy (7150)	8.51	Low carbon steel

See that is the example electron beam dissimilar materials so if you compare the iron and low carbon steel as compared to the other type of the materials. So higher see beck emf exists the electromotive force exists more in case of iron and low carbon steel. And at the same time higher relative permeability also exist in case of iron and low-carbon steel that actually the difference of the relative permeability and of course the higher see beck electromotive force drives the flow of the electron or maybe electron beam towards any one side of the material.

Or mostly which is having the relative permeability in that case that beam gets deflected towards that material. So if you show some similar to the results also the nickel copper alloy and low carbon steel. Here we can see the beam actually get deflected towards the low carbon steel. So if you compare that huge direction beam gets reflected and what maybe the typical deflection angle exists for different comparison of the dissimilar material.

First we will look into that iron and copper the deflected direction towards the iron stainless steel and low carbon steel deflected towards the low carbon steel and combination of the low carbon steel and nickel copper alloy. The beam gets deflected towards the low carbon steel so the minimum deflection angle in this case this so that means not much deflected to this but low carbon steel and nickel copper alloy the deflection angle is very high.

Probably the difference in the relative permeability between these two materials are high. So that may be the possible reason for beam gets deflected towards a low carbon steel as compared to the nickel copper alloy. So these are the typical difficulty or obstacles during the joining of the dissimilar materials. But how to remove all these things probably the counter act of the electromagnetic field can be created to avoid the deflection of the beam in a particular material.

Or maybe the thickness of the material can be joined reasonably good but if we consider the very high thickness materials probably it is really difficult to avoid this kind of problem. So in case of electron beam welding process.

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Comparison between laser and electron beam welding

Perspective	Electron beam welding	Laser welding
Weld zone and HAZ	Narrow/smaller	Narrow/smaller
Penetration	Deep penetration	Moderate penetration
Welding speed	Very high	high
Shielding gas	Not required	Nitrogen or argon shielding
Vacuum chamber	Required	Not required
Cost	Very high	Comparatively low
Generation of X-ray	Possible	Not-possible
Power efficiency	80-90%	10-20%
Size of work piece	Limited due to vacuum	Not limited

We can get a or analyse the comparison between the laser and electron beam welding process just of all idea between difference between these two processes we can from the different perspective. So first weld zone and HAZ definitely both the cases are narrow or it will be smaller origin can be created but this narrow zone can be more can be controllable or it can be controlled specific to electron beam welding process as compared to the laser.

Second penetration definitely the electron beam the high depth of penetration is very high or you can say that aspect is very high as compared to the laser welding process. Laser welding process also creates some kind of moderate penetration and both the cases the to achieve the high depth of penetration. Definitely the keyhole mode only should be preferred.

Welding speed since the electron beam can be used at very high welding speed but laser welding can be used not as much as electron beam welding process but it can be with very high welding speed as compared to the other arc welding processes. Shielding gas electron beam welding processes there is no need of the shielding gas because all the process happens under the vacuum.

But in case of laser welding process some sort of shielding gas sometime nitrogen or argon shielding gas can be used. Vacuum chamber in case of electron beam welding gas all happens under the vacuum conditions so vacuum chamber is required but that kind of requirement is not there in case of laser welding process.

So that is why cost of electron beam welding process is very high and but laser welding process is comparatively low and that means as compared to electron beam welding process the cost is low but as compared to the arc welding process the laser beam cost is very high. Electron beam welding process or scans creates or maybe there is a possibility of the X ray generation but it is not it is it does not happen in case of laser welding process.

So power efficiency of electron beam is very high 80 to 90% but in that case laser welding the power of efficiency is actually low 10 to 20% and but and advantages of laser welding process that the size of the work piece is not limited because it happens it under the shielding gas and of course it depends on the design of the fixture all these things. But in case we looked in electron beam welding process the size is completely limited by the size of the vacuum chamber.

