Metal Additive Manufacturing
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Lecture 04
Metal Additive Manufacturing, Glossary (Part 1 of 2)

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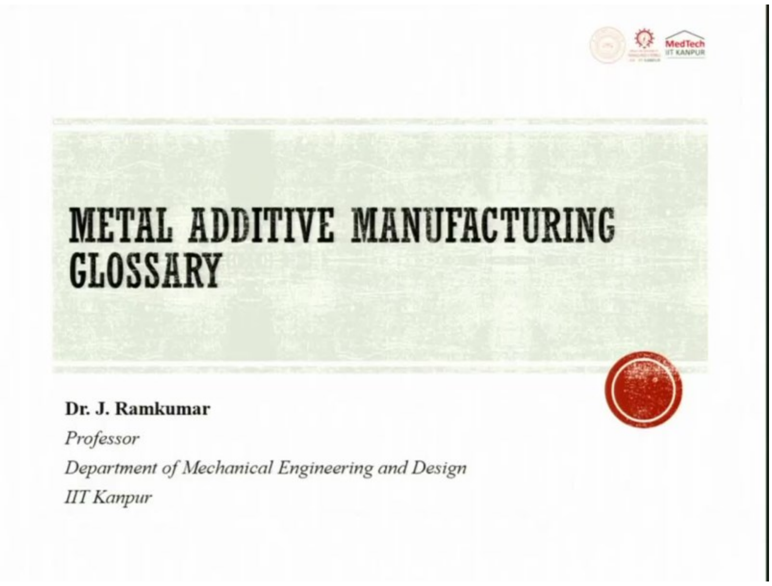

Welcome to the next lecture in metal additive manufacturing. This lecture, we will cover different definitions, phenomena which are involved in additive manufacturing. In short, we will be looking at that glossary.

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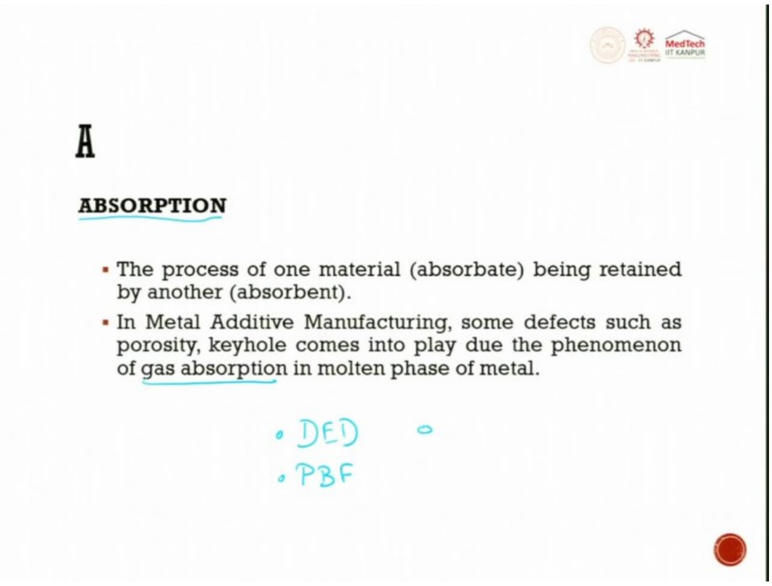

The first important phenomena, which happens in metal additive manufacturing is absorption. The word itself clearly says absorb, absorption the process of one material being retained by another. In metal additive manufacturing some defects such as porosity, keyhole comes into play due to the phenomena of gas absorption in molten phase of metal.

So, here last lecture we saw there is DED process the other one is PBF process, powder bed fusion, directed energy deposition. In both the cases what happens is, you will start with a powder, this powder will be melt and then this tries to fuse with the neighboring powder while doing so, if it absorbs or if there is an adsorption on the surface of oxygen, then that will lead to gas absorption. So, absorption is a phenomenon which is very important for two reasons. one gas absorption, 2 what is the influence of the heat source which falls on the powder. That is also termed as absorption.

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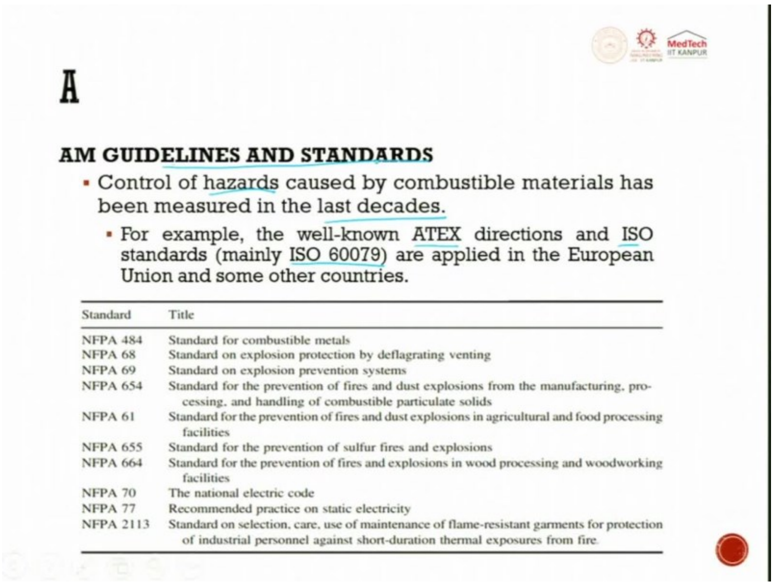

The next important thing which you have to know in AM is AM guidelines and standards. Though AM is a straightforward process where in which you start with a CAD file, tessellation, layer by layer slicing, then you do the process, post process if it is required you do so, these are the sequence of steps you know, but in this sequence itself, you have to understand there are several standards which are established, when we have to make a market worthy product or a customer worthy product it has to follow certain guidelines and standards.

So, here we are going to talk about control of hazardous cost by combustible material that has been measured in the last decade. So, here are some of the standards which are released by

ISO and ATEX. So, ISO mainly 6000 or 60079 series talks about this combustion. So, standard for combustible material explosion, protection by defragmenting venting, explosion prevention system. If you look at it, these are all more in details and all I have to tell you is AM also has guidelines and standards today. Please look at the standards when you are trying to develop your product or part for market worthiness or to put in service condition.

