Techniques of Materials Characterization
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Lecture - 34
Optics of SEM (Continued)

Welcome everyone to this NPTEL online certification course on techniques of materials characterization. So, we are on sixth seventh week and we are still discussing on scanning electron microscopy and we are discussing about the optics of SEM. And in the last class we started with optics and they are we were discussing about the minimum probe size and the probe current and how they are related. This discussion will continue in this lecture.

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The first thing we will discuss about the pixel size and how it is related to the resolution and then we will discuss about the depth of field in SEM and then how to calculate how to get the ultimate resolution of SEM what depends or what decides the ultimate resolution of SEM. And finally, we will discuss about the minimum attainable probe size in SEM because that is what will decide the final resolution in SEM.

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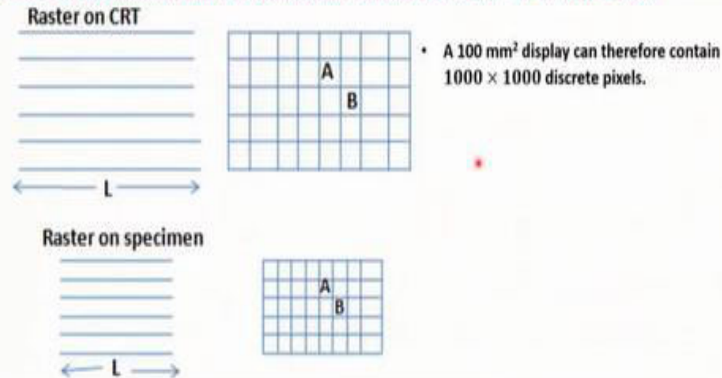

So, we already had discussed how image forms in SEM and we saw that the image formation process in SEM is quite different than in an optical microscope or in transmission electron microscope where the imaging is direct. The entire part of the specimen gets eliminated by the electron beam and finally it is collected on a screen, fluorescence screen or some kind of detector. But the entire image formation is simultaneous.

At one point of time the beam which hits the specimen will finally go and hit the image capturing device or the fluorescence screen. And we will get a contrast depending on what is the interaction happened with the beam and specimen but there is nothing like a scanning. Scanning electron microscope on the other hand side it is something related to movement of beam. So, the beam is moving we have a raster on the specimen and the beam usually moves on the square kind of grid.

If we can have a square grid, we can have a rectangular grid whatever it is, but the beam usually moves like on this raster over a line like this and then again it changes to the next one it comes back here and it goes like this and so on and so for. So, finally we get this kind of points raster here. And every such point we call it pixel the points where this specimen is hitting the square in the electron beam is hitting the specimen, those points we call it picture element or pixels.

And corresponding to the specimen raster we have a raster on the digital display CRT tube good old days there was CRT display. And now we have digital display and we have image capturing devices as well. And on there those devices we have a correspondingly same pixel, same kind of grid is used there and the same kind of movement. We make sure that the specimen the electronic circuits they make sure that the specimen there is corresponding to the specimen this raster pattern.

And corresponding to the specimen pixels there is an equivalent rastering pattern in the digital display or image capturing device and there is an equal equivalent pixel here in the specimen raster. So, these two rasters are related and the pixels are also related. And what happens is this pixels on the specimen is much smaller than the pixels on this image capturing device. So, that is how we achieve finally the magnification here.

So, this pixels on the display here the displaced pixel after from now on we will be calling them in order to avoid any ambiguity. We will call them this will be the specimen pixel and this will be your display pixels. So, typically these display pixels are of the size of point one millimetre that is around 100 micron that is a typical size that is used in image capturing device. We can change that; we can change in digital display or image capturing device there.

These days, there are far better image capturing devices are there which are where we can have even bigger size of the pixel and we can change those pixels size and so on and so for. But typically, we can imagine those pixels are around point one millimetre thick or size, diameter 100 micron. That means if we have a 100 millimetre square display or image capturing device that will contain around 1000 into 1000 discrete pixels.

