Metal Additive Manufacturing
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Lecture 23
On - machine Sensing in MAM (Part 1 of 2)

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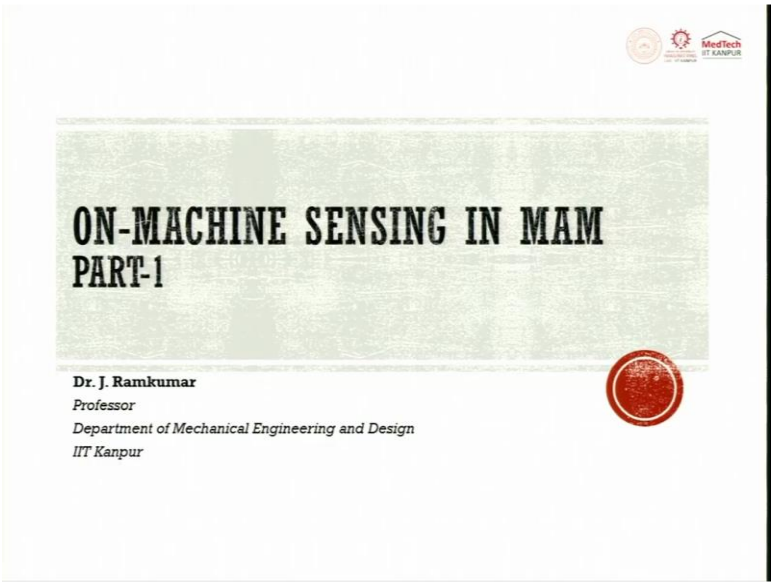

Welcome to the next lecture in the series of Metal Additive Manufacturing. We are trying to give you a holistic view of metal additive manufacturing processes. So, when we talk about metal additive manufacturing, today we are getting into the era where we are trying to integrate industry 4.0. And we are also talking about integrating IoT in the machine itself.

Today, the machines are getting connected through Wi-Fi and it gets to cloud from cloud the supplier of the machine tries to track the health of the machine plus the process which is going on. Very recently, we have bought a metal additive manufacturing machine at IIT, Kanpur. So, we were trying to process the job goes for 24 hours. Late in the night when we were all off from the office, we got a phone call from our supplier saying that the gas cylinder is drained out. Please replace it.

So, what am I trying to tell you is this additive manufacturing is now getting into a new era, where we are trying to talk about online monitoring of the process and getting connected with the supplier for technology or technical support. So, in this lecture, we will try to cover some sensing devices which are used in metal additive manufacturing. So, this lecture will be on-machine sensing in metal additive manufacturing.

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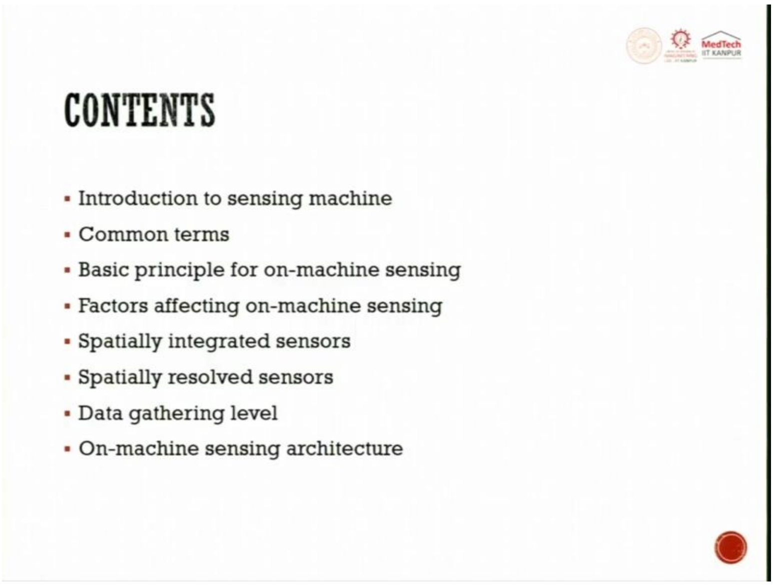

The content of this lecture is going to be introduction to sensing machine, common terminologies used in a closed loop metal additive manufacturing system, basic principles for online sensing. So, if it is cutting tool or a machine tool, you will try to put a vibration sensor, you will try to put four sensors, you will try to put acoustic sensors et cetera et cetera. But here what do we do and how are these sensors working?

So, that is what is basic principle for online sensing. Then it is factors affecting on-machine sensing, then we will have spatial integrated sensors, then spatial resolved sensors, then data gathering level then on-machine sensing architecture. This architecture is a protocol, which we follow at the machine to see how do we control the process.

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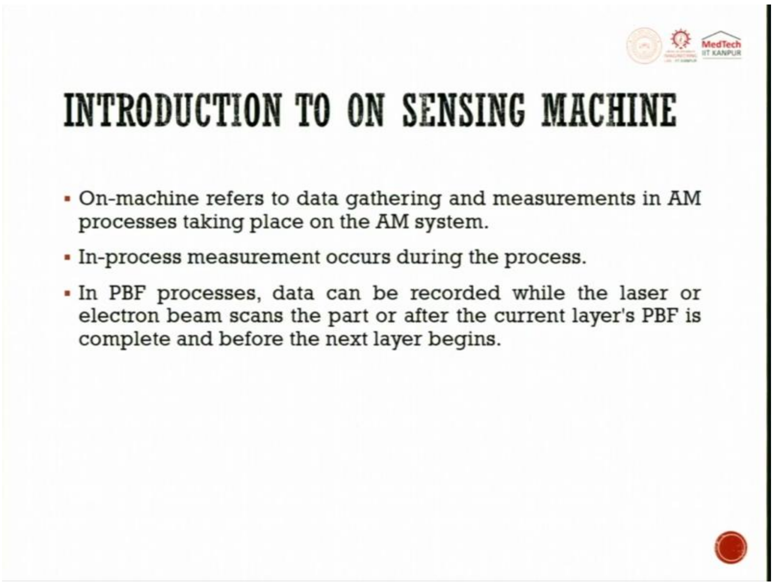

On-machine refers to data gathering and measurements in AM process taking place on the AM system. One is data gathering, the other one is measurement. So, you measure, you gather the data, you process the data and online you take a decision of the data to be done. For example, if there is a thin layer getting selectively sintered using laser beam powder bed fusion method.