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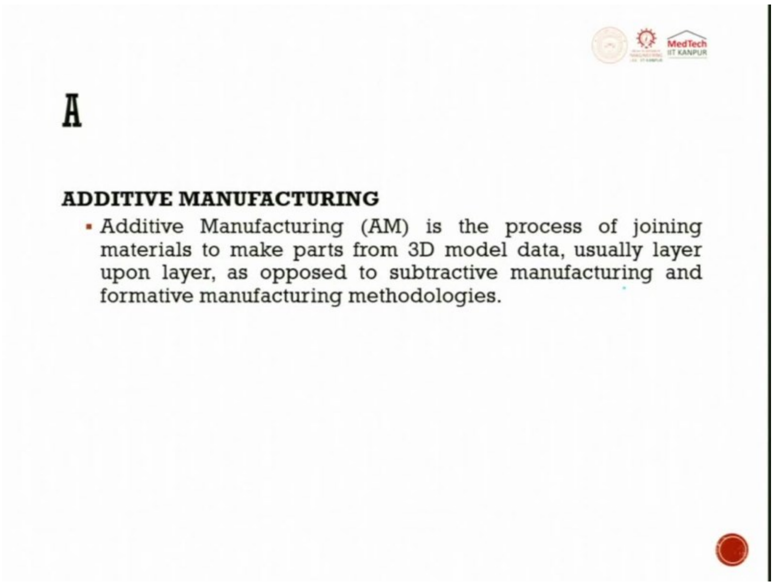

Additive manufacturing- multiple times we have seen that definition additive manufacturing is the process of joining materials to make parts from 3D model data usually layer upon layer as opposed to subtractive manufacturing and formative manufacturing methodology.

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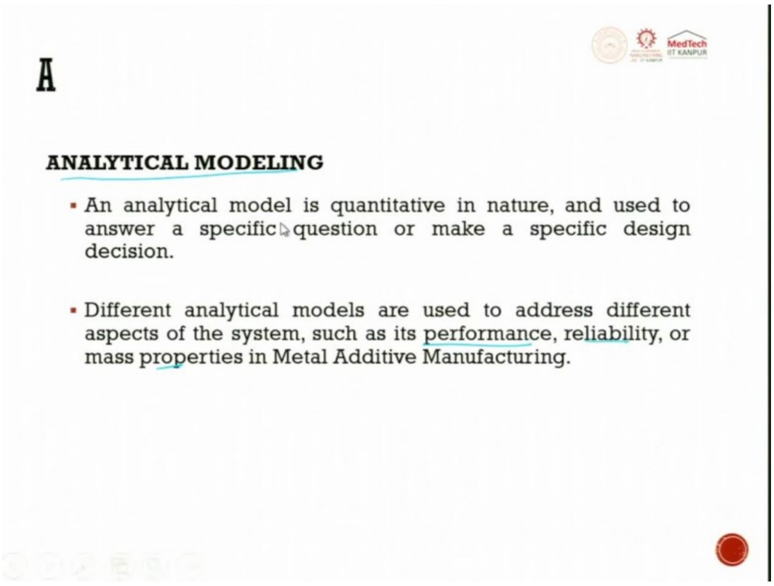

If you want to understand additive manufacturing and have to control the process nicely, you have to understand the analytical modeling of additive manufacturing. There are two types of modeling: One is statistical modeling, the another one is analytical modeling. In analytical modeling, we try to take the basic fundamentals and try to develop a model where the science is involved to get to a finished product.

And analytical model is a quantitative in nature and used to answer a specific question or make a specific design. Decision is done by this analytical modeling, when we cover the process in depth, we will try to also touch upon and cover few of the analytical models which are involved, why are these models so very prominent because by doing modeling you can do simulate the process and understand the cause for the defect.

So, wherein when you do the experiments, you do not make such mistakes, different analytical models are used to address different aspects of the system such as performance, reliability, mass properties in additive manufacturing.

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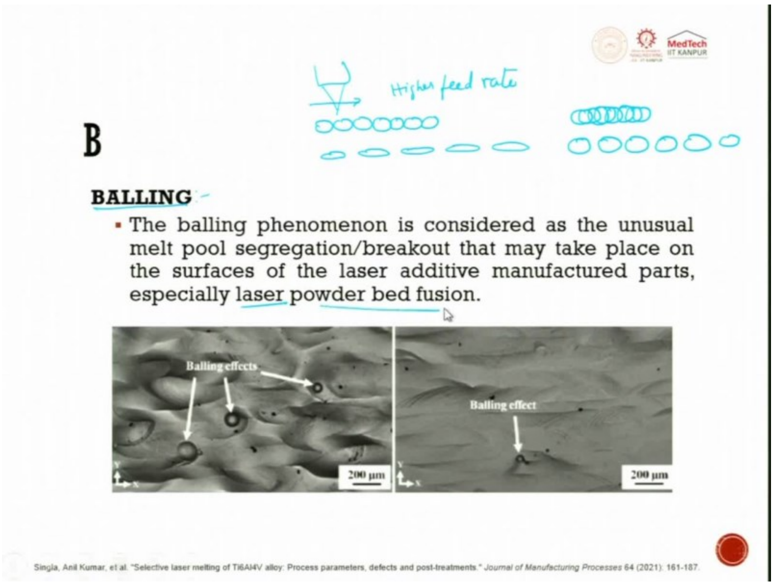

Balling, balling is a phenomenon which is very common, when there is an improper choice of process parameters. So, when you have material, which are all powder in nature, and when we try to move the laser or electron beam across it, so, if we have a higher feed rate, or if the power is very low or the viscosity behavior of the material or the surface tension behavior of the material, if it is not properly sink, then the balling effect comes into existence, the balling phenomena is considered as the unusual melt pool segregation slash breakdown. So, instead of this continuous what happens in balling is you will have melt solidification of metal powders like this. So, this is called as balling.

Balling phenomena is considered as an unusual melt pool segregation/breakdown that may take place on the surface of the laser additive manufactured part especially, laser powder bed fusion. When we try to move at a faster rate, when the feed rates are small or low, what happens is you will have an overlap of the spot. This is at a lower feed rate when you have a higher feed rate, you will have your mark which is made like this. So, when this happens, then the material melts and it surface tension dominates it rolls and makes like small balls. So, this is a major defect which comes while using laser in powder bed fusion.