So, 1000 number of discrete so one megapixel around. We can imagine that this is containing almost one megapixel of or slightly higher than or one megapixel around one megapixel this display or device its capacities around one megapixel. And you know that these days we have displays or we have image capturing device even better. That is how the pixels are defined and that is what is the; relationship between the specimen pixel and the display pixels.

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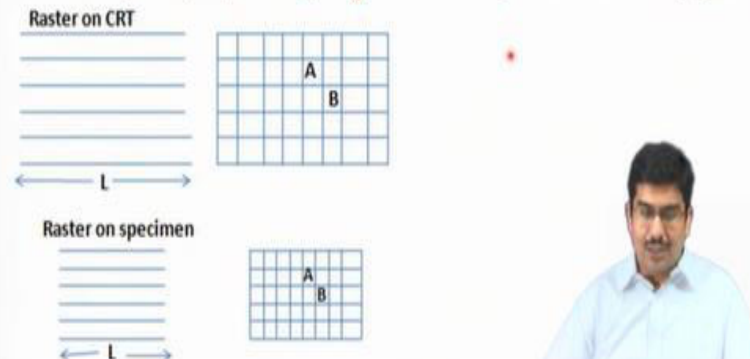

Now in a digital display, we know that image is recorded by a frame store. So, it is a frame by frame the image is recorded and they are contained the similar number of pixels and so on. And the spot here on the on the specimen whatever the pixels the movement of the electron beam, it is exactly mimicked in this specimen rastering here. So, the size of the specimen pixel if we have the size of the display pixels is this if the size is S and the magnification is M.

Then the size of the specimen pixel is basically P. We discussed this all some magnification in scanning electron microscope is basically the ratio between this displace pixel and the specimen pixel, that is it. So, here we are referring the specimen pixel P, the size of the specimen pixel is (S/M), S is the size of the display pixel and M is the magnification so, that is relative. So, this specimen pixel size basically the point is the specimen pixel size is related to the display pixel size.

And already we discussed the display pixel size we cannot change it. This one we cannot change, what we can change is basically this specimen pixel size. The magnification, for a fixed magnification we have to change the specimen pixel size in order to get certain amount of magnification in other words. Because the specimen display pixels size that is constant that we cannot change that.

So, physically that is a display there or an image capturing devices there without changing that display or the image capturing device physically we cannot change the display size of this more or less generally. We cannot change the size of this especially displaced pixel size. So, in order to change the magnification, we have to change the pixel size, specimen pixel size that can be changed.

And that is related already we discussed that is related to the size of the beam wherever the beam is falling and what is the next position that will decide that size of the pixels.

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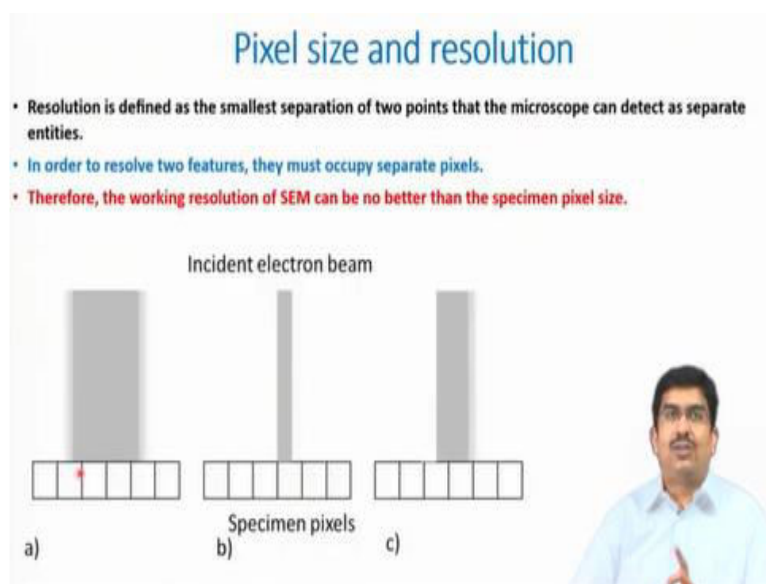

So, how this two is related? How the pixel size and resolution is related? Now resolution we know traditionally it is Lord Rallies criteria and all of this just recall all of them. So, resolution is defined as the smallest separation distance between two points or two features in the microscope which can be identified as separate entities. That is the traditional classic definition of resolution.