So, you might sense the residual stress. How is it done? It is a question. Today, do we have a technology, we have an indirect technology to measure residual stress. So, residual stress can be measured and based upon the residual stress, the next layer thickness or the laser power can be tweaked to meet out to the requirements. So, in process, measurement occurs during the process.

In powder bed fusion processes, data can be recorded while the laser or electron beam scans the part or after the current layers in powder bed fusion is completed and before the next layer is begin. So, this transition time it is too small. So, within the transition time, they assess the printed layer with all these details and then they try to play with the laser parameters or the process parameters to get a sound quality output.

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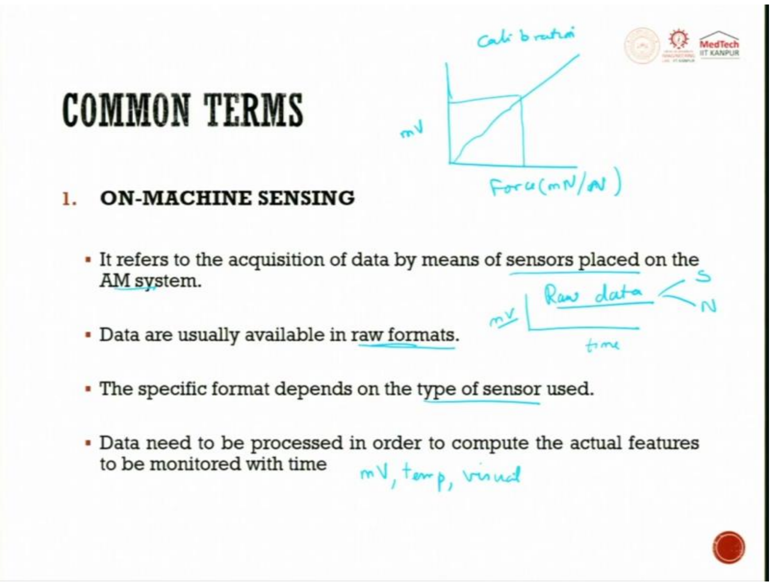

So, on-machine sensing, it refers to acquisition of data by means of sensors placed in the AM system. The data are usually available in the raw format. What I mean here raw format is, suppose you are trying to measure the force, you will always get the output with terms of milli voltage with respect to time. So, now, this is the raw data. From this raw data, you would have done a calibration. This is the raw data. You would have done a calibration which converts force and then millivolt. So, maybe you will try to have a response like this.

So, then what you do is you try to get the millivolt. From the millivolt you try to find out what is the force. This can be in milli newton or it can be a newton et cetera et cetera. So, you try to figure out from the calibration chart, what is the force and then you try to report the force. So, what you acquire here is a raw data. Again, in a raw data, you have two things. One is signal. The other one is noise.

So, when we talk about data, there are two types of data. You will have signal. You will have noise. You apply many times filter to the noise and try to acquire the signal. When we acquire the signal, we can process it raw with respect to time or we try to do frequency response with respect to the output and then we try to look into it. So, those information are called as raw formats. The specific format depends on the type of sensor. You can try to have output in terms of milli volts. You can try to have the output in terms of Celsius depending upon your requirements.

Suppose you are trying to measure fumes, then we tried to do it in parts per million, you can try to record. So, data need to be processed in order to compute the actual features to be monitored with respect to time, that is what I explained here, you can have millivolts, you can have temperature, you can have something which is related to smoke, something you can try to have with respect to visual. So, where the visuality is affected. So, you can try to take all these data, process it and try to use it.

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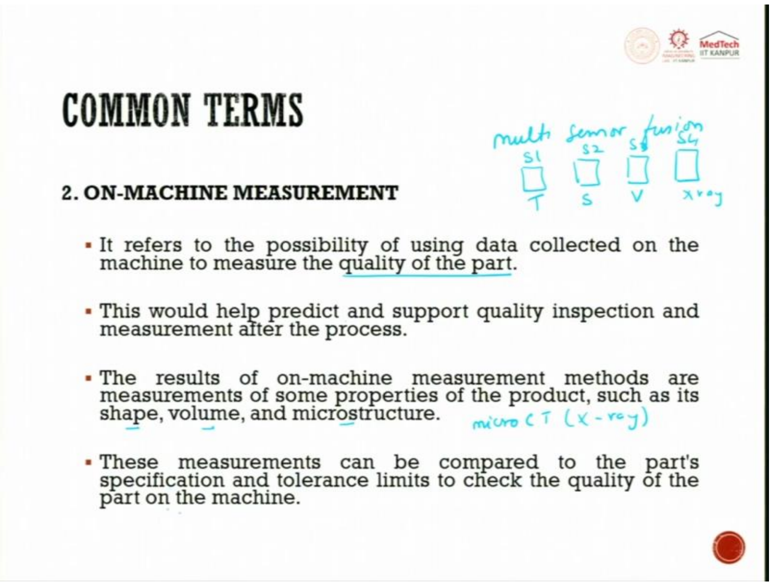

When we try to talk about on-machine measurement, it refers to the possibility of using the data collected on the machine to measure the quality of the part. Finally, what do you want is a quality of the part. You measure all these things. So, we call it as multi sensor fusion, is done where in which you have multiple sensors, S1, S2, S3, S4 you have multiple sensors.