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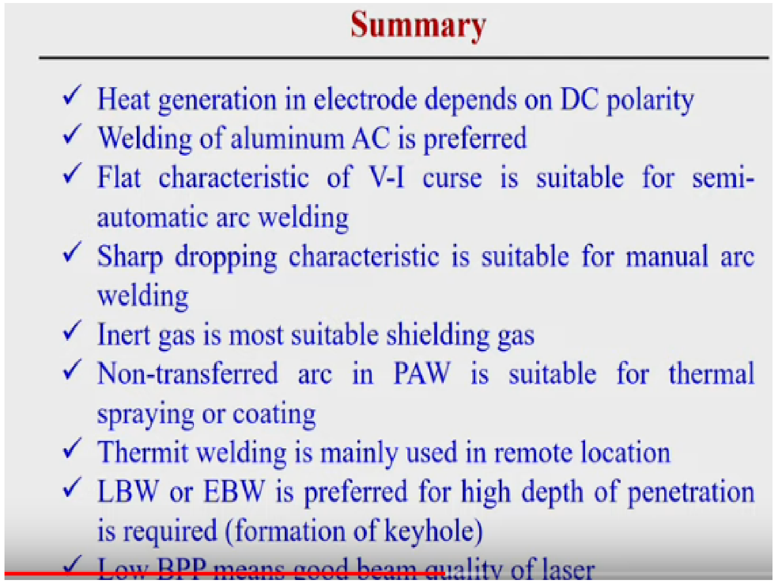

Since summary for all this different aspects of the different welding processes mainly the friction welding process I have covered in this in this part. So if we look into and summary that heat generation in electrode actually depends on the DC polarity that means whether we should use DC EN polarity or DC EP electrode negative or electrode positive based on that the amount of the heat generation normally absorb in case of arc welding process.

In case of welding of aluminium normally AC current is preferred because there is a change of the polarity in half cycle and that aluminium having the high affinity to the oxygen and it gets easily clears the aluminium oxide that may be the reason to use the AC polarity in case of aluminium and of course aluminium the temperature melting point temperature is relatively low as compared to the steel.

So in that case by applying the AC current is possible to control that maximum temperature in the or we can moderate that maximum temperature as compared to the DC current. So that may be another reason to prefer aluminium by using the AC current. Flat characteristic of voltage ampere curve is very much suitable for that semi-automatic arc welding process because semi-automatic arc welding process the arc gap is constant and in this case also welding speed is constant.

So in this case flat characteristic of the voltage ampere is more suitable but if you look into the manual arc welding process there maybe the variability of the arc length because an of course there maybe variation in the speed of the welding. So in that sense the sharp dropping characteristic is more suitable in manual arc welding process. So if you discuss the different types of the shielding gas.

So inner type of gas is most suitable for this shielding gas because even at very high temperature it becomes nonreactive to the processed materials. Non-transfer we have seen that plasma arc welding process we can use the transfer arc which may be used for the welding purposes. But non-transfer arc can also be used in case of plasma arc welding process which is most suitable for the thermal spring or the coating purposes.

Thermit welding is more suitable in case of remote location when there is a problem of the electric power. Laser or electron beam welding process is prepared when there is a need of high depth of penetration because both can from the keyhole mode welding process but if we look the very precision welding process in that case electron beam welding is more preferred than that of laser beam welding process.

The low BPP beam product parameter that actually represents the quality of the laser beam. So this parameter in practical we always measure to justify or to identify what is the quality of the laser beam is used in case of the welding or any other manufacturing processes.