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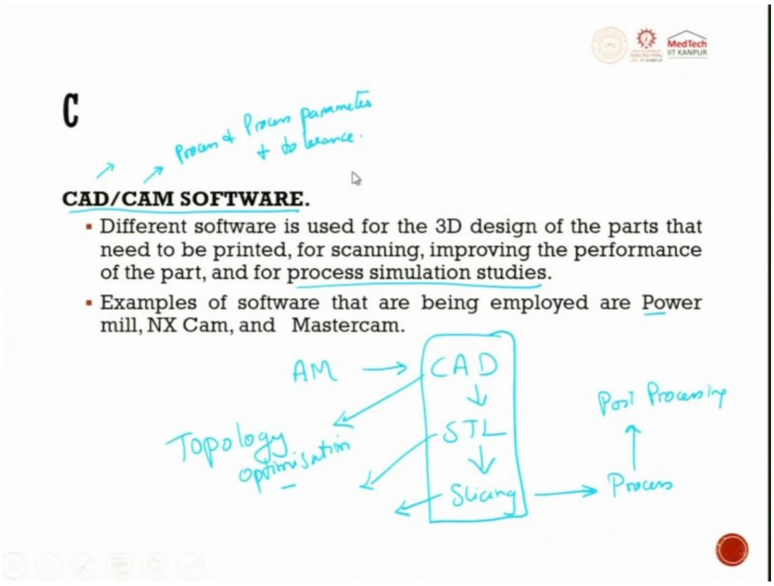

CAD CAM software, the CAD CAM software is very important because in additive manufacturing we use CAD followed by that is STL file, tessellation, then we try to do slicing, and then we try to take the process or the machine and then we try to do post processing. When I try to talk about the software, I club all these things and then on top of it I also tried to do topology optimization for size, shape, strength and STL files for error prevention, slicing to reduce the layer thickness and to increase the production process.

So, all these things predominantly go around the software which is involved. So, there are CAD 3D software available exclusively for additive manufacturing. There are the softwares, which are used in developing supporting structures for CAD, all these things are available. So, different software is used for the 3D design of the parts that need to be printed for scanning, improving the performance of the part and for process simulation studies. So, both we try to use the software. Example for software that are used generally in CAM are Powder Mill, NX cam and master cam. So, CAD is used. CAM also tries to give you the process and process parameter details apart from tolerance. So, all these things are given by CAM software. So, CAD CAM is very important as far as additive manufacturing is concerned.

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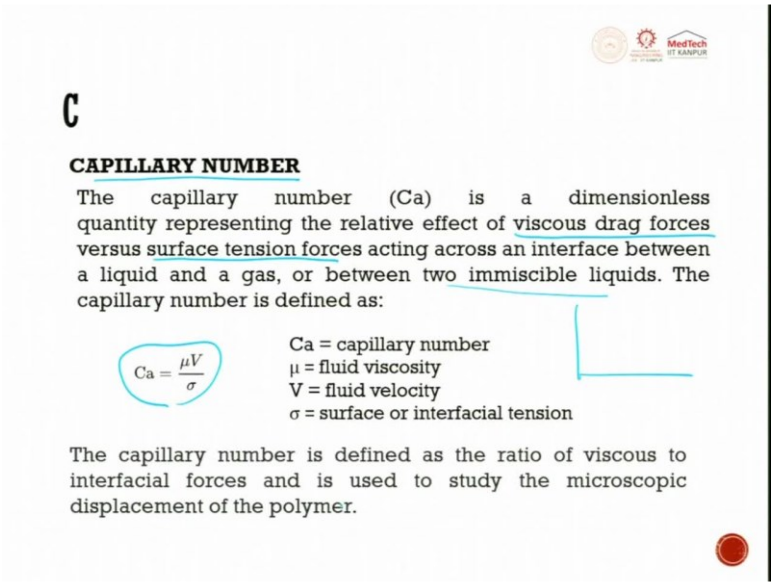

There is something called as a capillary number. So, this is also very important, because when you try to melt a metal powder or a ceramic powder or a polymer powder, there is always surface tension phenomena happening. So, this surface tension phenomena will try to give you a poor quality or yield a bad quality product. Capillary number is a dimensionless quantity representing the relative effect of viscous drag force versus surface tension force acting across an interface between a liquid and gas or between two immiscible liquids.

So, when we use alloys, it can give you two immiscible liquids when you try to build a functionally graded material, you will have these two immiscible liquids in some cases might happen and where in which you have this interface between liquid and gas, you try to have a viscous drag force and surface tension force it is a plot between these two. The capillary number is defined as:

$$\mathrm{Ca} = \frac{\mu V}{\sigma}$$

Ca = capillary number
μ = fluid viscosity
V = fluid velocity
σ = surface or interfacial tension

So, this tries to dictate the capillary number, capillary number is defined as the ratio of viscous to interfacial force and is used to study the microscopical displacement of polymers or metals in particular.

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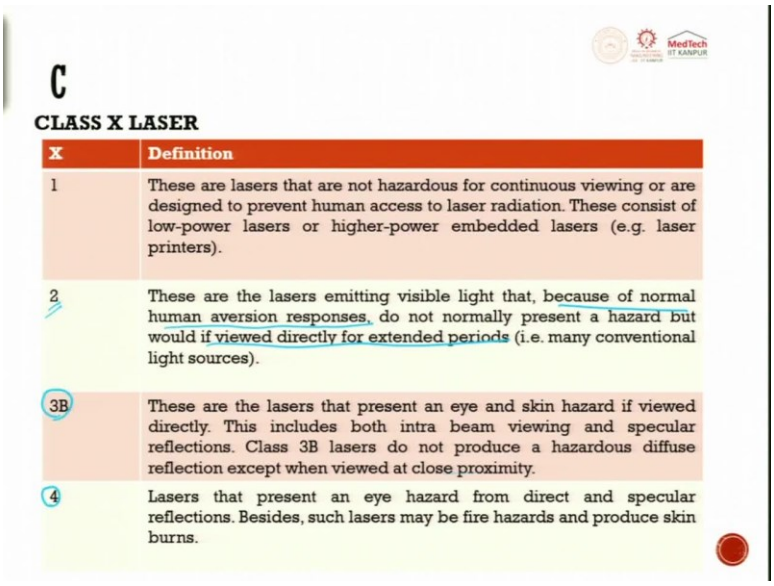

So, when we try to define about laser, laser is defined by various class. So, you can have class 1, class 2, class 3 B, class 4. So, you have to understand which of the class laser is integrated into the machine and what it can and what it cannot do, when we talk about Class A or class 1 laser, these lasers are nonhazardous for continuous viewing or are designed to prevent human access to labor radiation. These consists of low power lasers or high-power embedded lasers. example laser printers.