All these sensors can be of different different kinds. Generally, what we use is temperature, we try to use smoke, we try to see the visual accuracy of the part, we also tried to do an indirect with an X-ray to find out what is happening during the process. This would help predict and support quality inspection and measure after the process.

Generally, what we do is we try to make a part and after the part is made, we try to do offline monitoring or offline measurement of quality. So, I would put it this way, offline monitoring we will do, measurement and inspection we will do and then evaluate the quality of the product. So, this would help predict and support quality inspection and measurement after the process. The result of on-machine measurement methods are measurements of some properties of the product such as shape, volume and micro-structure. So, this area is becoming very tough.

Today what people are trying to do is they are trying to use micro CT, Computer Tomography, micro CT where in which they use an X-ray as a source. They are trying to do the X-ray after every three layers and five layers to measure the quality output. These measurements can be compared to the parts specification and tolerance limit to check the quality of the part on the machine.

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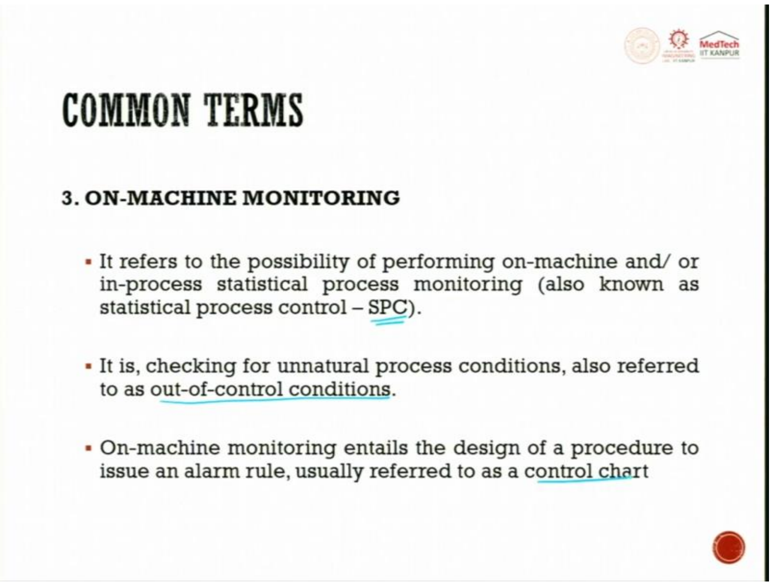

So, it refers to the possibility of performing on-machine and or in process statistical process monitoring. They are also trying to talk about statistical process control,, charts to be filled online by the machine to understand the quality of the output. It is checking for unnatural process conditions, also referred to as out of control conditions can be easily monitored. While processing itself, if you make a defect or if the defect happens, then you stop the printing from there and start fresh. So, that is what is when there is an offline control you start doing it. On-machine monitoring entails the design of a procedure to issue an alarm rule, usually referred as a control chart.

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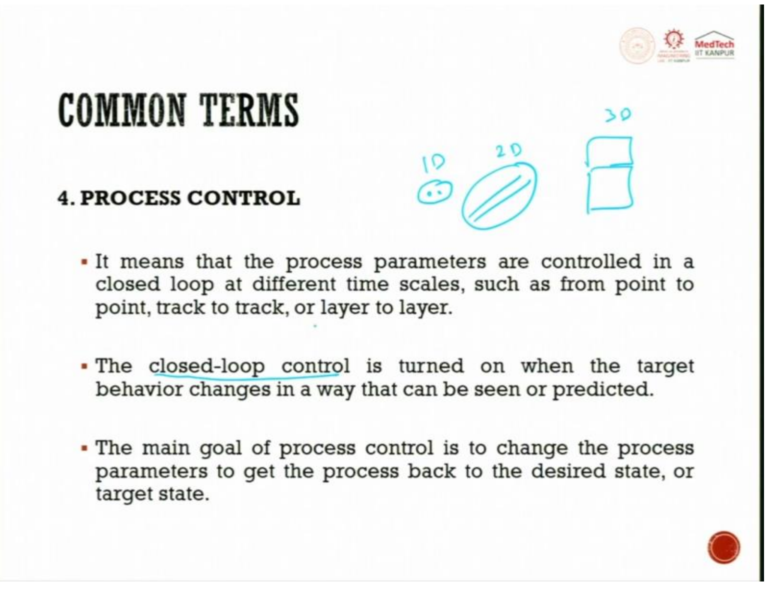

In process control, it means that the process parameters are controlled in a closed loop at different timescales such as from point to point, track to track, layer to layer. This is what we are doing so, 1D, 2D, 3D. So, it means the process parameters are controlled in a closed loop at different timescales such as point to point, then track to track, then you will have layer to layer. The closed loop control is tuned on, when the target behavior changes in a way that can be seen or predicted. This is why we use the closed loop control system.

Closed loops of control system even today are in the research stage, certain machines have, but many of them do not have. The example I gave from the machine whatever we have, a nitrogen cylinder which has a pressure gauge. This pressure gauge is connected online with a system where in which we have integrated IoT. The main goal of a process control is to change the process parameters to get the process back to the desired state or target state.