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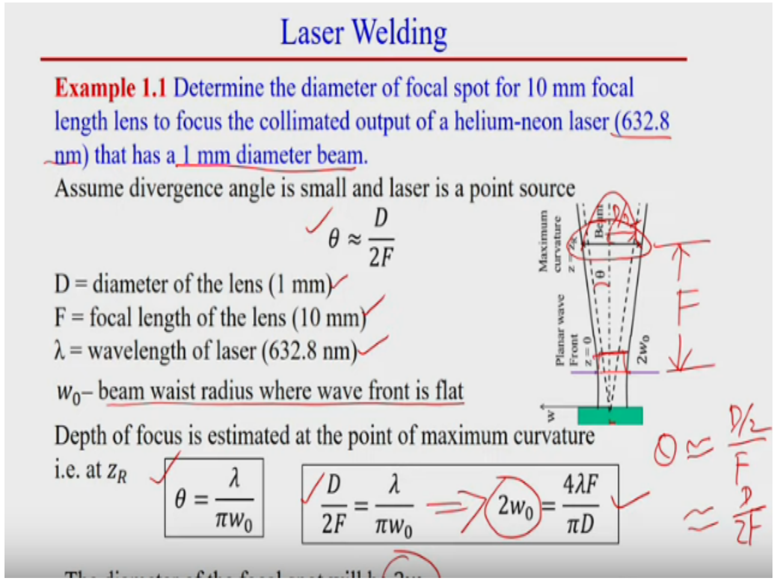

So now we will try to discuss that some simple mathematical problem and related to the this laser welding processes. So here I will try to look one by one first one is that first example indicates that we need to find out that diameter of focus spot for 10 millimetre focal length lens to focus the collimated output of a helium neon laser. The wavelength of the laser is given that is 632.8 nanometre that has 1 millimetre diameter beam.

If you try to attempt to solve this problem, we have to look back the optics of the laser and we have a litter discuss the optics of the laser and here we see the plane wave form when Z=0 the beam waist radius or the wave front is flat but we have already discussed and of course this we assume the focusing size on the workpiece.

Now if you assume the divergence angle is small basically half divergence angle is theta and then this is the this is the parameter D/2 where D is the diameter of the lens and F is the focal length of the lens. So I think this way you can define F is the focal length of the lens then lambda is the wavelength of laser it is defined. Focal length of the lens is defined and the diameter of the lens is one millimetre.

So that has 1 millimetre diameter beam so in focus on that the lens is normally put in that position. So here we can here it is defined the diameter of the lens and we can roughly estimate theta sin theta tan theta =in the terms D/2/F or it is approximately D/2F. So from that point we can find out what is the half divergence and now in the other way also depth of focus is estimated at the point of the maximum curvature I that Z=ZR the maximum curvature actually followed.

So here the almost flat curvature of the intensity but here is the maximum curvature is 4. So based on that we define the distance as F. So then we can use this relation theta=lambda/pi w0, w0 is the waist beam radius. So from here this expression and so we compare this theta and this theta D/2F between these two then we can relate this expression and from that we can find out the 2w0 is the diameter of the focal spot.

It depends on the wavelength that focal length of the lens and diameter of that lens. All this parameter is defined it is here it is defined so therefore we can estimate the what is that focal spot is in this particular case. So that may be useful to estimate the focal spot when the laser is focused on the workpiece because that actually estimate what from that point of view we can find out what is the power density actually falling on the work piece or we can utilize in case of laser welding process.

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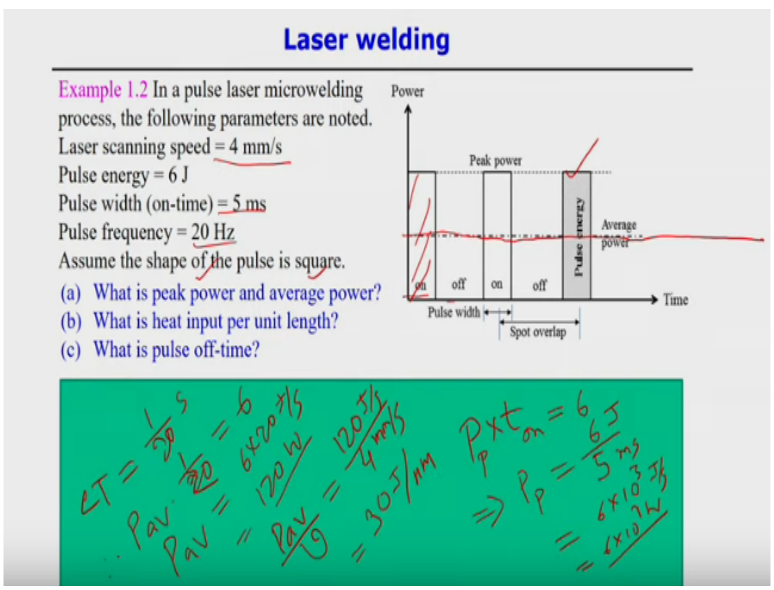