For SEM or for scanning mode of image capturing any kind of scanning mode of image capturing. Even in the TV which runs on a scanning mode like images getting formed point by pixel by pixel. We can define the resolution as like in terms of these pixels. So, in order to resolve, in a scanning mode, in order to resolve two different features, these features must occupy two different pixels, separate pixel. So, pixels there are the minimum entity that could be identified separately.

That is a difference. So, there in order to identify some two features which are next to each other, let us say. Let us imagine that two features are there which are just next to each other. In order to define them, they must lie on two different pixels otherwise they cannot be identified. So, the resolution here is equivalent to the pixel size. So, this is the working resolution of any SEM cannot be better than the specimen pixel size. So, specimen pixel size is basically it is deciding the resolution of this SEM.

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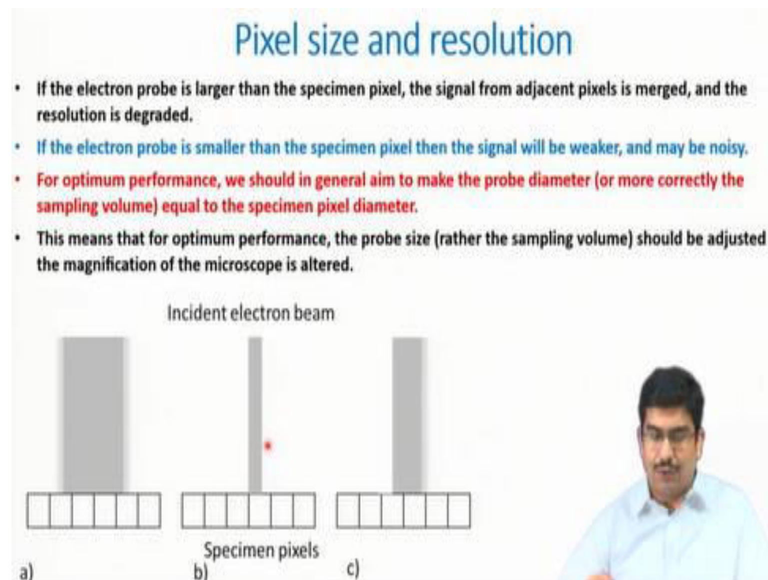

So, that is for an SEM, the working definition of resolution. Now, if the electron probe size is larger than the specimen pixel then what will happen. So, imagine this is the situation, so this is the specimen pixel. Specimen pixel in the sense the magnification then remember the P = (S/ M). So, here what is happening is S is constant M we are desiding we are saying the microscope, okay Let us I want to have something like 1000 x magnification, I want to have million x magnification.

I want to have 10000 x magnification whatever that means the computer or that system now is deciding the pixel size. It is in the specimen raster; it is deciding the pixel size as per the specimen display pixel size and the magnification I want. So, depending on these two things, the specimen pixel size is decided on the specimen surface that what is the minimum distance the electron beam will travel and what will be the distance between two nearby pixel, everything is fixed on that.

Problem is if we have an electron beam if we do not properly control the beam spot size and somehow the electron beam is much larger the diameter after all the condenser lens, aperture lens, if you do not control the strength of the condenser lens if you do not select a proper working distance and so on. And the beam diameter, final beam diameter, spot diameter that we get is somehow larger than the specimen pixel size which is decided already.

