Surface Engineering for Corrosion and Wear Resistance Application
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Lecture - 51
Electron Beam Welding

Welcome to the 51st lecture of Surface Engineering. This particular episode is connected with the generation of Electron Beam, high power density electron beam and utilization of that for welding. Though, welding is not truly completely surface engineering process, but nevertheless the process, the mechanism and the micro structural evolution these are very similar to surface engineering. And also in some other cases, the principles of welding is very well applicable to various types of surface engineering applications.

Now first of all we must realize that for an isolated neutral atom or an atom belonging to an aggregate, the electrons either to the conduction band or the valence band they are connected with the atom with certain amount of binding energy. So, obviously, the conduction band electrons are easy to eject or emit the binding energy being lower, but whether its metallic or nonmetallic systems with high band energy of band gap we certainly can eject electrons from a neutral atom by way of certain excitation.

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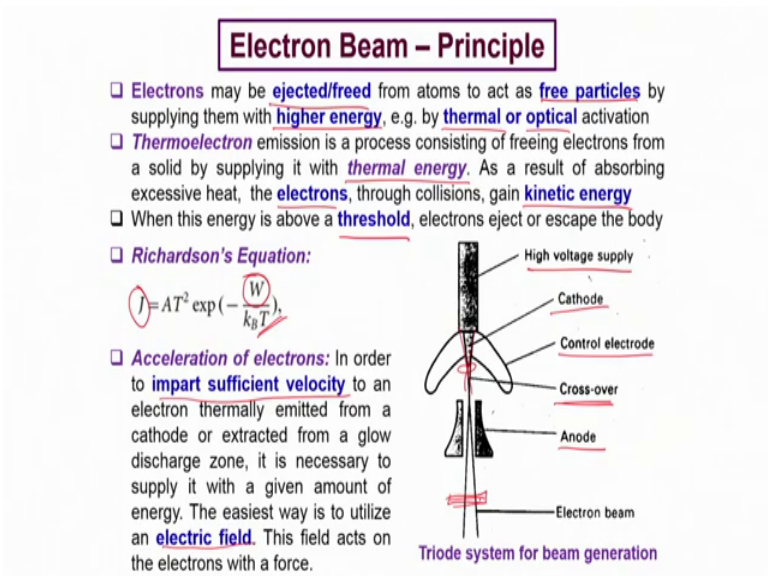

So, if you look at this view graph here, you immediately realize that for obtaining a certain flux, if you supply sufficient energy which is beyond the particular threshold then this the amount of a so called work function if you overcome that then the electrons are likely to be ejected. So, when a electrons are ejected or freed, they actually act as free particles massless, but carrying certain negative charges and so, in order to do that as I said we have to supply a external energy at a very high level either in the form of thermal activation or it could be even optical ray.

So, in the process we call them thermo electrons or photo electrons and so on. So, thermo electrons are ejected when we supply sufficient thermal energy; that means, we excite the atoms and in the process, we excite the electrons also and the once at the outer orbit are likely to be ejected when we cross the threshold. Once the electrons are ejected they gain sufficient kinetic energy and that allows them to travel and in order to make them directed, we actually have to create an electromagnetic lens system so, that they are accelerated and they move faster through a desired part.

So, for thermo electron emission we actually have to make use of thermal activation and as we see that the flux is proportional to is an exponential function of temperature. So, the whole idea is about we have to not only eject the electrons, but also impart sufficient kinetic energy. So, that move they move in a path in fact, move in a convergent fashion and this is possible again by application of certain electrical energy.

So, we should have a cathode and supply high voltage in energy and the cathode is can be typically a easy thermionic emission material like tungsten for example, which has a lower threshold for ejection of electron and also has a very high melting temperature so that is how it is very. So, it does not oxidize very easily particularly under vacuum, has very high melting temperature, retain strength at high temperature, but most importantly has a lower threshold of work function for electron emission.

So, tungsten otherwise lanthanum hexaboride is another very ideal material for electron ejection or emission. So, we use certain control electrodes which actually focus the electrons and so, they initially come through a convergent they follow a convergent path and then undergo crossover. So, this crossover is basically the focal point depending and in fact, we will see that in the actual processing this particular crossover is taken advantage of for the input of energy. The anode basically allows the beam to be focused and to be attracted towards it and then also to be focused.

And so, this is the beam that emerges and if you have a work piece here, the work piece of quiz is going to get irradiated very heavily by this incoming electron.