So this is the next example you can see that other laser welding process specific to pulse laser welding process here see then in a pulse laser micro welding process the parameters are given. Laser scanning speed=4 millimetre per second that means we can see the welding speed =4 millimetre per second pulse energy is given 6 joule pulse width is given that means pulse on time 5 millisecond and pulse frequency is 20 hertz.

So we assumed the shape of the pulse square that means this is the suppose this is the shape of the pulse then it will be easy to estimate for the different parameter. So pulse energy is given 6 joule and average power is given that first step to estimate that what is the peak power and average power? So we see the peak power we can find the relation also peak power*pulse on time that should be equal to the area that means pulse energy that means 6 joule.

So from here peak power we can estimate 6/pulse on time 6 joule/pulse on time=5 milli second. So that means 6*10 to the power 6 joule per second or 6*10 to the power 3 is basically what? So this is the peak power but how can I estimate the average power. So average per unit we are estimating we should consider the one cycle time. So 1 cycle time=1/pulse frequency 20 hertz 20 cycles per second.

This is second 1/20 seconds then over the 20 second the average power is applied over the 1/20 second pulse cycle time that should be equal to the pulse energy 6six p average should be six and two 20 joule per second. So that means so that we can see that average power and there is a huge difference in the average power and the peak power. So P average should be 6*20 joule per second so that means so therefore you can say that average power and there is a huge difference in the average power and the peak power.

So average power means from it is obvious average power means we are continuously maintaining this power with the application and over the time but pulse power means from or during pulse on time we are applying the energy supplying the energy but obtain there is no application of the energy that means is equal to 0.

So that means laser fluctuation kind of this thing pulse on and then off pulse on and off in that way we are applying supplying the energy that should come that can be rapidly estimated that average for that is equivalent to the average support over that long time. So therefore first we can estimate the peak power and average power from the data given here then what is the heat input per unit length.

Actually heat input per unit length should be measured with respect to the average power. So once we estimate the average power so P average power/the velocity of the that actually indicates the heating per unit length. Let us say 120 watt average power that means joule per second/velocity means here 4 millimetre per second. That actually indicates that 30 joule per millimetre.

So therefore that heat input per unit length is the 30 joule per millimetre. Actually the heat input per unit length is significant and there is a in case of linear welding process that indicates because it is a indicative of it takes care of the what is the welding velocity we are using. If very high welding velocity heat input per unit length will be less the velocity is very low in that case heat input per unit length will be more.

That more amount of the energy will be deposited at low velocity and high amount a low amount of the energy will be deposited in case of the high velocity and high amount of the energy will be deposited in case of the low velocity. So that the combination of the laser power energy and laser velocity by to signify or to indicate what is the heat input or energy supplied to per unit length. And what is the pulse off time?

So pulse off time if you know the cycle time is 120 second and pulse on time is I think 1/5 millisecond so 5*10 to the power -3 second. So that is that should be the pulse off time so here we see the pulse off time is very high. So therefore very small duration actually practically a small duration this is the application of the high amount of the energy and remaining part which are we are not supplying any amount of the energy. So this is the typical characteristic of the pulse laser welding process.