Decided based on the; magnification and the display pixel size. This pixel size is decided on the specimen if the electron beam is larger form that size somehow. Then what will happen is that the signals this is the situation this is the electron beam which is much larger than this specimen pixels. So, now the signal that will come because of this electron material interaction so, electron is falling over this entire region of the specimen surface.

And remember that will come, there is a something called sampling volume which is even more severe that makes this interaction volume bigger and we have to take that also in consideration. So, now just imagine that the beam itself is bigger than these specimen pixels. What will happen is now the signal from adjacent pixels will be merged and this will degrade the resolution even if we expect the resolution to be of the order of pixel size here because the beam is much bigger than the pixel.

So,the signal that will come finally. So, let us say the beam is falling here and it generates some kind of a signal let us say SE signal. It generates SE signal that SE signal will come with as per this schematic minimum of two pixels. So, those two pixels the signal will be mixed and the resolution will degrade. Because then if we have two different features which are lying on these two different pixels features are of such small that.

They are of the same order, same size as the pixels. We will not be able to differentiate them just because the electron beam is simultaneously hitting them and the signal is produced simultaneously from both of these two features. So, that is the relation between the size of the beam and the size of the pixel. Now, let us imagine another situation where this electron beam size is much smaller than the beam.

In that case the first problem that will happen is that if the size of the beam is very small even smaller than the specimen pixel, then first thing the beam current will be very low. So, the signal strength will be very very less and sometimes the signal to noise ratio will be very high and signal will be very very noisy. So, that is also not something very suitable and also, we can have is that if the beam size is very very small many a times smaller than the pixel.

This can hit the beam size it could scan; it can hit two pixels at the same time, it can hit at the boundary between two pixels that also is another possibility. And that will make again the same thing resolution will be reduced, two features will be contributing simultaneously for one single beam position. So, for optimum performance we need in general we should aim to make the beam diameter or the probe diameter such that this is equal to the specimen pixel size.

If that is true; then we can avoid each of this situation, we can perfectly get the resolution of the order of pixel size. We can get a signal which is not matched between features which are of the size of the pixels there will not be much of a noise much of it and the beam strength. The strength of the beam also will be so high or will be adequate to generate signals from each of these pixels. So, that is what is the most desirable situation.

And in order to achieve high resolution at high magnification or any desired magnification to achieve the best resolution, we have to properly adjust the beam diameter and beam current. That is the relationship between pixel size and the resolution and the probe diameter, probe current, beam current and so on. Now, as I said that sampling volume is ideally, we should not only talk about the probe size we should be talking about the sampling volume.

Because the sampling volume is something even maybe even bigger than the probe size itself. But we will come to that in a minute. And finally, the message here is that if you want to adjust the magnification if you want to go higher and higher magnification going higher and higher magnification means is S/M. You are reducing the pixel size on the specimen you are asking the beam to scan it at a much lower size the distance between two pixels is now reducing.

So, you have to correspondingly you have to make your beam finer and finer, smaller and smaller. If you are going higher and higher magnification, you must adjust the size of the beam in such a way that you are still hitting at least one pixel at a time. So, that is the relationship between pixel size resolution magnifications and so on.

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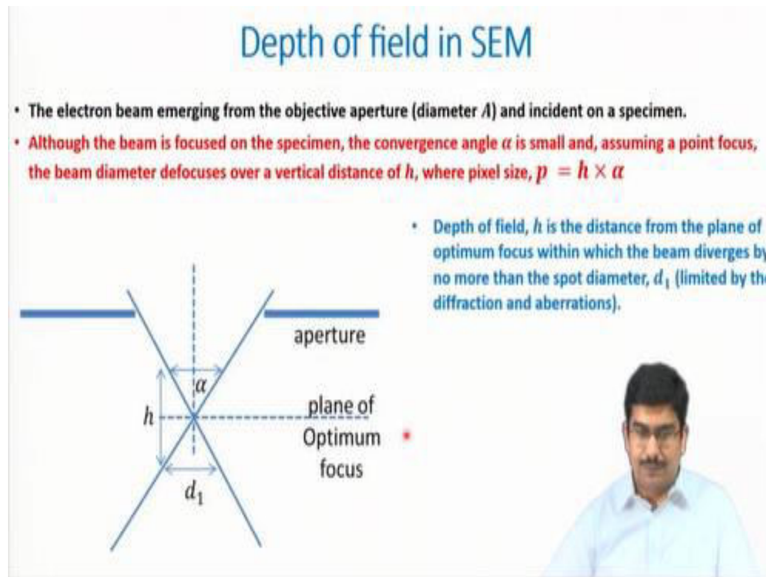