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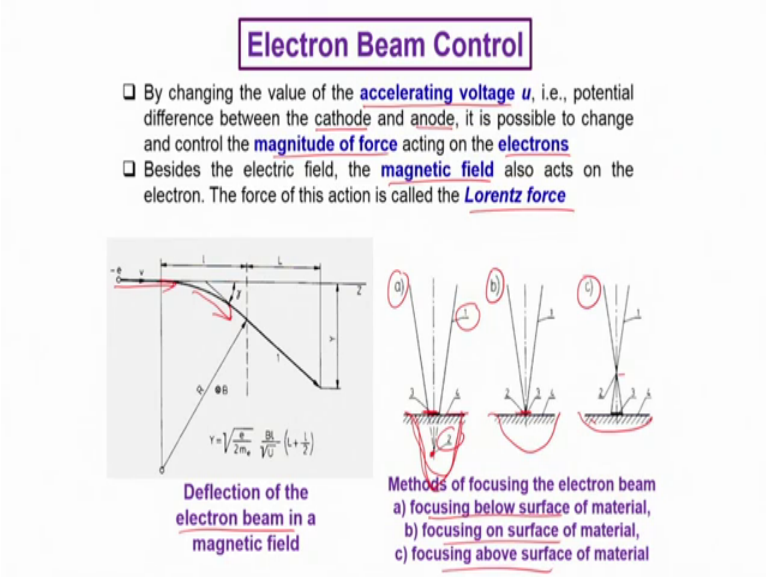

So, this is typically the triode system for beam generation. As I mentioned that if you actually apply sufficient acceleration voltage then the electrons will be acquired will acquire very high kinetic energy and that is possible by this voltage is applied between the cathode from which the electrons are emitted and the anode which is the work piece or the stage on which the work piece is located.

So, the magnitude of the force that is the electrons that they we actually this is the make the force actually controls the energy with which the electrons move and we so, when we talk about the acceleration voltage, we are talking about the electrical energy or electrical field as the measure for acceleration. But when we apply an large electric field of course, there will be a magnetic field as well at the so, called an Lorentz forces. So, apart from the electrical forces, we also have the magnetic forces and by applying or by manipulating with the current of these controlling lenses, you actually can make the beam follow a particular path.

For example if the electrons are flowing in this direction, you can make certain deviation or deflection by application of a magnetic field and this is useful particularly, in order to make the beam converge on a particular point and the point of convergence or so called the crossover point could either be below the surface for example, here so, the focal point is in this case so, this is level 3 is the substrate on which you are irradiating and 4 is a level for the sample and 1 is the electron beam.

So, the focus of the beam which is a marked by number 2, is in this particular case a, below the surface in this case b, it is coinciding with the surface and in the last case c, it is above the surface. So, as a result one can easily intuitively understand that the maximum amount of energy that you are supplying to the material will vary.

So, the max, this is the point where it is not just the energy also the maxima of the energy where it is deposited. So, when the energy is deposited below the surface then; obviously, the so called heated zone would be deeper, when it is coinciding with the surface then also it will be fairly large, but the shape of course, is going to be more of semi circular or electrical. And in case, where the beam is way above the surface or certainly above the surface then the shape will be shallower.

So, I can have anything like a conduction melt pool to deep penetration melt pool by way of simply shifting the focus with respect to the position of the surface or substrate surface. So, this is exactly, what is shown here in this particular figure.

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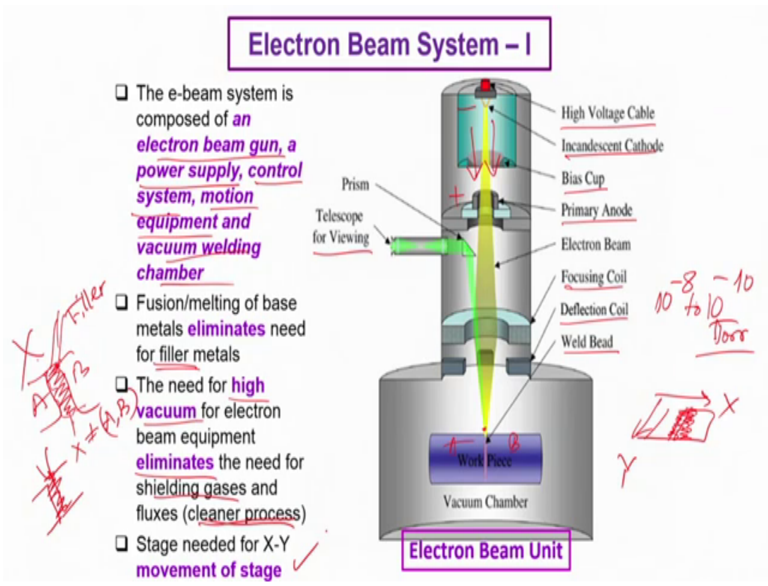

The electron beam unit, we already have discussed that the principal things the principal features are the following that we supply very high voltage to the cathode and the cathode emits electrons, we have certain bias cup grids through which the electrons flow and then we have a primary anode. And then this is where this is why the electrons actually would certainly flow in this direction because this is the polarity, which actually drives the electrons to move in this direction. And then through this primary anode with a certain central hole, the electrons pass through and then eventually this is the crossover or the so called point so called focal point.

Now, so if this is the work piece maybe this is A and this is B, we can join along this particular seam and so that is what we call a weld bead. But in order to make the beam fall exactly at the point and move also and maintaining a certain geometrical coordinate, we need certain focusing and deflection coils and these are as I said through the Lorentz forces or the magnetic lenses which control this the precise location.