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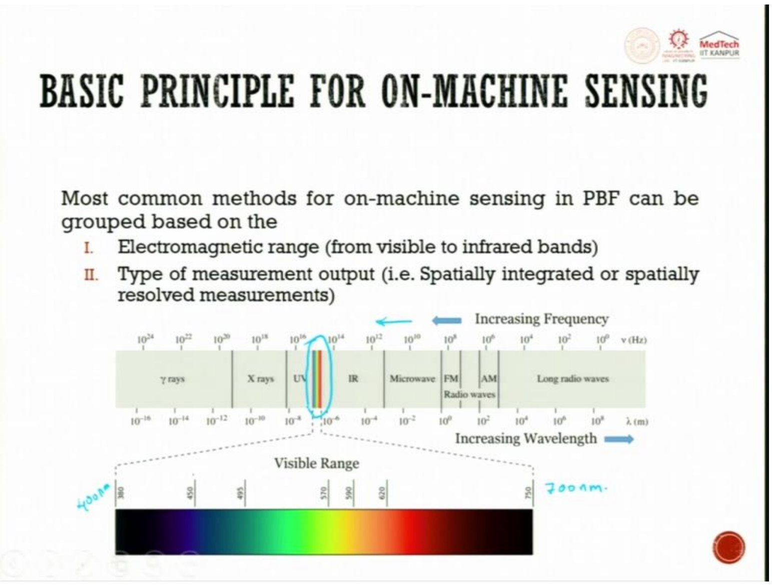

So, principles for online machine sensing, we will be trying to use this visual range. Most common methods for on-machines sensing of powder bed fusion can be grouped based on electromagnetic range from visible to infrared band. Type of measurement output can be spatially integrated or spatially resolved measurement can be done. So, we predominantly work on sensors, which work from 400 nanometer range to 700 nanometer range.

So, here we use this is a spectrum of electromagnetic waves. We try to work on using these electromagnetic waves. So, this is the increased in wavelength and this is the increase in frequency. If you move this direction frequency in this direction, it is wavelength. So, you try to have this visual range for doing output. So, this many of the sensors which work use this as a range for working.

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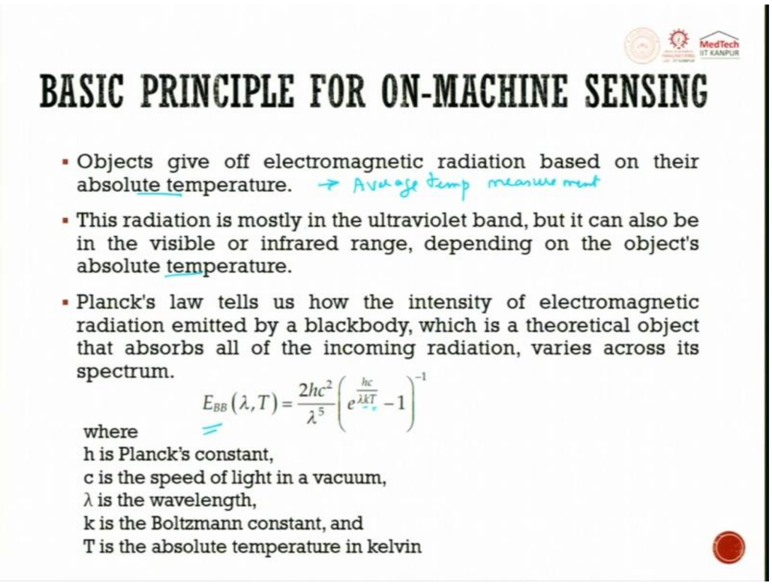

The objects give off electromagnetic radiation based on their absolute temperature. We are trying to hit that IR based sensors. So, objects give off electromagnetic radiation based on their absolute temperature. So, you will try to have your red hot one means a red display will be there, blue is lesser, whatever it is you can try to have, but here whatever you have is going to be an average temperature measurement.

If you want to do at a point, it is very difficult. You can IR laser assisted sensors, that gives you a point, but not on an area, but here when we try to use it with the infrared imaging cameras, it is averaged out, but you can try to get a large area. So, you have to hit that trade off. This radiation is mostly in the ultra violet band, but it can also be in the visible or infrared range depending on the object's absolute temperature.

Let me give you a simple example. We all suffer from fever now and then because of climatic change and other things. When we suffer from fever, we always measure the fever using a thermometer or a thermocouple or a device whatever, we try to stick in your forehead. We try to see the response of the body.

So, the response of the body when it is 99 or 100 or 102 you will see that there will be a scale and the sensor will display red color. So, that means to say you are running a temperature at the higher scale. Let us go vice versa. If you have a cold fever, which generally comes in north India and in cold countries. Kids suffer from cold fever. Their temperature falls below 98.4. And that condition, we do not have thermometers, which can measure cold fever.

Though the technology is known and we try to work on object temperature, which is on the higher side, but on the lower side, the technology is not available so easily.

So, this is what I am trying to impress you saying that higher temperatures can be measured. If it is cooled down and if you want to find out it is not possible. Planck's law tells us how the intensity of the electromagnetic radiation emitted by a blackbody which is a theoretical object that absorbs all the incoming radiation varies across its spectrum. So, this is the Planck's law.

$$E_{BB}(\lambda, T) = \frac{2hc^2}{\lambda^5}\left(e^{\frac{hc}{\lambda kT}} - 1\right)^{-1}$$

where

h is Planck's constant,
c is the speed of light in a vacuum,
λ is the wavelength,
k is the Boltzmann constant, and
T is the absolute temperature in kelvin

So, here the intensity of the electromagnetic radiation emitted by a black body can be found out.