So, all these things use Class A laser which is very safe. Class 2 lasers- these are lasers emitting visible light that because of normal human aversion response, do not normally present a hazard, but would if viewed directly for extensive period that is, many conventional light sources are falling in this class 2 where if you view it for a longer time, because the normal human aversion response do not normally present a hazard, but would if viewed directly for an extended period.

So, this is called as class 2 laser. Class 3 lasers are these lasers that present an eye or a skin hazard if viewed directly. They include both intra beam viewing and specular reflection. Class 3B lasers do not produce a hazard diffuse reflection except when viewed at a closer proximity. But class 4 lasers present an eye hazard from direct and specular reflection, besides such laser may be fire hazardous and produce skin burns. Generally, what we do is we try to use class 4 or class 3B in additive manufacturing.

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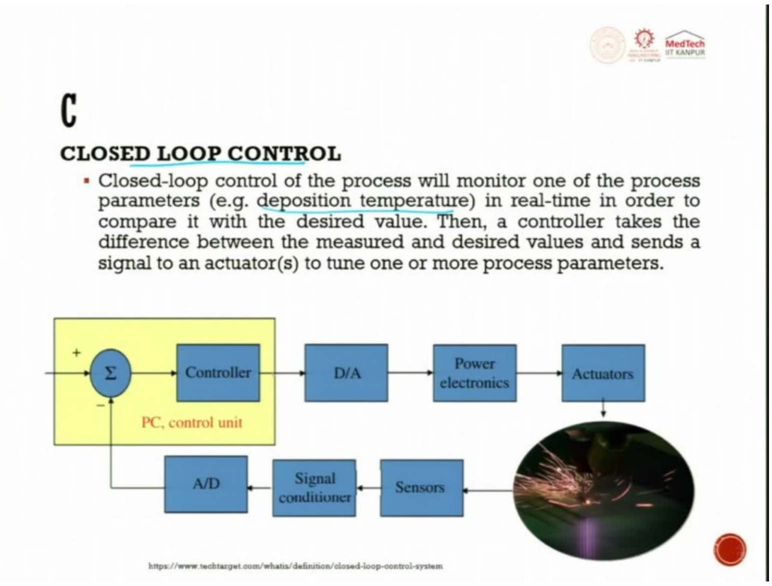

Today, we are talking about industry 4 point 0 and we are trying to talk about smart manufacturing where in which additive manufacturing plays a role. If additive manufacturing machines have to be made smarter and more productive, they should have a closed loop control. So, what is a closed loop control there is a controller then there is a digital to analog converter, you have a power electronics you have an actuator, then a sensor that is used to measure the actuator movement and this gives us a signal and this signal is conditioned and it is converts analog to digital data.

And then it is summed up in and it is given to the summation where a new signal comes and the old existing signal path or point is referred that difference is calculated and based upon the difference again the controller is moved. So, this is a closed loop system where in which they would like to have the control over deposition temperature, gas getting formed, fuse getting formed all these things are closed control loop controllers which are established in additive manufacturing. The close control loops of process will monitor one of the process parameters, it can be one or it can be many in real time in order to compare it with a desired value. So, some value x is there, it compares with x. If it is zero then the next set of signal is given if it is not zero, the corrections are made.

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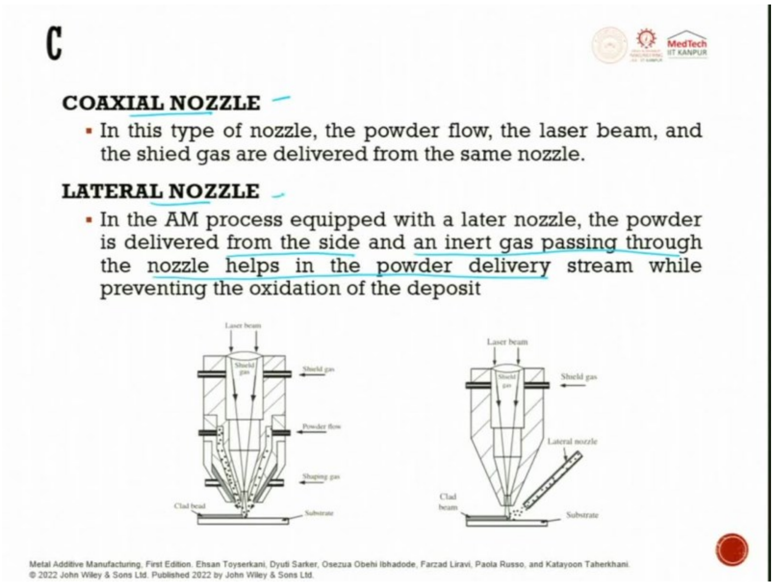

So, coaxial laser and coaxial nozzle and lateral nozzle, coaxial nozzle means in this the powder flow happens. The powder flow, the laser beam and the shielding gas are delivered from the same nozzle. So, you will have powder flow, laser beam, gas all the three are in the same axis and they all are given through a single nozzle. So, those nozzles are called as coaxial nozzles. What are lateral nozzles, in lateral nozzles the powder is delivered from the side, and the inert gas passes through the nozzle helps the powder deliver delivery stream while preventing the oxidation of the deposit.

So, what happens here is you will try to have a shielded gas also coming, then laser also coming, the shielded gas tries to protect the laser when it is getting in the laser, when it applies heat for the powder it melts, it tries to form a jacket and oxidation is prevented. So, there are two types of nozzles which are predominantly used in metal additive manufacturing one is coaxial, the another one is lateral nozzle.