We also need to see now electrons actually there will be certain weaving necessary because, otherwise the whole process may go here where so, we have to make sure that we are able to see so here is a viewport and the viewport actually allows optical raise to be incident on to the spot and then reflected back so that, we can use this as a viewing window and the prism allows exact location of the beam onto the point of interaction.

So, the system essentially will have an electron beam gun, a power supply which supplies very high voltage, the control system, the motion of the equipment not only the beam has to rest it otherwise if this is the sample we are talking about then and if we have to for example, if we plan to weld along this path then we need to apply we need to allow the beam to move with this direction. In fact, in some cases if we want to irradiate the entire surface or larger area of the surface then we have to actually have to allow the beam to oscillate over the surface.

So, in that case, we need a movement both along X and Y and then of course, a chamber which is at very high vacuum now that is a very important part which we should spend a minute on. Electrons if it is to encounter air or atmospheric gases inside the chamber then it will lose its kinetic energy very easily so there will be a lot of collision and in the process it will lose its energy and will be deflected. So, there will be also unnecessary ionization in the chamber if you have gaseous gases present inside. So, this chamber before the beam is put on or the energy supplied for electron emission, first has to be evacuated and this has to be very high vacuum easily 10 raise to 8 to about 10 raise to 10 Torr.

So, fairly high vacuum is needed. So, this is what I was saying we the advantage in case of electron beam is that in case of welding here, we do not need to use any filler metal. Now for example, if you want to join A and B and if you use a filler metal the filler will have a different composition and so; obviously, when we allow the filler metal to be melted and flow into the gap then of course, it is an easier way of wetting these two parts and joining them well, but in the process the composition here is going to be different this composition is going to be different than either A or B.

So, that creates the thermal stresses that creates other issues in case of electron beam, we do not have to do this, we in case of electron beam, we simply can use A and B and the beam here can simply melt these parts. So, there is no need of any filler metal; since we are not using any filler metal so, the composition is exactly the same so, you retain the same substrate composition. You also eliminate the need of shielding gases now in case of normal welding particularly in case of tig or mig or advanced type of welding processes, you need a shielding gas to avoid unnecessary oxidation during welding process.

Since this is in large vacuum as I have just now said so, there is no need of any shielding gas so; that means, there is very little contamination, there will be extrageneous contamination possibility. So, it is a very very clean process, but of course, in order to manipulate we need certain movement of the stage either in X or both X and Y directions.

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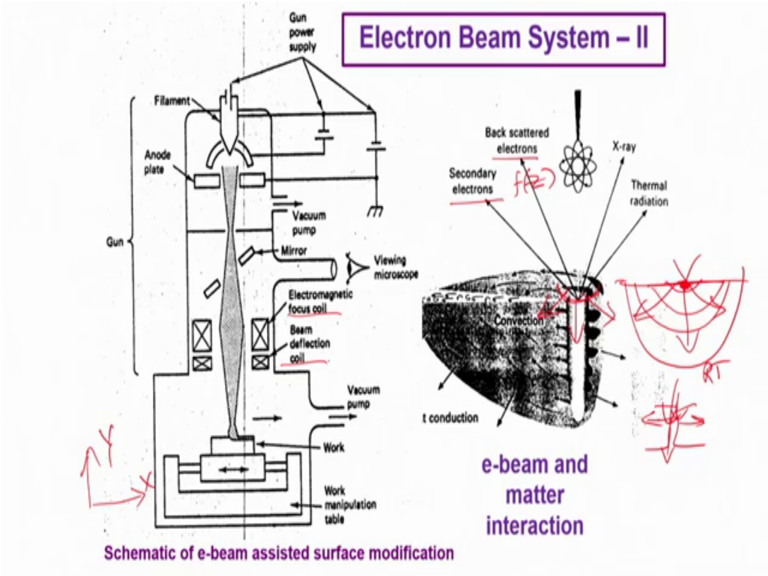

So, this is the overall chamber this is the gun side. So, emission then focusing deflection and then eventually irradiation onto the substrate and in fact, through this mirror, you actually can change the direction not like optical rays, but electromagnetic focusing lens. So, this is the focusing lens and this is deflection lens through the Lorentz forces, you actually can change the shape of the beam and also make it convergent onto a point.

And then as I said there will be a manipulation table so, the manipulation table will allow you to move either X and Y direction in this case, but before you start the process you first have to evacuate. Now, when the beam actually irradiate so, if this is the substrate and this is where the beam is incident now this region will actually immediately before the incident energy, the electron beam energy is absorbed and converted into lattice heat sensible heat certain process can happen. So the incident beam is a stream of electrons carrying certain energy and charge is liable to produce also certain or make after incidence can actually emit certain other types of rays.

For example it can emit electrons; it can emit secondary electrons or backscattered electrons. Now, secondary electrons are basically loosely bound electrons which are ejected from the surface, backscattered electrons may actually carry certain relationship with the atomic number of the substrate. So, whatever it is, I mean they carry their own kinetic energy and obviously, you cannot just allow them to escape into the air so, they carry enormous energy and they can certainly cause very major damage to either inorganic metals or other solids substances, but if it also happens to for example, come in the way of in human tissue it can certainly damage burn and so on. So, one has to take care of these things.