And we will also discuss about this sampling volume in a few slides from now. Now, let us discuss about some other aspects of SEM. So, we know that depth of field in SEM is very very good and that is much better than the optical microscope, we will discuss about that. From our discussion still now, whatever we discussed about the probe diameter and probe size and the pixel size let us see how the depth of field in SEM is calculated and what it depends on.

So, let us just even imagine we remove all the lenses all other the schematic ray diagram, we remove everything there. And just imagine that we have an aperture here on the objective lenses. We have an objective aperture and we have this specimen surface, this plane of optimum focus is basically the specimen surface. Because as I said that in case of a scanning electron microscope, the purpose of the objective lens is to make the beam focus always on the specimen surface.

Then we should get the best quality image. Now imagine that this aperture diameter is a and then the electron beam from the objective aperture it is causing the beam to converge on the specimen surface that is the plane of optimum focus and this convergence angle is alpha. The

semi angle of this convergence is alpha. Now although the beam is focused on the plane of optimum surface which is usually the specimen surface and the convergence angle is very very small.

Then the beam will still be defocused over a vertical distance. So, if we move anywhere from this plane of optimum focus by certain distance let us say that distance is h. So, this distance over which over this vertical distance here, this distance still we will have it be defocused. This defocusing distance and the semi angle will be related to special pixel size on the resolution by this formula. p = h in to alpha, that is the specimen pixel size.

Here expressed in terms of the depth or expressed in terms of the distance over which this defocusing is happening and that is the depth of field. So, depth of field we know that is the distance from the plane of optimum focus within which the beam diverges no more than the spot diameter d_1. And spot diameter here means this is basically the pixel size that is why we are able to write this equation here.

The spot diameter if the sport diameter is say d_1 which is limited the spot diameter is basically limited by diffraction, aberrations and so on. And we have seen that how the spot diameter can be calculated from the crossover size. If we know crossover size, what should be the beam diameter that also we know, how we can calculate that and then there are diffraction aberrations and all those effects will come into that. But whatever it is, let us say this is the spot diameter.

And this depth of focus here, depth of field is here is expressed as that distance over which the defocusing is of the order of this beam diameter. And in scanning electron microscope or scanning electron microscope this beam diameter is related to this pixel size. So, that is how we get a relationship between the pixel size, divergence or convergence angles semi angle of convergence and the depth of field.

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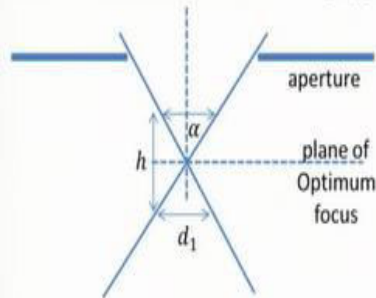

Now, how we can use this? So, the distance this h over with the specimen will remain in focus that is the depth of field this one is again what we can write from that equation p = h in to alpha, from there we can get this depth of focus as this p/(alpha) and p/(alpha) we know that S/ M, M is basically the magnification and S is the display pixel size. So, now the depth of field we are expressing the depth of field in terms of the specimen pixel size.

And convergence angle in turn we are expressing that with magnification and the display pixel size. Now, the convergence angle of the beam that also we can express in terms of the aperture diameter a and the working distance, working distance means this distance the sample the plane of optimum focus to this objective lens or for that matter, we can imagine this is the distance between aperture and the plane of optimum focus.