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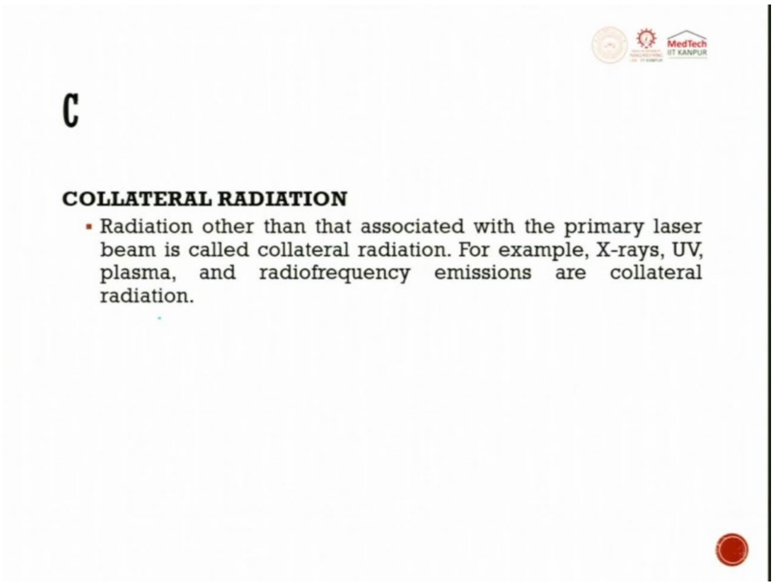

Collateral radiation- radiation other than the associated with the primary laser beam is called as collateral radiation. For example, X- ray, UV, plasma, and radiofrequency emissions are collateral radiations which are created in a small extent while the process happens.

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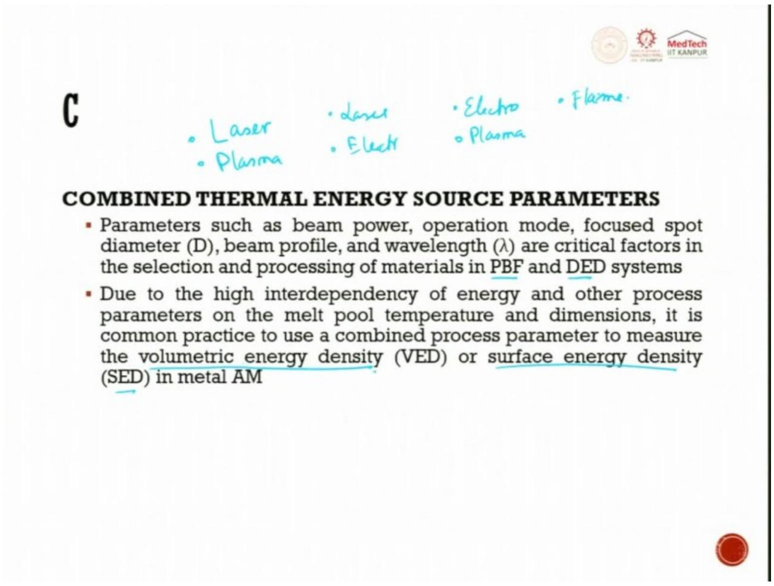

So, today we talk about hybrid additive manufacturing process in order to enhance the productivity and to produce a better-quality output. So, today we talk about combined thermal energy source parameters, parameters such as beam power operation mode, focused spot diameter, beam profile, wavelength are critical factors used in the selection of processing, selection and processing of materials in powder bed and then directed energy deposition system. Due to the high interdependency of energy and other process parameters on the melt pool temperature and the dimension it is a common practice to use a combined process parameter to measure the volumetric energy density or the surface energy density in metals.

So, you see here they are trying to use 2 thermal sources, combined thermal sources it can be laser, plasma, electron beam, it can be electron beam and plasma, all combinations you can think of it. So, here combined thermal energy source parameter means you are trying to combine energy source and also the parameters, beam power, operation mode, focused spot diameter, beam profile, wavelength, etc.

So, finally, it is a common practice to use your combined process parameter to measure the volumetric energy density or the surface energy density.

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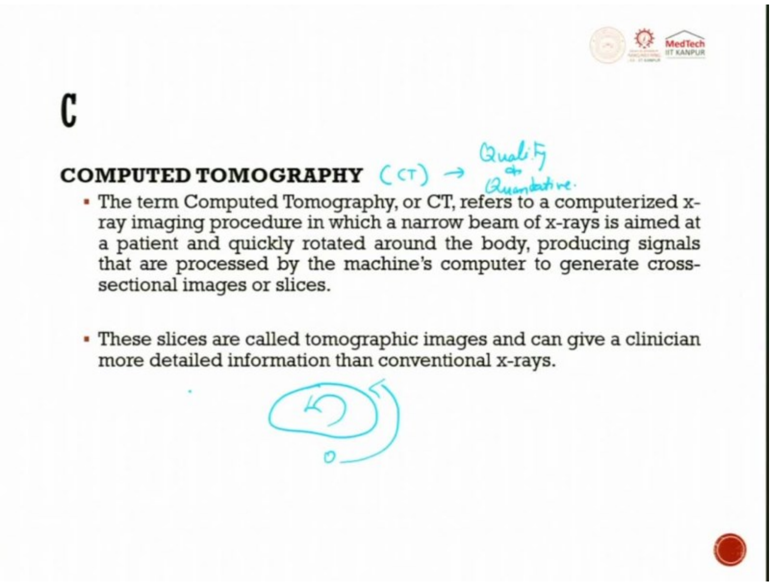

CT or computer tomography, this is exhaustively used for qualitative parameter and quantitative parameter. So, here what happens is, it is a non-destructive way. So, refers to a computerized X ray image procedure in which a narrow beam of X ray is aimed at a patient and quickly rotated around the body producing signals that are processed by the machines computer to generate cross section image or slices.

It is just like your CT scan what you do for your skull or hand or whatever it is, it tries to give you one layer of information. So, now stacking the several layers of how do you get this one layer of information, either you rotate the object or you rotate the source, you rotate one of them and then try to get the layer of information. So, this several of these layers when you recast, and then you try to get it, it forms a 3D object, these slices are called as tomographic image and can give your clinician more detailed information than conventional X ray.