So, the heat that is generated here is through a process of activating the electrons to higher energy state and then subsequent falling back into the lower energy state. So, in the process the energy is absorbed by the lattice that takes certain period of time, but usually very very fast process, but the most important thing is once heat is generated, then heat flows usually in the vertically downward direction, but also in lateral directions.

So, you actually create a zone below the radiation spot, which is at a higher temperature in fact, if you can draw, you possibly can show that there will be such iso temperature contours and this contour is ideally one would like to see a one dimensional heat flow. So, that in case of a welding, you actually we will see as if the heat is flowing only in the vertical direction downward.

But that is not possible because heat will be conducted not only in the vertical direction, but also in lateral direction. Of course, one can try and manipulate with the beam size with respect to the material that you are dealing with to make sure that the beam diameter is fairly wide and as a result the heat conduction will be more into the vertically downward direction than the lateral directions, but nevertheless you cannot prevent heat to the flow by in the lateral directions. So, initially there will be heat conduction and subsequently there will be a melt pool and there will be heat convection and there will be also radiation from the outer surfaces.

So, heat will flow out and below a certain depth the temperature will be the highest at the surface and obviously, temperature will be lowest at the or gradually will decrease along the directions of x y and z and there will be at; there will be certainly a line or a semicircular boundary beyond which the substrate will still remain at room temperature.

Now, I mentioned the need for vacuum. So, if the whole solid is under very high vacuum then heat transfer is actually slow and as a result there will be considerable heat buildup around this. In fact, one needs to be; one needs to design the process such a way that excess heat generation is avoided which may lead to evaporation from the substrate or creation of certain depression onto the weld zone.

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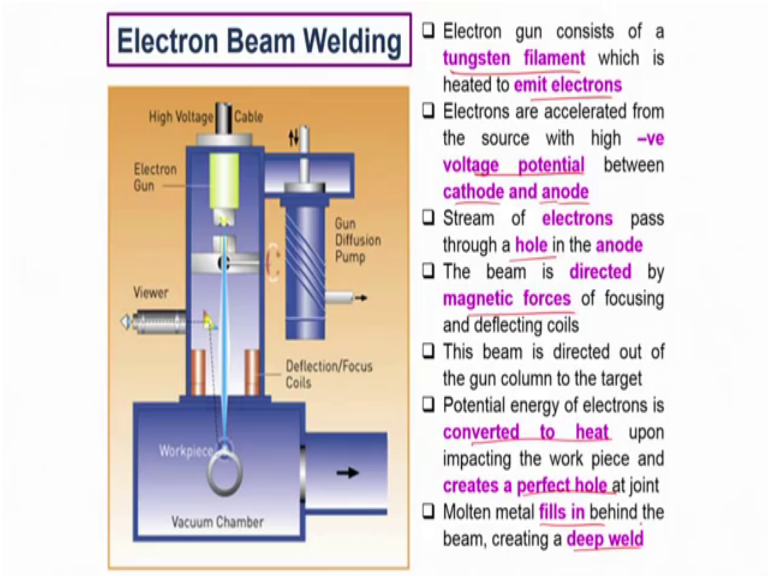

So, this is another view of the beam welding unit which will possibly have a tungsten filament which will emit electrons very high voltage applied between the cathode and anode for electrons to be directed. And the stream of electrons actually will pass through the hole the so called anode with the with opening and then you use the magnetic forces of the focusing and deflecting coils to make them incident at the desired spot.

And once the electrons interact with the solid substrate then it will convert gradually the incident energy that the kinetic energy that the electrons are carrying into lattice heat. And this creates a so called hole at the joint and then immediately the wall around the hole will collapse because of high temperature, get molten and we will fill up the gap. So, that is how you create a deep weld you can create a very deep weld.

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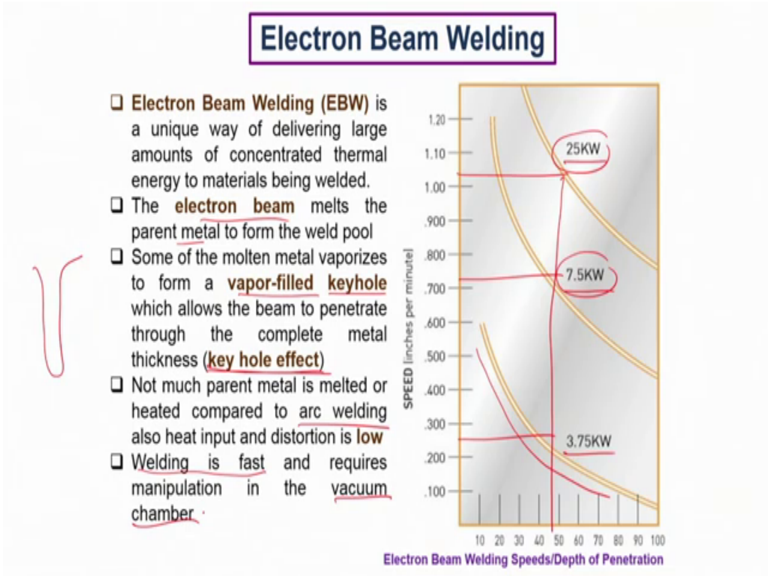

Now, process parameter wise of course, you actually would like to control the flow of electrons will depend upon the potential that you apply at the at the cathode side. So, the beam current so called beam current or the applied voltage at the for thermo ionic emission thermo electro thermo electron emission is very important.