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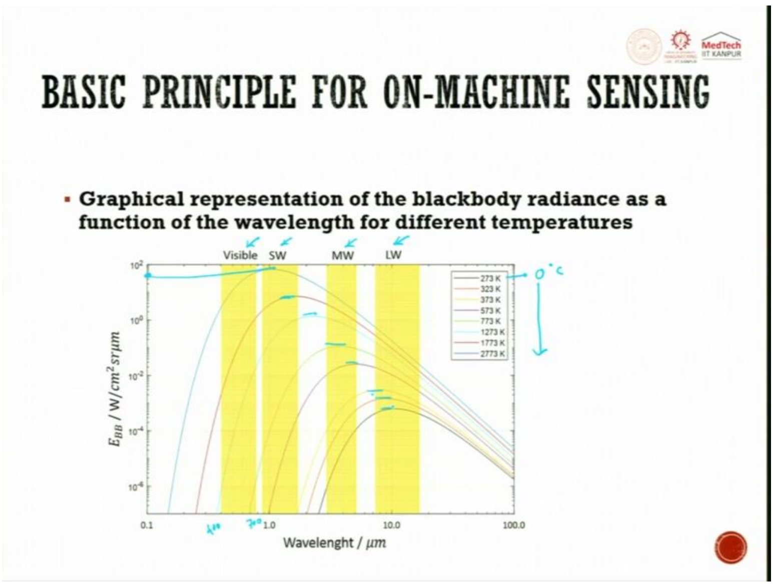

The graphical representation of a blackbody radiance as a function of the wavelength for different temperatures are already plotted and it is kept. So, now, you can see here at 0 degrees Celsius, you can keep going down to 773 Kelvin. So, you can see here, this is the wavelength and these are all the emissivity you can have.

So, you can see here this is visible, this is short wave, medium wave, long wave in terms of electromagnetic radiation, this is the wavelength. So, when I say visible, it is 400 nanometer to 700 nanometer. So, you can see here the representation of radiance. So, how does this change with respect to the wavelength.

You can try to see for example, the spectrum if you try to plot it here, you try to get somewhere close to 10^{-6} to 10^{2}, whatever it is, so, you try to get the range there. So, as and when the temperature goes high, the waves which are getting formed, the radiance are going down.

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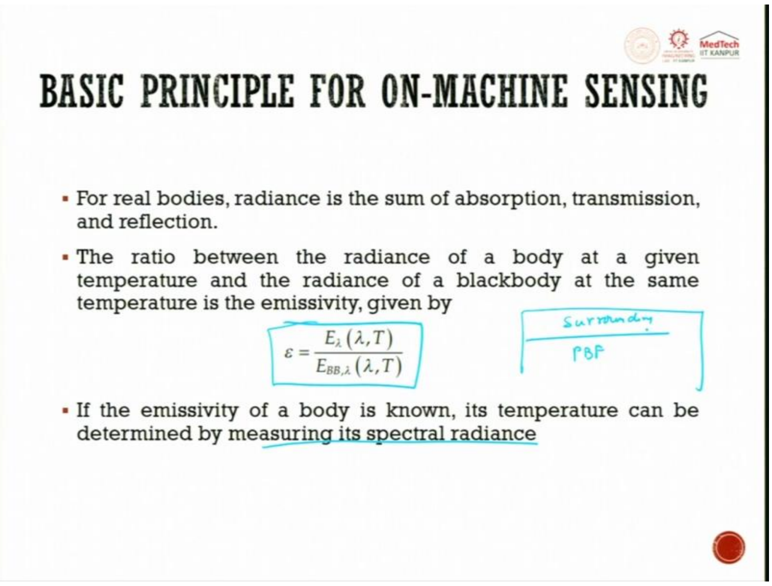

So, for a real body, radiance is the sum of absorption, transmission and reflection. The ratio between the radiance of your body at a given temperature and the radiance of a black body at the same temperature is the emissivity given. So, this is a factor which is very important. If they tried to measure the emissivity of the powder bed single layer then they can try to find out what is that temperature over there. Then, they can try to find out a relate to temperature between PBF and the surrounding. The temperature gradient can be figured out and for this gradient if the gradient is small, then you are able to produce a sound quality output.

So, here if the gradient is very large, it introduces the thermal stresses. Thermal stresses means residual stresses are there. It might lead to delamination or cracking, if the emissivity of the body is known, its temperature can be determined by measuring the spectral radiance. Now, what did I do? I measure the spectral radiance. I convert this into temperature, what is happening on the layer and from that, I can try to figure out what will be the residual stress, which is getting created with respect to time.

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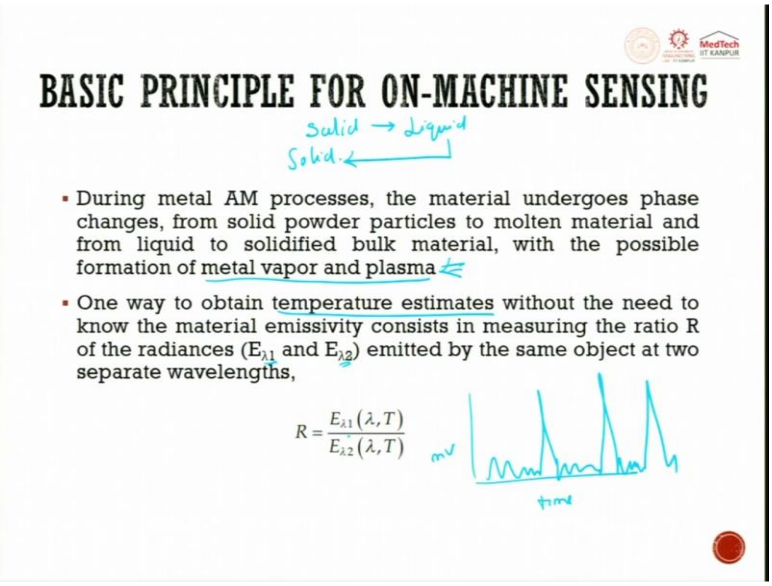

During metal additive manufacturing processes. The material undergoes phase change from a solid powder particle to molten material and from liquid back to solidified bulk material with the possible formation of metal vapor and plasma. Now, if I can measure the plasma using spectroscopic device, so, then I can try to find out what is the electron density. From the electron density, I can try to figure out the plasma temperature. There are famous equations like Saha’s equation, modified Saha’s equation where they measure that plasma and talk about the temperature and the electron density. They do a correlation.