So, this convergence angle depends on the size of the aperture and the working distance. Finally, if we add up all of this what we can get is that the depth of field h = (2S ×WD)/ (A× M). So, that means, h will depend, number one on the aperture diameter inversely related to the aperture diameter. So, if we increase the aperture diameter or other way, if we decrease the aperture diameter if we make the beam smaller and smaller here.

If we are decreasing this aperture diameter, we should increase the depth of field that is the first thing. If we increase magnification again, we should get lower depth of field. So, aperture if we

decrease the aperture if we make the beam smaller, we are getting higher depth of field first thing. But, remember the problem if you are making the aperture small if you are making the beam smaller the beam current will decrease. So, that is again a trade-off.

If we are going at higher and higher magnification already, we discussed that for that we should the pixel size are reducing. So, we should make the beam smaller. So, even if we are going to higher magnification if this one increases depth of field should decrease that we are balancing somehow by using a smaller beam anyway. So, it is all a trade-off everything and of course working distance. If the working distance is increasing then the depth of field will increase.

That means if we come very closer to the objective lens that depth of field will also reduced and obviously specimen this displaced pixel size we cannot do much about this. So, we do not need to consider that. So, basically what this one means is if we are increasing magnification and we are trying to get a high resolution image by bringing it either making the aperture smaller or by bringing it closer to the objective lens by reducing the working distance.

All of these things will simultaneously reduce the depth of field. So, we have to have a trade-off between this improvement in resolution and the reduction in depth of field. This is something similar to what we have already discussed for TEM or for optical microscope where we saw that these two things goes in opposite direction, improvement in resolution and improvement in depth of field these two simultaneously does not cannot be achieved.

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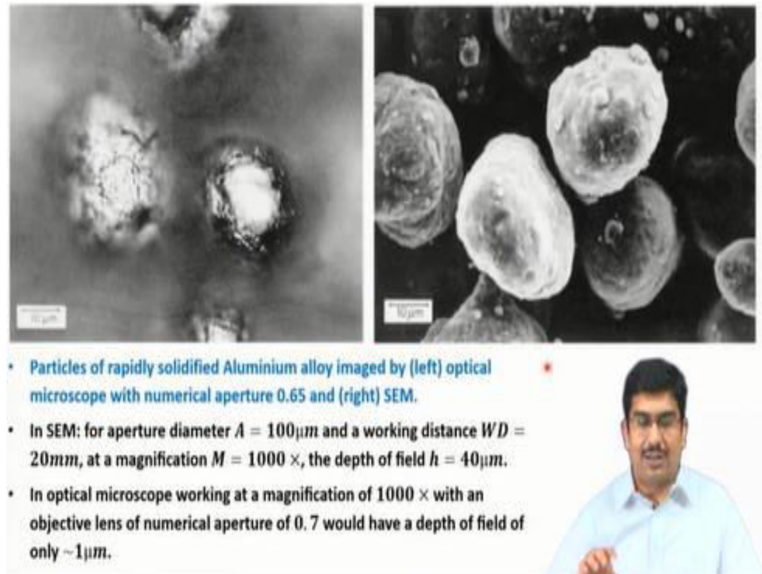

But over and above this is how the depth of field is controlled in case of scanning electron microscope. And if we put some typical numbers here, then what we can see is that this depth of field of scanning electron microscope is far superior than the depth of field of optical microscope. So, let us put some numbers here. For example, in SEM if the aperture diameter is around 100 nanometres, 100 microns which is pretty much a good one for getting a magnification low magnification.

For higher magnification you need to use even smaller and smaller aperture. So, let us have an aperture diameter of 100 micron, working distance 20 millimetres, magnification around 1000 x, the depth of field is around 40 micron. So, that is quite a lot up to 40 micron here on either side around 20 micron on either side. This can be focused still appear in focus the specimen surface even if it is rough and up to 20 micron it will appear in focused condition.