So, you can control the excitation current that is supplied to the cathode, you can control the voltage that you apply between the cathode and the anode and the level of vacuum that you maintain inside also the focusing the current at the focusing and the deflection lenses electromagnetic lenses there that also will make the beam narrower, sharper or wider.

And accordingly the power density will vary. Finally, the beam spot size including the location of the crossover or the focus with respect to the surface if whether its below the substrate surface or coinciding with the substrate surface or above the substrate surface, will determine what is the effective energy density that you are supplying on to the substrate surface and depending upon that energy.

So, the point is if actually if you have if you apply a higher amount of a excitation voltage so, higher the voltage so, for the you. So, this is basically the variation of speed versus the depth so, if you increase the speed then; obviously, the amount of energy that you are allowing to be incorporated will decrease and hence the depth will decrease.

So, as you increase the speed that this is the general trend the depth decreases, but for the same depth in order to achieve the same depth, you actually can afford to use very high speed, if the incident excitation voltage is higher. So, for a given applied voltage the electrons will carry the amount of energy that the electrons carry will be proportional to the applied voltage. And hence, you can achieve for getting the for maintaining the same depth let us say for maintaining this level of depth, the speed that you can afford to make a afford to actually move the beam or move the sample stage that speed can be much higher if the applied voltage is higher compared to the lower voltage levels.

Now, the electron beam melts the parent metal and there is no filler. So, the molten pool subsequently solidifies and in the process form good metallic bonding, the there could also be a possibility if the amount of energy input is so high that you actually create a hole the so called keyhole which is. So, it not only melts if you actually give so much of heat input that you also encounter evaporation and with the evaporation, there will be a certain amount of region filled with the vapor and in the process you actually can if you trap that vapor film you actually will retain a hole inside and that is not desirable.

So, you actually create this pole only to increase the energy absorption capacity and this is what is known as the keyhole effect, but eventually the gases or the vapor that you create collapses and gets filled with metal. But because the presence of these vapor filled hole, you actually are able to connect or couple a higher increase the coupling of the energy to a higher level and in the process the heat penetrates deeper inside. So, you end up getting a deep penetration hole like this and that is the so called keyhole effect.

Now, the in case of arc welding, you actually will end up creating more volume melting the melt volume the melt pool volume will be larger, in case of electron beam you actually can confined to very narrow region it can be deeper much deeper than arc welding or other kind of tig or mig welding, but the total melt value is smaller. So, which is even more beneficial because, then the not only the weld pool is shallower will not only the weld pool volume is smaller, but it is a actually deeper not shallower and at the same time the total heat affected zone will be smaller.

So, the total thermal shock that you apply will be lower, but you actually have to you prefer to have a welding process which is fast enough. So, you need a faster speed because otherwise there will be huge accumulation of heat and will lead to unnecessary welding of regions which are not required to be molten, but I mentioned about the role of the vacuum chamber. But vacuum chamber is desirable because we need to actually reduce or prevent any kind of undue oxidation or any gas metal reaction, but the high vacuum also works against the interest by reducing the cooling rate that is possible. So, we have to that is why we cannot afford to do it very slowly at maintaining very high vacuum.

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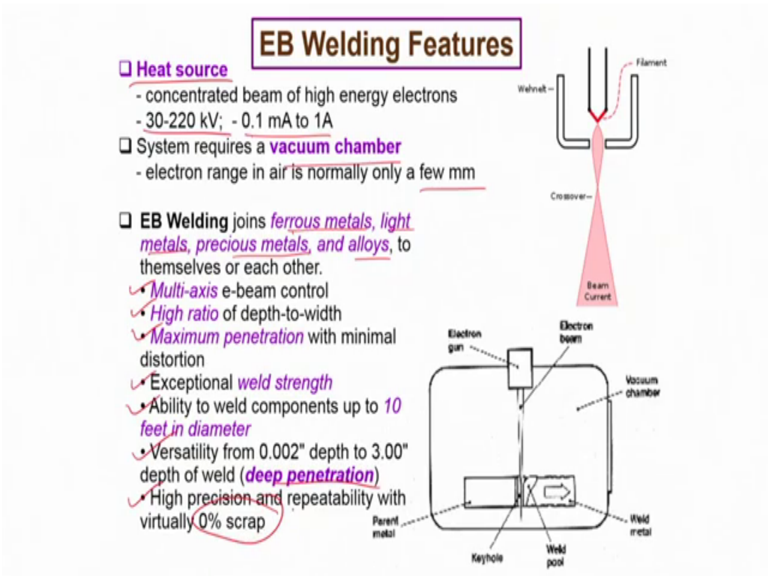

So, typically you have a heat source applied voltage would be anything 30 to several 100, 30 to 300 let us say in that range of kilo volt and the current will be 0.1 to 1 ampere edge. So, you have a high vacuum the electron range in air is normally a few millimeters so, you actually require a very high vacuum otherwise the beam will not penetrate or flow.