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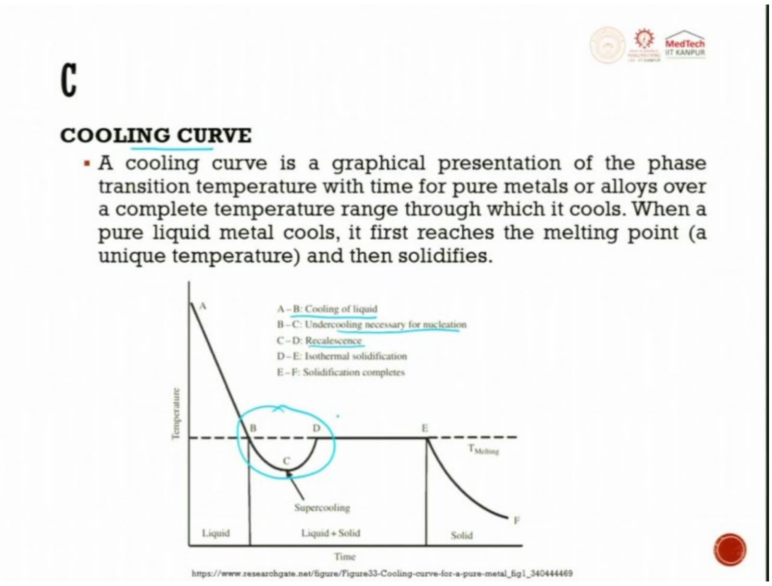

When we are trying to talk about metals or ceramics, when you try to heat the metal, the most important thing which comes into existence is the cooling curve. A cooling curve is a graphical presentation of the phase transition temperature which is a temperature versus time graph. So, when you try to hit or melt a powder, the curve with respect to temperature follows like this. So, A B is a cooling of liquid.

So, this is liquid, this is liquid cum solid and this is solid. So, you try to hit from here A to B when you try to move the powder which is hit by the laser is in a molten state or is in a liquid state, then as soon as it hits from here, it tries to move from B to C which is nothing but under cooling necessary for nucleation. So, once it is formed in the liquid, so it has to get converted into your solid. So, what happens is it tries to further cooled down, so that the nucleation can start.

Once the nucleation starts, then what happens there is a release of energy. So, the temperature once again goes from C to D which is recalescence. So, then this happens between C to D and then after D it is isothermal solidification, so, it moves towards a solid, now here it is, D is a solid liquid combination. So, from here it moves to E till it achieves E it is a semi solid or a mushy state and after E reaching it, E to F is a solidification complete, so, you have a liquid phase you have a liquid cum solid phase you have a solid phase, every metal or ceramic follows this curve, if you try to plot a temperature versus time curve, it follows this.

So, the most important parameter to understand is the cooling curve. So, cooling curve necessary for nucleation so, this is how because the nuclear sites has to be formed. So, that it goes into this and then after reaching it recalescence happen and then it tries to increase the temperature. So, a graphical representation of phase transition temperature with time for pure metals or alloys over a complete temperature range through which it cools from here to here, when a pure liquid metal cools it reaches the melting point and then it reaches solidification, this is all holds good for a pure metal, but when you do alloy in reality, there will not be alloy, there will be a drift in the curve response.

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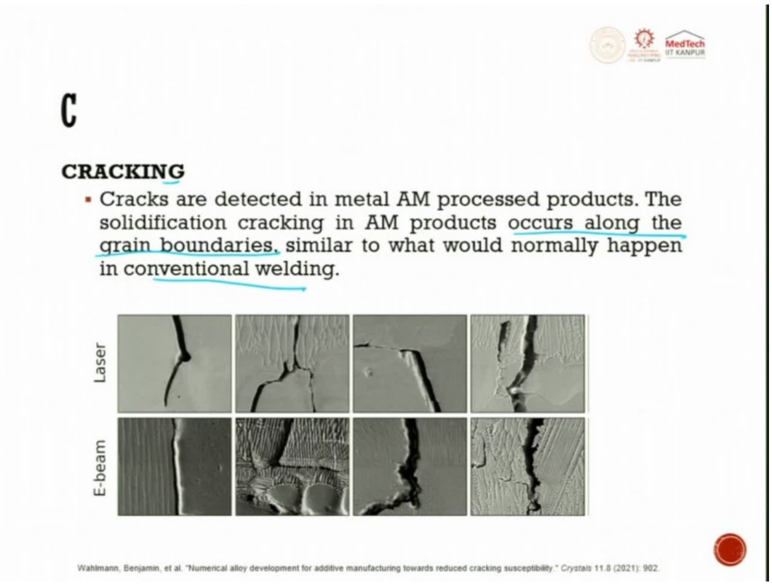

These are some of the defects which are called cracking, cracking are defects in metal additive manufacturing process, process to product. The solidification cracking in AM products occur along the grain boundary this is very important along the grain boundaries similar to what would normally happen in the conventional welding. Along the grain boundary you can see the cracking. So, cracking should never happen. So, how do you avoid cracking, you have to think about it in the beginning? So, after the process is done, you can also do heat treatment to remove the crack. So, when we try to do with laser you can see how the cracks are formed with the same material when we try to do with electron beam you see how good is the response.

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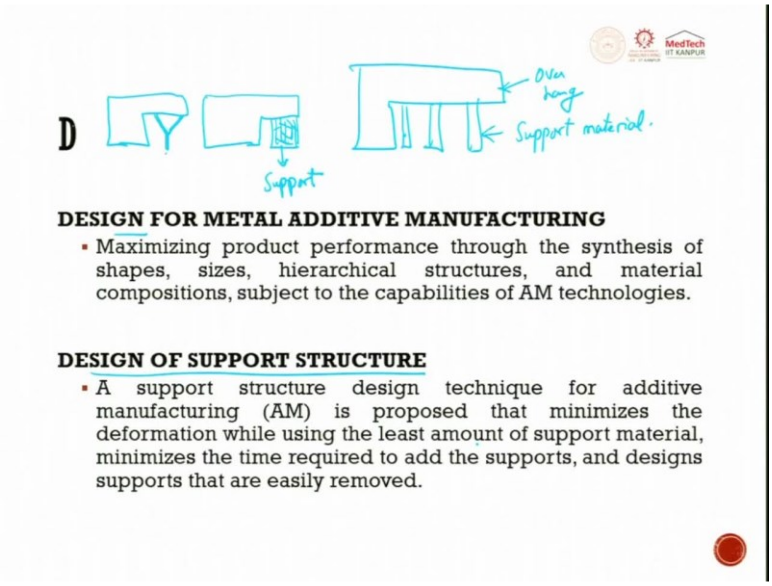

So, then designed for metal additive manufacturing is a concept which is coming up. So, here in order to maximizing product performance through the synthesis of shape, size, hierarchical structures, and material composition subjected to the capability of AM technique. There is a new field which is called Design for metal additive manufacturing like design for manufacturing. We also call design for metal additive manufacturing, the next is designed for support structures as I told you, whenever you have a free hanging structure, this free hanging structure has to be supported.