So, during metal additive manufacturing, it is pretty interesting from solid. It goes to liquid and then from liquid it comes back to solid, solid to liquid, liquid back to solid. In this transition, it tries to release vapor and it tries to release plasma. If you can measure the vapor density or if you can measure the plasma density you can try to talk about the temperature.

One way of obtaining temperature estimates without the need to know the material emissivity consists in measuring the ratio of the radiance:

$$R = \frac{E_{\lambda 1}(\lambda, T)}{E_{\lambda 2}(\lambda, T)}$$

E lambda 1 and lambda 2, when we get the spectroscopy, you get the raw spectroscopy with respect to time, you get the raw spectroscopy. Now, what we do is we try to take the first peak and the second peak ratio and then talk about it from that you can try to calculate the temperature estimate. You can do through plasma spectroscopy or you can try to do with again spectroscopy ratios you can try to talk about it.

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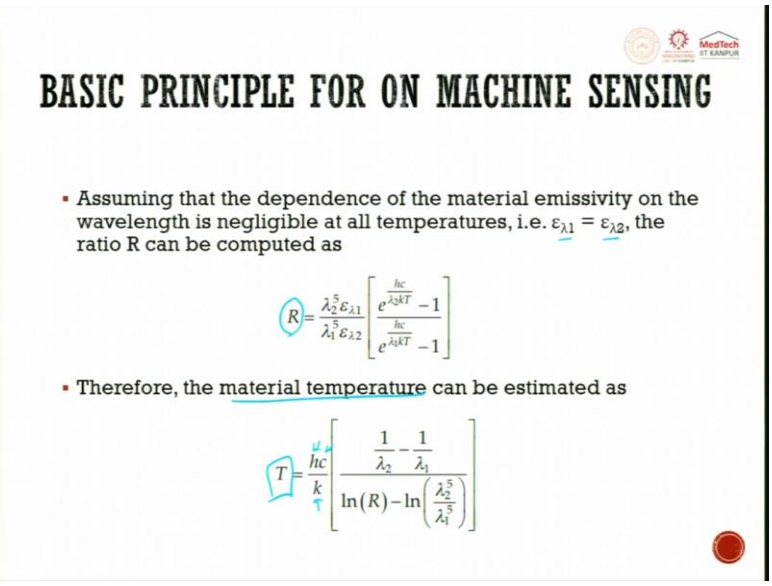

So, assuming that dependency of the material emissivity on the wavelength is negligible at all temperatures, that means to say, $\varepsilon_{\lambda1} = \varepsilon_{\lambda2}$. Epsilon lambda 1 is the peak for the same material, epsilon lambda 2 is the second peak for the same material. The ratio R can be computed easily. Therefore, the material temperature can be estimated by this formula T is:

$$T = \frac{hc}{k} \left[\frac{\frac{1}{\lambda_2} - \frac{1}{\lambda_1}}{\ln(R) - \ln\left(\frac{\lambda_2^5}{\lambda_1^5}\right)} \right]$$

h is Planck’s constant,

c is velocity of light,

k is Boltzmann constant.

You can try to calculate the material temperature. So, now, this material temperature indirectly you can try to find out the residual stresses.

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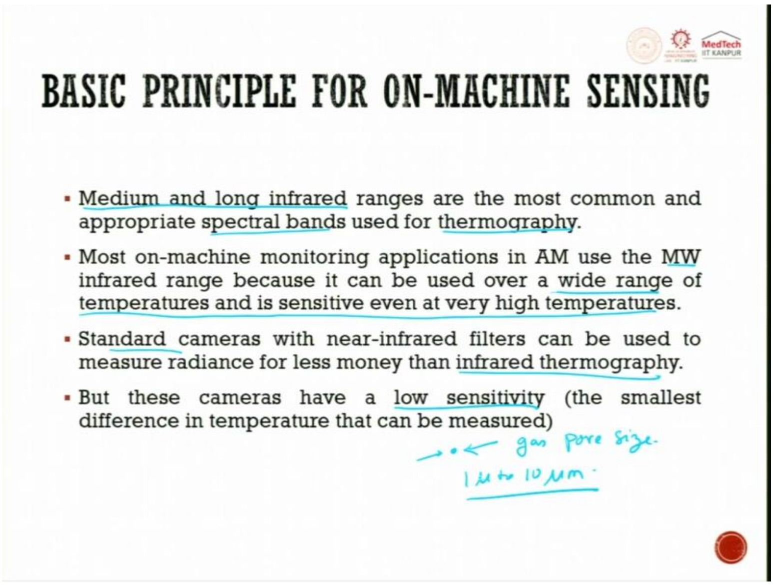

The medium and long infrared ranges are the most common and appropriate spectral band used for thermography. We talk about IR camera. This is what is IR camera, where we talk about thermography. It works on medium and long range spectrum. Most on-machine monitoring applications in AM uses medium wave infrared range, because it can be used over a wide range of temperatures and its sensitivity even at very high temperatures are very good. So, we try to use medium or long infrared range cameras for measuring. Standard cameras with near infrared filter can be used to measure radiance for less money than infrared thermography.

See in cameras, what we do in cameras we will have filters. If you can remove the filter near infrared filter, then it turns to the standard camera which we use generally. For example, the camera which you use on a desktop that camera itself removing the infrared filter, you can try to capture the infrared emission which comes and that will be a low-cost version of infrared thermography, what you get will be a picture and that picture will be averaged out, from that you have to calculate the temperature.

But these cameras have low sensitivity. When we are talking about gas pore size, sometimes the gas pore size ranges from 1 micron to 10 micron. Many a times it is 1 micron to 10 micron gas pore size. So, there if you have a low sensitivity standard camera, you cannot capture those details.