You can subject all kinds of iron based metals or light metals like aluminium, titanium or precious metals and alloys they actually they you can join let us say aluminum to aluminium, but you may also try to join aluminium with another metal and this kind of a similar or dissimilar welding is better conducted in an electron beam welding setup than normal or conventional welding processors.

So, you can have that is because you can have multi axis beam control, high ratio of depth to width so; that means, you can make a deeper penetration and the maximum penetration with minimum distortion similarly the weld strength that you derive will is supposed to be all is known to give better in fact, you can also make very large welding inside if it can be accommodated inside the chamber then there is no limitation.

So, you can also make deep penetration and the precision and reproducibility both are extremely high and another very important or interesting feature is that, there is particularly 0 percent scrap; that means, in case of welding normal welding processes, you actually end up creating certain laps or excess parts which actually are machined out or ground off and so on. But in case of electron beam welding, you actually do not need any post processing machining at all so; that means, there is no scrap or undesirable parts of the material.

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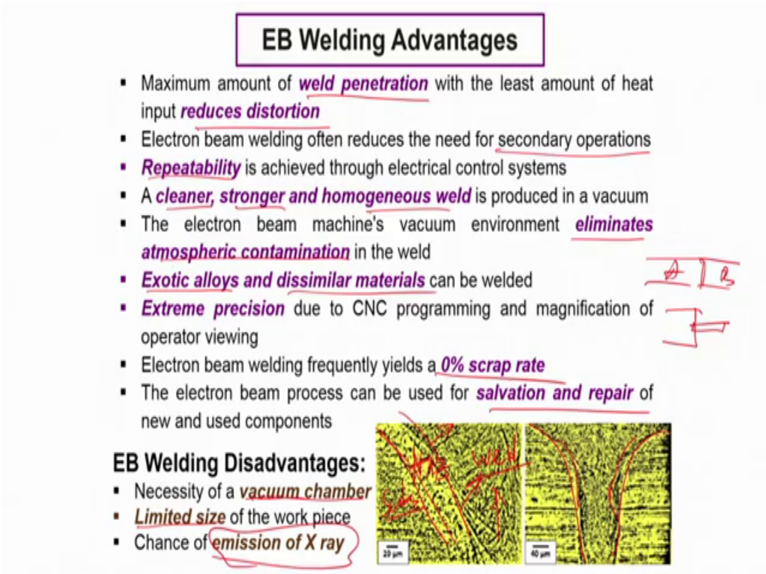

So, I already mentioned advantages let me list out again the maximum amount of weld penetration, very little distortion there is no post welding processing required. So, there is no need of any secondary operation, there is always a very good repeatability, one can create a cleaner, stronger and a more homogeneous joint and because of the high vacuum, there is no chance of contamination coming from oxidation or any other gas getting absorbed. Various types of very important or sophisticated or expensive alloys can be welded, can be treated in electron beam easily and also dissimilar materials for example, aluminium to titanium or nickel to titanium and so on.

Now, these are not easy processes, but if at all it is possible through fusion joining then electron beam is the material is the process. In fact, by dissimilar one usually means that

I am talking about A and B, but that A and B need not be compositionally different in fact, you can try to, if you want to try to weld a thinner section to a thicker section, that also is dissimilar welding. Now, if these materials are reactive type particularly in the presence of oxygen or any other gaseous substance then electron beam welding is always preferred. I already mentioned that there is no scrap at the end of the welding so there is no material loss.

Another very important application we will discuss that in the next lecture is about the possibility of a restoration or salvation and repair jobs. But the difficulty is that, you require a very high vacuum and the whole chamber needs to be at in very high vacuum so, this is a very expensive affair and its difficult affair because you need to maintain not just heat normal I mean a low vacuum, but very high vacuum.

Also because you are dealing in a chamber inside a chamber vacuum chamber so, that puts a limitation that you cannot take large sample, if you have to weld something by electron beam then the chamber size has to be extremely large because you cannot take the electron beam out in air and then pass it on and make it incident on a solid substrate outside vacuum.

Once the beam comes out of the vacuum then it cannot travel more than a centimeter or so before it gets completely dissipated. Another very important hazard of electron beam processing is that high energy electron beam when it actually gets rapidly decelerated then it is likely to emit X ray.

So, not only the emission possibilities exist for secondary and backscattered electrons also there is possibility of emission of X ray in fact, this is the reason why all electron beam chambers will actually be confined or covered by a very thick sheet of steel or other extra absorbing materials. And generation of X ray is a quite possible because we are applying over 200, 300 kilovolt, electrons coming at very high energy incident on the solid substrate maybe a metal and gets rapidly decelerated and in the process there will be emission of continuous way of X ray.

So, if this is the deeper penetration weld that you actually can create. So, along the substrate this is the biggest one of the biggest advantages is that along the when you zoom in go to twice the magnification, you easily see that this is the substrate side.