The support materials are not integral part of the product. So, these are support material, they are not support material, they are not integral part of the object, but they will be removed during the final processing or the post processing stage, this is an overhang, so it is used. So, see they realize that this is now you add material and then you just throw the material because it does only support action.

Now, what people are saying is let us start developing a design for structural material rather than say for example, if you have a hand like this so, all throughout you can try to fill a secondary material, secondary structure material, this is a support structure but, if my job is only to support and I want the material for the support structure to be reduced, then what do I do is? I try to draw or I try to develop like a tree branch, some thick one and one thin one whatever support structure this was doing this also can do, now what have you done, you have optimized the supporting structure material, in order to understand these things, there is a new topic which is coming up called as designed for support structures.

So, your support structure design technique for additive manufacturing is proposed that minimizes the deformation, while using the least amount of supporting material, minimizing the time required to add the supports and design supports that are easily removable. So, all these things are part of design for support.

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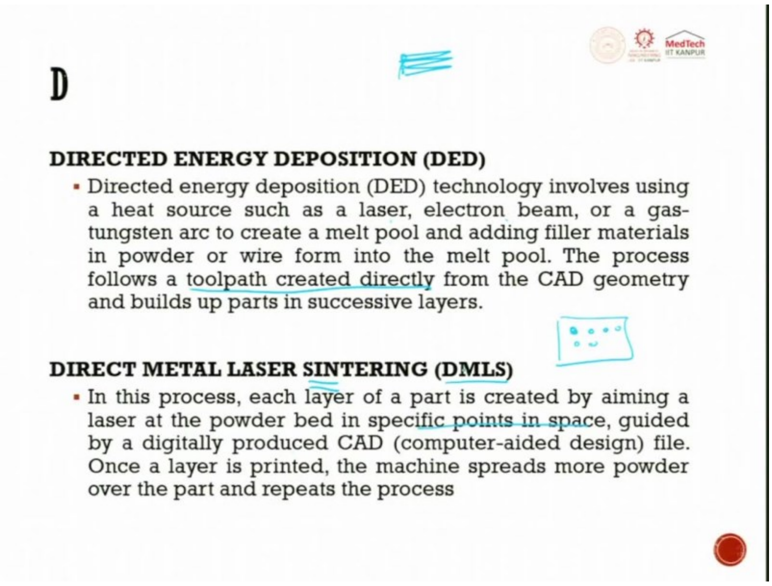

DED, we have seen at least in brief, we have seen directed energy deposition technology involves using a heat source such as laser electron beam or gas tungsten arc to create a melt pool and adding filler material in powder or wire form into the melt pool. The process follows a tool path created directly from CAD and build up the part in successive layers. So, first it will try to melt the material and then it will try to form your hatch pattern and this hatch pattern will try to form a single layer several layers forms you the output, direct metal laser sintering DMLS in this process, each layer of a part is created by aiming a laser at a powder bed in specific points in space guided by a digitally produced CAD file.

Once a layer is printed, the machine spreads more power over the part and repeats the process. So, here it is very clear it is laser sintering. So, here created by aiming a laser at the powder bed in specific point and space. So, if you have a table this is what is a powder, so, specific point in the space guided by a digitally produced CAD, CAD file once the layer is printed, the machine spreads powder on top and then you start doing it.

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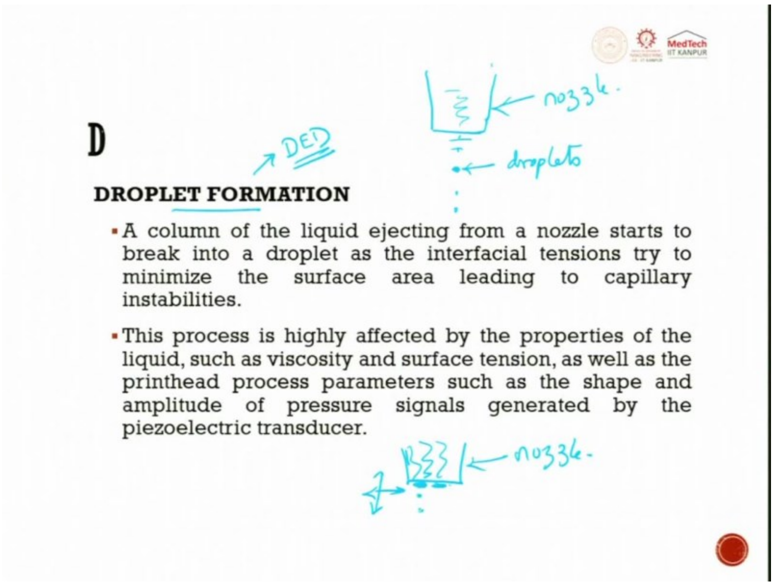

Droplet formation the column of liquid ejected from the nozzle starts to break down into droplets. Say for example, when there is a liquid which comes out of the nozzle assuming that the liquid comes out from the nozzle. So, then what is injecting from the nozzle, it starts to break down into droplets these are all droplets, breaks down into droplets as the interfacial tension tries to minimize the surface area leading to capillary instability.

Droplet formation is very important in the process of DED, where it can be a wire or it can be a powder which is put for melting. This process is highly affected by the properties of the liquid such as viscosity and surface tension as well as the printed head process parameters such as shape and the amplitude of the pressure signals generated by the piezoelectric transducer plays an important role for droplet formation. So, what are they trying to say? You have a liquid which is trying to flow through the nozzle, this is a nozzle and same way this is a nozzle so, and here you will have piezo crystals, which are moving up and down left and right. So, they will try to allow the liquid to flow and they will try to open and close so fast. So, what you see will be droplets not a continuous one.