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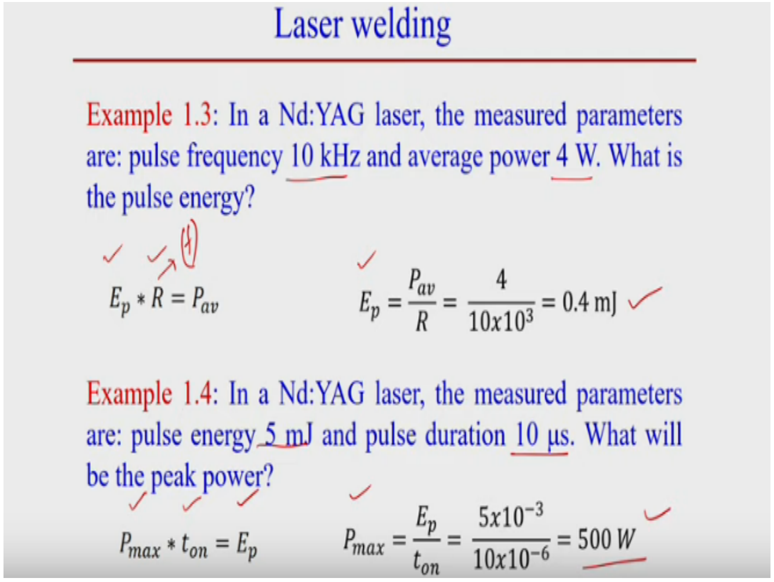

We can see the other example also in your laser measuring parameters of pulse frequency is given 10 kilo hertz average power is given pulse energy it can be easily estimated that pulse energy*pulse repetition rate or we can write or pulse frequency that is equivalent of the average power. So from here we can estimate the pulse energy=average power/pulse frequency. So that it indicates that around 0.4 milli joule in this case.

Similarly, per pulse energy is given and pulse duration pulse energy is given 5 another example the pulse energy is given and pulse duration is also given what would be the peak power that peak power*pulse on time we are making the energy balance here. Pulse energy from that we can estimate the maximum power=pulse energy/on time here estimate that now maximum power=500 watt.

So this way we can estimate in the different parameters in case of a laser welding pulse laser welding process.

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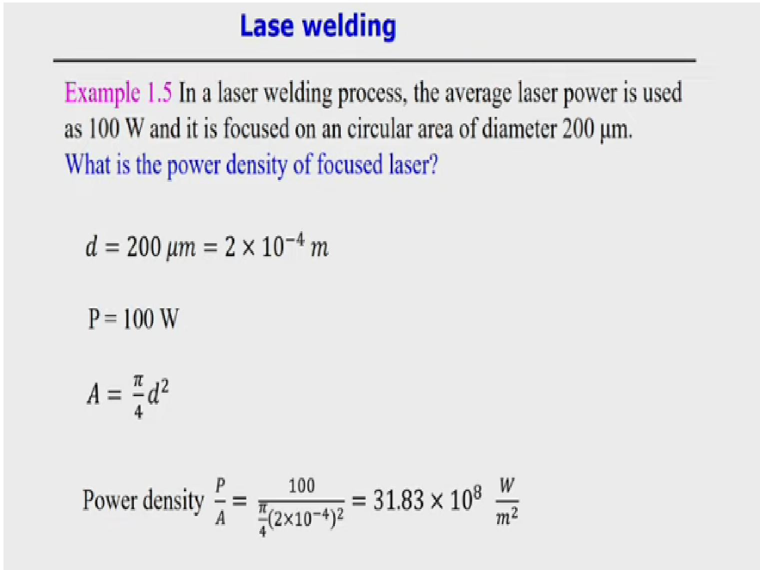

Now another problem which is related to that laser welding process the average laser power is used as 100 watt and is focused on a circular area of diameter 200 micrometre in this case what is the power density of the focused laser. How to estimate the power density in case of laser welding process? Diameter is given diameter means exactly laser is focused on the work piece on the surface at which area or the laser is focused.