So, this is the substrate size and this is the higher heat affected zone and so, this is substrate and this is the weld micro structurally its almost seamless there is no major crack or discontinuity even the micro constituents of shape size of the phases are very comparable and in fact, the growth within the melt pool from the wall would be like this, so, it is a very uniform or a smooth surface the weld substrate interface is a very smooth surface.

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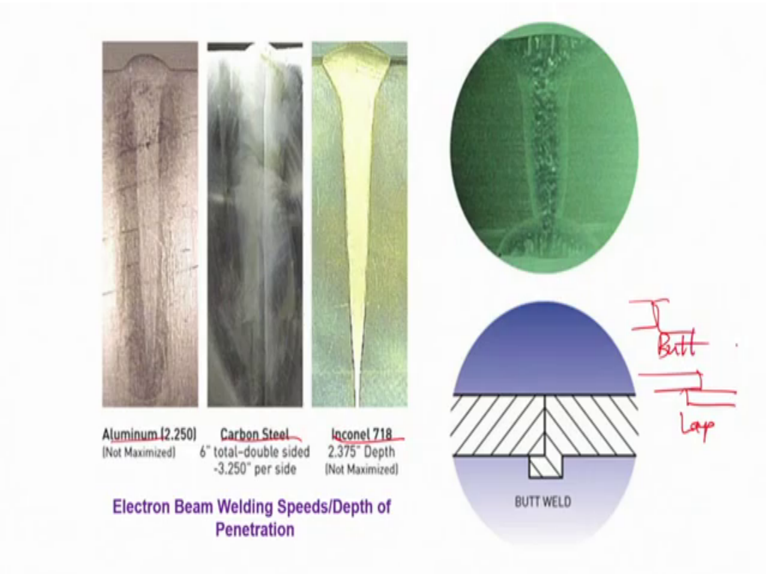

So, these are just examples picked up from various sources to tell you that, you can weld aluminum, steel, nickel based super alloy, merging steel, titanium alloys, magnesium alloys, very reactive alloys elements and so on and usually these welds are all in butt configurations so somewhat like this, but in it is also possible it is quite possible that you can also do in lap configuration.

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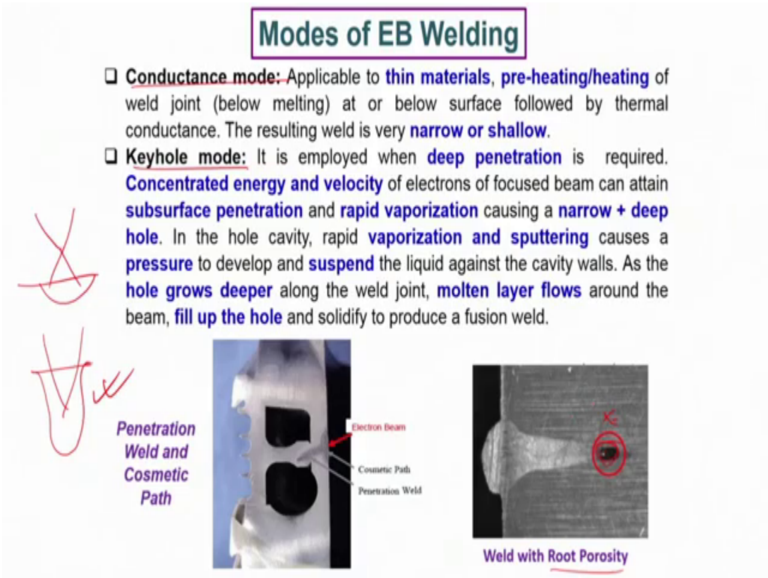

So, there could be two major modes of welding, conduction mode and the keyhole or the deep penetration mode. So, if the focus of the electron beam is here, then the melt pool that you create is shallow and wide. So, you call it a conduction mode, conduction melt pool or else you can have a situation where the crossover of the electron beam is below the surface and there the weld pool that you create is deep penetrating type or a keyhole type. So, this is the biggest advantage of electron beam welding in fact, the thickest possible sections that you can that if you need to weld, will be more amenable to electron beam welding then the conventional types of welding.

Of course, one needs to avoid this kind of a defect, where the metal that flows in cannot fill up the gap and as a result you actually are left with certain gap at the route or which are called route porosity, but the maximum penetration that it can happen without bringing in a filler metal is possible only with electron beam.