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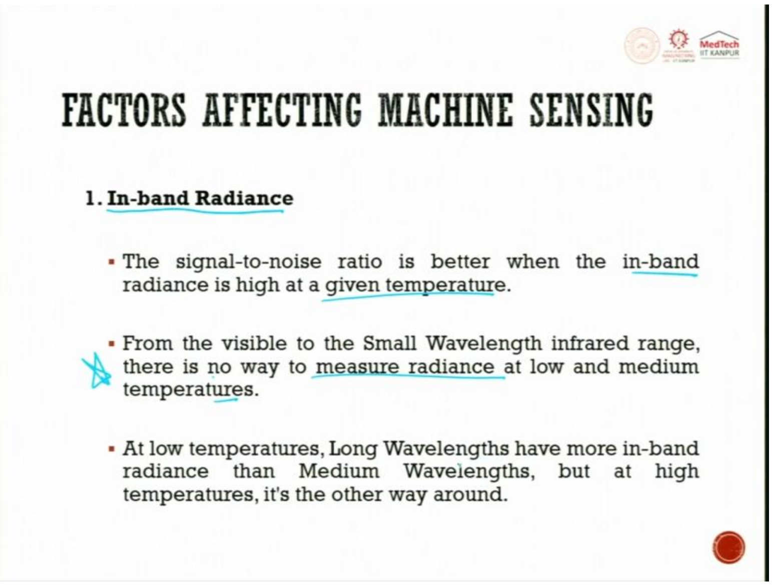

So, also the factors affecting machine sensing is in-band radiance. In-band radiance is nothing but the signal to noise ratio is better when the in-band radiance is high at any given temperature. The signal to noise ratio that means to say signal is higher as compared to that tough noise. Many a times when you work on pico volts and nano volts and micro volts, you will see the signal will have a voltage output which is very small and the noise will be of the equal size. So, signal to noise ratio if you have a higher signal, so, then or a good signal then it says signal is high as compared to the noise.

So, this will be, if it is better than in-band radiance is high at a given temperature. From the visible to the small wavelength infrared range, there is no way to measure radiance at low and medium temperature. Important point to note, from the visible to the small wavelength infrared range, there is no way to measure radiance. We should also know what is there, if you do not know what is not there, then that is also good enough for you to understand what you can do and what you cannot.

At low temperatures, long wavelength have more in band radiance than the medium waves, but at high temperature, it is the other way around. So, depending upon the temperature, you choose long wavelength or a short wavelength or a medium wavelength, infrared range.

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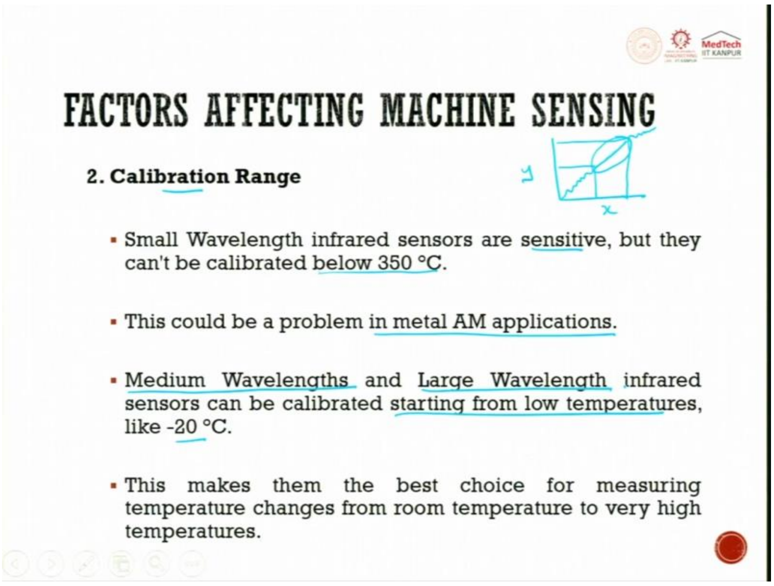

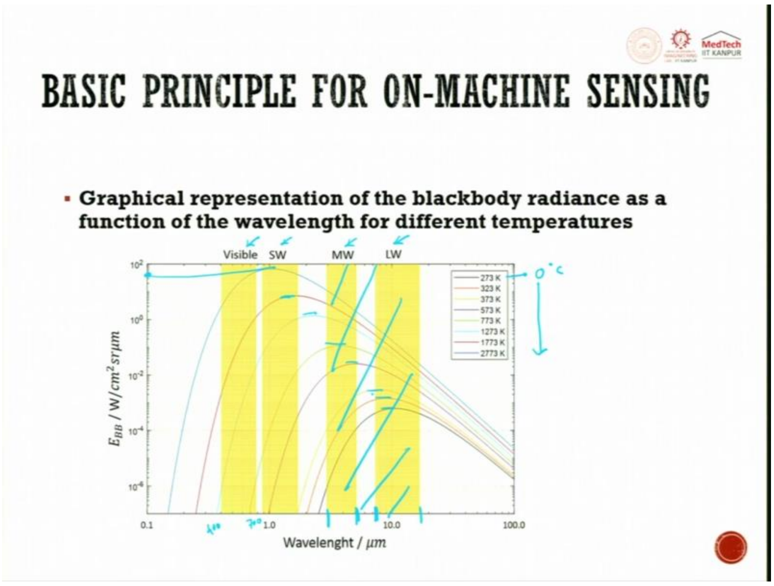

For all these things, the toughest problem is calibration. Calibration, when we try to do a calibration between y and x, it can be any parameter. If you have a chart like this and then somewhere it is linear and then it is nonlinear, we should always try to choose the linear portion of the sensor. So, from here to here, you might have nonlinear and again nonlinear. The sensor has to be chosen in one particular range where their responses are linear.