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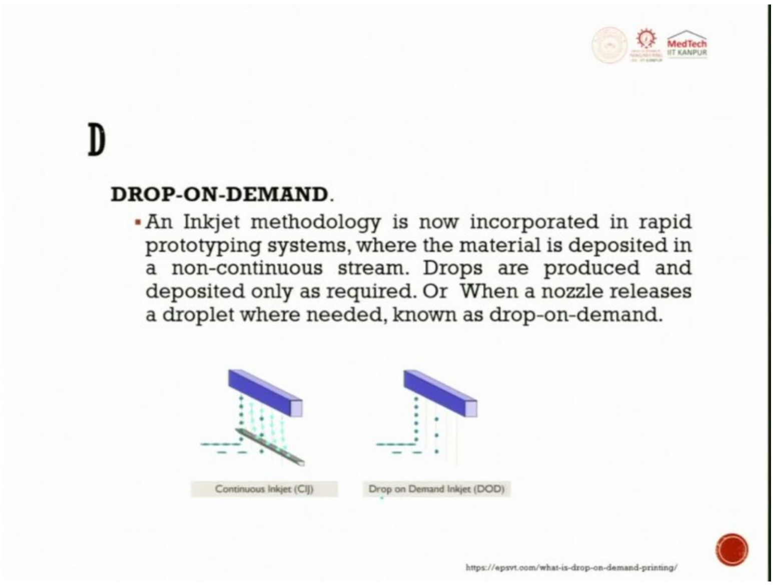

So, these are continuous inkjets these are drop on demand inkjets whatever we have discussed. So, this is continuous, this is drop on demand.

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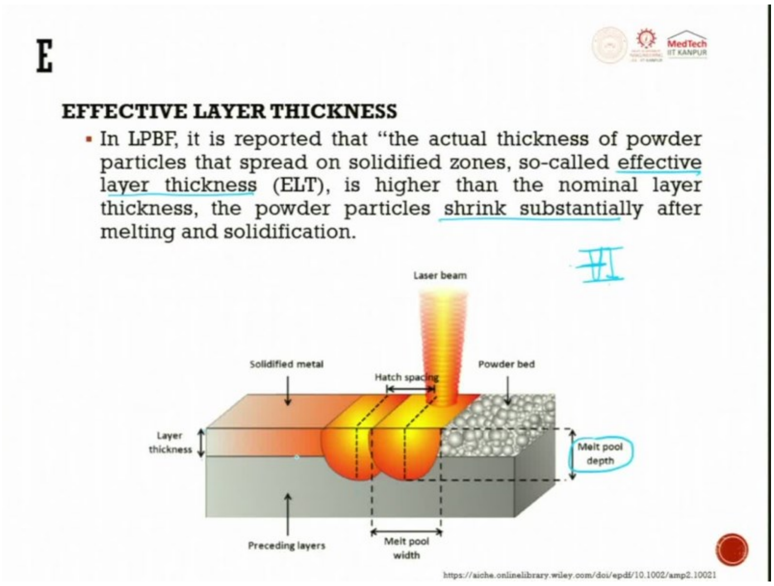

Effective layer thickness- effective layer thickness everywhere we talk about layer by layer by layer. So, the effective layer thickness is the actual thickness of the powder particle that spreads on solidified zone, so-called effective layer thickness is higher than the nominal layer thickness. So, nominal layer thickness will be this much, effective layer thickness will be this much. So, every time when you try to hit a laser, it is expected to do here, but it also goes to the last part and comes back.

So, that is what it is said, the actual thickness of the powder particle that spreads on solidification zone, solidified zone is called as effective, the complete is called as the effective layer thickness. This is always higher than the nominal layer thickness. So, this only will try to make sure shrinkage is not there, delamination is not happening, porosity does not come. So, nominal layer thickness, the powder particles shrink subsequent substantially after the melting and solidification so, that is why what we do is we always have a layer thickness, this is effective layer thickness, this is where it is melt pool depth. So, but this is what is the layer which you have spread.

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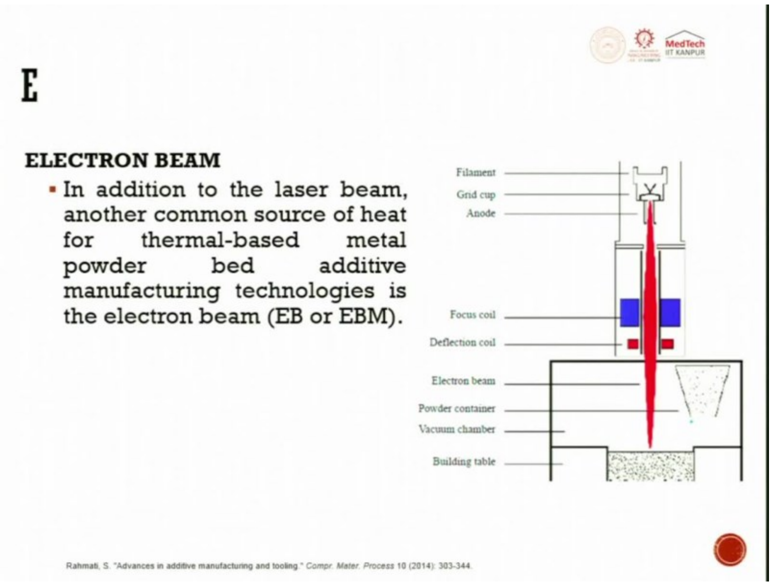

So, like laser, we have another powerful source which is called as electron beam in addition to the laser beam another common source of heat through thermal based metal powder bed additive manufacturing technology is the electron beam usage, electron beam usage gives you a better performance, the focusing spot size is very small and you have magnetic lenses which can help you in focusing to a very very small point as compared to that of your laser. So, electron beam is another powerful source which has been used exhaustively in metal based additive manufacturing process.

Friends till now we have seen the glossary up to E. So, we will continue this in the next lecture I will explain because all these fundamentals you should understand little bit before getting into the process and appreciating the process parameters involvement. Thank you very much.