So that area we can estimate=pi/4*d square d square is given that means diameter is given and power is given. So power density can be estimated that the power divided by area over this laser is focused that indicates that watt per meter square 31.83 *10 to the power 8 watt per meter square. So that power actually in this case the power density is very high but how to lower down the power density in this case.

So we can lower down the power density simply by increasing the area that means by increasing the laser focus diameter. If we increase the laser focus diameter, then power density can be decreased or other way also. If we decrease the laser focus diameter that actually increase the power density so that that is a one way to control or to modify the power density in case of laser welding process.

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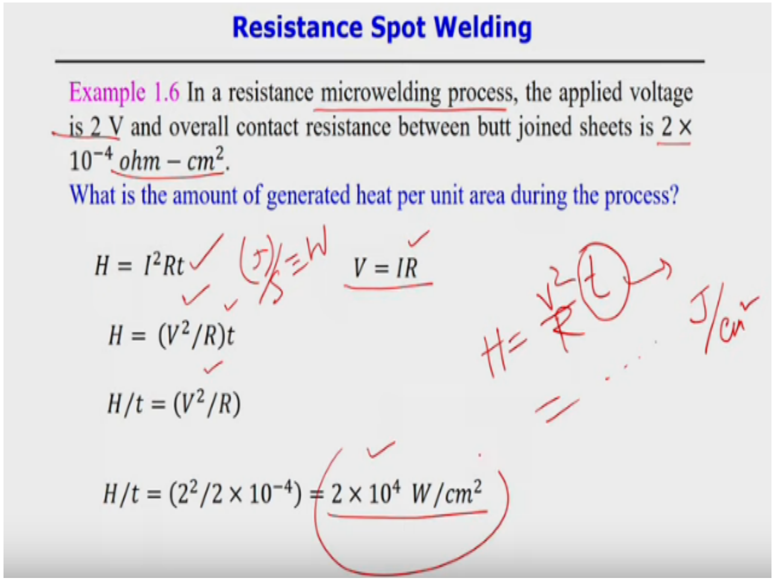

We will look into another example 11 to the resistance spot welding process. So resistant spot welding process in a resistance micro welding process the small scale welding process the applied voltage is 2 Volt and overall contact resistance between the butt joined sheets is given ohm centimetre square. Now how to estimate the heat generation in the resistance for spot welding process.

We can we should use the joule heating so here we need to estimate the amount of the heat generated per unit area during the process. So we use this expression H=I square Rt R is I think I is not given here current is not given that the voltage is applied voltage is given here. So then we can use this relation voltage=I*R R is the resistance and then we replace in terms of V and R. So V square/R and then multiply by t and H/t=V square/R.

So H/t can be estimated that by using this V square and R is given. So in this case we can found out that H/t H is actually measured in terms of in this scale as a unit you would d say joule. So H/t t means in second that is equivalent to the what so then it becomes watt per unit area. So we can estimate the amount of the heat generated per unit area during the process. So here we can estimate directly that what is the amount of the heat generated and watt per centimetre square.

If we given the if welding time is defined, then we can estimate the only H=V square/R* t t means over which we keep on supplying the voltage or supplying the current in the resistance spot welding process. So that is typically in the range of the millisecond. So if it is given then we can estimate the this what is the amount of the energy in terms of joule per centimetre square.

It is actually whether this power per unit area or volume that depends what are the unit of the R is given resistance is given contact resistance or it is a volumetric bulk resistivity or bulk resistivity is given then we can we can estimate the what is the contact resistance in this case but we have to be very careful in this whether the resistance is defined what is the unit of the resistance or whether the resistance is defined per unit area or not.

Based on that we can estimate all this perimeter increase of resistance spot welding process. So thank you very much for your kind attention. So in this model we have tried to look into that different fusion welding processes and then we discuss advantage disadvantage of these different welding processes and of course we have tried to do some small problems relevant to this fusion welding processes.

So next part we will try to discuss the mathematical modelling approach in case of fusion welding process. So thank you very much.