Now, with this linear response, what you do is, you try to do calibration. When we tried to do calibration, we try to do an indirect measurement on the output whatever we want. So, like that small wavelength infrared sensors are sensitive, but they cannot be calibrated below 350 degrees Celsius easily. This could be a problem in metal additive manufacturing. Medium wavelength and large wavelength infrared sensors can be calibrated starting from as low as minus 20 degrees Celsius to as high as 800-900 degrees Celsius. This makes them the best choice for measuring temperature change from room temperature to very high temperature is medium wave and large wavelength infrared.

So, now, let us go back and understand what is this medium wave? Medium wave works somewhere between here to here and long wave is from here to here. So, this entire region, where whatever we do, if we can try to have an infrared camera that can be used to measure the radiance on the temperature which is getting released.

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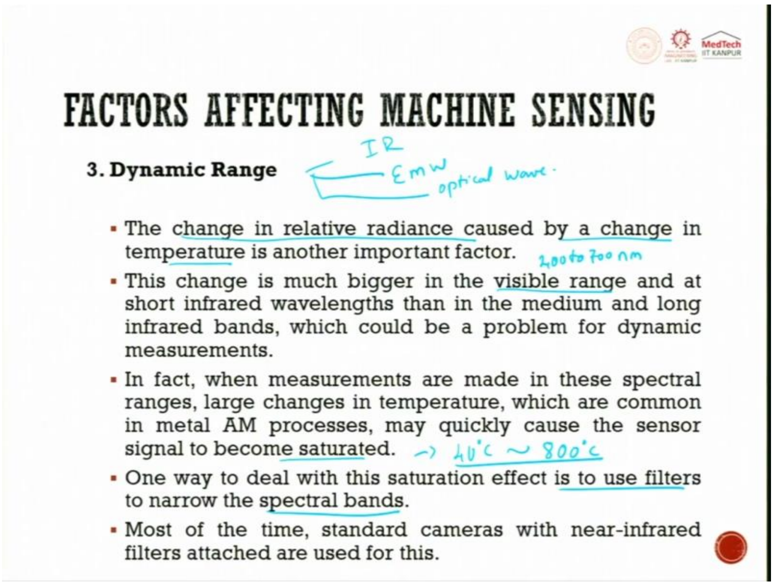

There are lot of dynamic changes which happens during the process. So, rather than measuring a static value, it is always good to measure a dynamic value. So, the dynamic range for every sensor is very very important. So, in the dynamic range, what we do is, we try to measure the change with respect to time.

The change in relative radiance caused by change in the temperature is another important factor, change in relative radiance caused by change in temperature. This change is much bigger in the visible range and at short infrared wavelengths than in that medium and long infrared band. The change is much bigger that means to say the amplification something like that, that this change is much bigger in the visible range.

So, visual range is 400 to 700 nanometer and at shorter infrared wavelength than in medium and long infrared band which could be a problem for dynamic measurement. In fact, when measurements are made in these spectral range, large change in temperature, which are common in metal additive manufacturing may quickly cause the sensor signal to become saturated. See, what we are trying to say is all the sensors will have a range with which it can work and this range is the frequency and the absorption, moment it gets saturated then onwards it will not capture any signal at all. And this is very common when we are trying to use electron as a source or photon as a source of optics.

So, in fact when measurements are made in these spectral ranges, large changes in temperature which are common in metal additive manufacturing processes may quickly cause the sensor signal to become saturated. One way of dealing with the saturation effect is to use a filter and narrow down the spectral band. Whatever I talk here is common for IR, is also common for electromagnetic waves. It is common for both. It is also common for optics or optical wavelength.

So, when the measurements are made in this spectral range, large changes in temperature, which are common in metal additive manufacturing process may quickly cause the sensor signal to become saturated. Why? Because you operate somewhere from 40 degrees Celsius to 800 degrees Celsius. Most of the time standard cameras with near infrared filters are attached and it is used for monitoring the process continuously.

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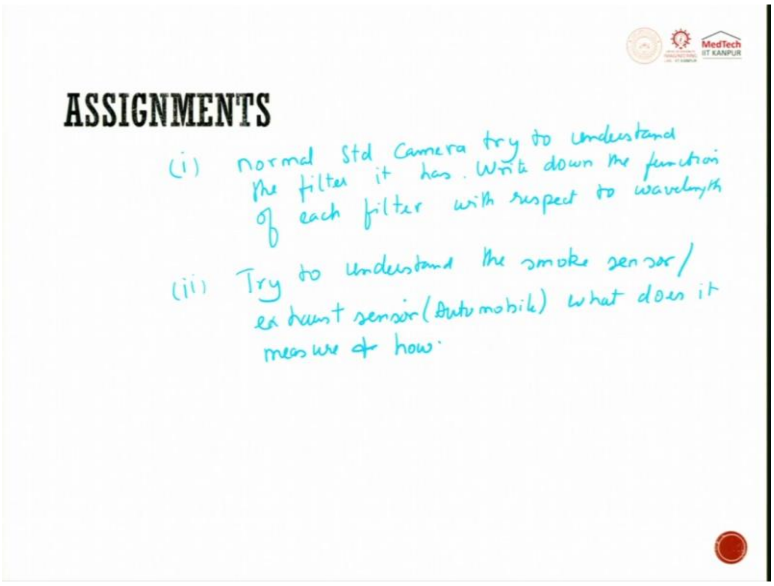

So, assignments as usual you do not have to submit. So, we will try to have two assignments. So, try to take a normal standard camera which we use in our desktop Try to understand the filters it has. Write down the function of each filter with respect to wavelength. So, that is one. Two, try to understand the smoke sensors or the exhaust sensors used in automobile, what does it measure and how? So, try to solve or understand or try to do this assignment. So, this will try to give you more understanding about multi sensors of different different output parameters you get and then through that you try to monitor the process. Thank you very much.