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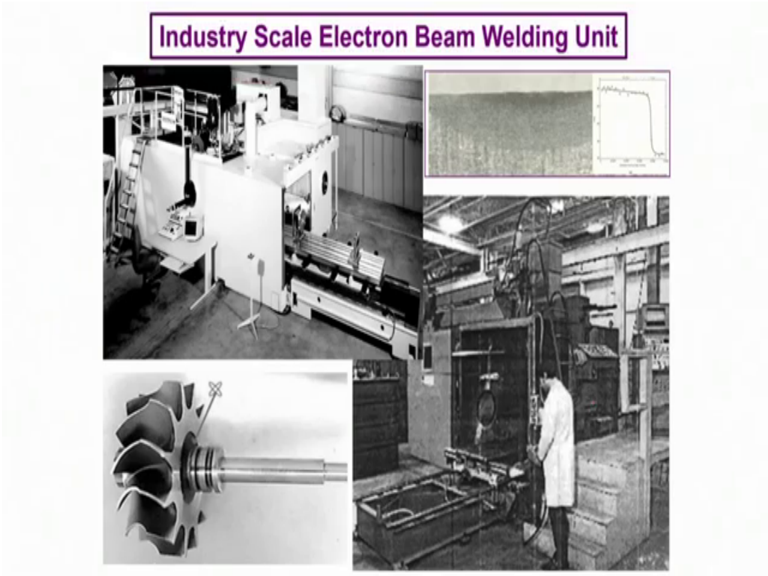

So, these are large industry scale applications, just to give you a feel of how big the machine could be I mean this is easily cannot be done inside a normal room like this has to be done in the shop floor. If you are trying to weld very sophisticated and large components like this rotor then it has to be done inside such a huge chamber so, bigger than an usual furnace and so on.

And also you may require a special sample handling processes, but if there is a very sophisticated unit that you are trying to weld or do a surface treatment like a component of a fusion reactor or a some parts of a big submarine or ship or even some of the aircraft or automobile components which are complex in nature, then you require a large electron beam unit for welding like this.

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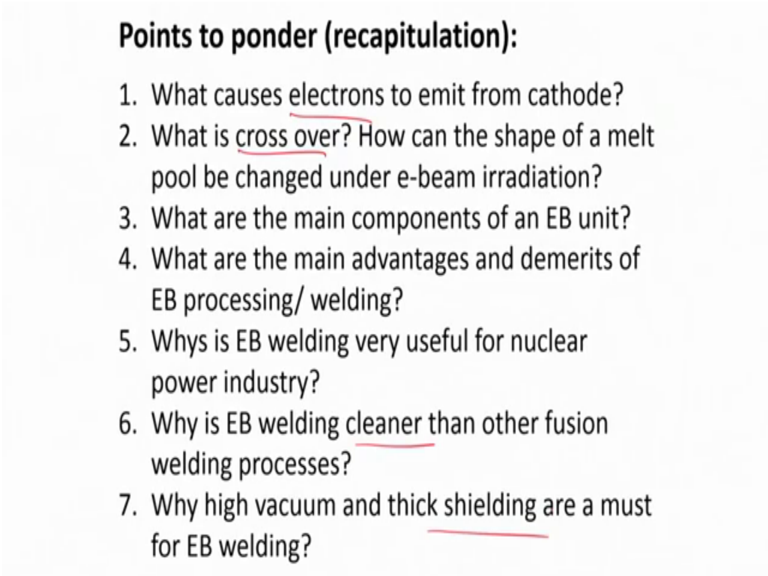

So, let us try and wind up now so, first thing we have to understand that the agency for heating here is electrons and these electrons are emitted from the cathode by way of thermal activation so they are thermo electrons. The crossover is basically the focal point and depending on the location of this crossover or the focal point with respect to the substrate surface, we can have a deep penetration or shallow or conduction melt pool.

So, we need component wise whole unit will require the cathode, the focusing lenses, the anode, the deflection and focusing lenses, electromagnetic lenses, very high vacuum and then sample handling stage for manipulation in x and y direction maybe also theta rotation and so on.

So, there are large number of advantage very attractive advantages for electron beam assisted welding, but there is also demerit there are a few demerits like large I mean chamber size limitation, high vacuum, scope of X ray emission, then various I mean accessories needed for supplying high voltage, maintaining high vacuum and so on.

But then when you are dealing with very sophisticated or crucial components like for a nuclear power reactor or a submarine or a special chemical plant or something which you cannot weld, you cannot afford to weld because of possibilities of contamination or very weaker, very deeper penetration of welding, in such a very specialized cases; obviously, electron beam is the final, I mean one of the best possible answers that is possible.

And the penetration depth is one of the biggest or the unique advantage of electron beam welding, if you really need very deep penetration, very deep welding then; obviously, you would prefer an electron beam over either conventional or even sophisticated techniques like laser beam.

It gives you a very clean surface very clean weld because of lack of because of absence of filler metal or lack of any atmospheric gases in the chamber and so, one of the cleanest possible, cleanest possible technique for adopting fusion welding as a method.

We require a very thick shielding that is one of the, I mentioned already one of the biggest so called requirements to ensure that there is no emission of secondary or backscattered electrons, from the chamber and most importantly no X ray which is more penetrating than the electrons themselves out of the chamber so, you need thick lead shielding at the surfaces to prevent that.

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So, overall we realize that the electron beam is one of the possible three possible directed energy beams, which is ideally suited for deep penetration welding and this is where it scores an advantage over all other possible either direct energy beams or other sources of heating. But of course, we need a chamber or sophisticated and a very crucial chamber with certain features and handling also requires certain amount of skill sets right. So, we will stop here and in the next lecture, we will discuss about the utilization of electron beam for surface engineering.

Thank you.