Whereas if we go for an optical microscope with a magnification of 1000 x and a numerical aperture is 0.7 then we will have a depth of field of only one micron. Remember the numerical aperture they are in the optical microscope in direct imaging, the numerical aperture basically decides the mu sin alpha that term. The mu sin alpha for term basically decides the depth of field and resolution as well.

But here in scanning electron microscope the depth of field is not only controlled by numerical aperture and all because it is related to the scanning. So, here it is controlled by the working distance as well as magnification and aperture diameter and convergence angle. Basically, aperture diameter is coming from the convergence angle only here and you can see these images this is a particle of rapidly solidified aluminium alloy.

So, left side this is imaged with optical microscope with a numerical aperture of 0.65 and the right side this is imaged within scanning electron microscope. You can very clearly see not only is a good resolution, you are able to see the small particles. But you are able to keep the entire region focused the backside also, these smaller particles are focused as well as the top side these particles are also in focused.

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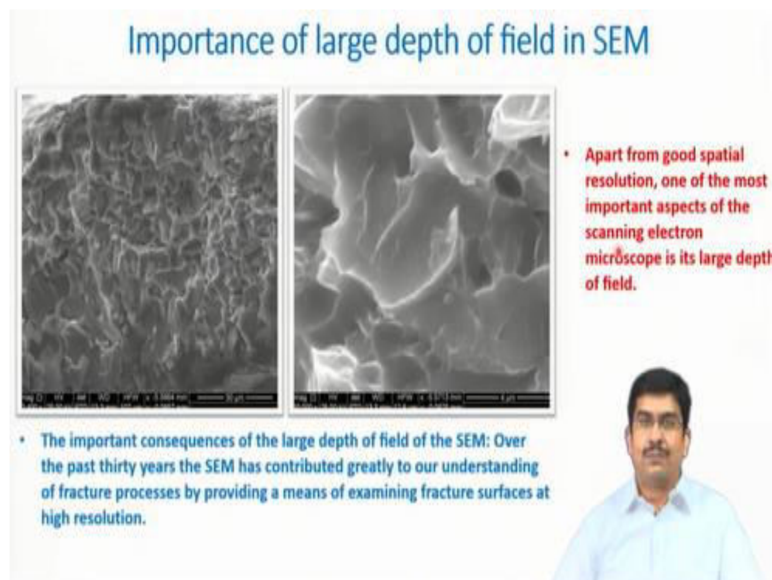

Now, where this; we will end here today's class at least. So, where this high depth of field is applicable? So, why within this SEM? I just picked up one such example from my own research work. So, these are something called factographs. So, when a specimen one when we do some kind of tensile testing or some kind of compression testing or whatever when we do a mechanical testing, the material fails and the failures or the surface over which the crack propagates or the surface on which this specimen fails.

That surface have very typical features like this. These are called dimples; this is a typical tensile feature and tensile fracture feature and this is called so. So, this fracture surface is very very rough usually. Now, what happens is this fracture surface if you try to focus if you are seeing it at high magnification and a smaller walking distance and so on at a small beam size, if you try to see it then you will be not able to focus this entire region.

You will be focusing possibly you can see this is a secondary electron image. So, this is giving basically a topographic contrast and you can see that how rough this surface looks like and this roughness is often in the hundreds of microns range in that level also the roughness can be. So, if you can see that this is almost like 30 microns and this surface roughness is around 100 microns almost.

So, even and this magnification is something I would say the magnification it is not very clear here. But I think it is around 2500 times magnification with this one itself and this is even higher magnification around 10000 magnification here. So, the depth of field of course here is much less than here. But still, you are able to see these different regions and different features at various depths, you are still able to see.

So, for fractographic analysis this is just one simple example I am giving. For fractographic analysis this large depth of field of scanning electron microscopes are very very important and very very useful. Not only that, high resolution is useful here, but also this large depth of field is important. And one more thing one more you can see that this working distance here working distance of almost 13 to 14 millimetre.

So, usually in order to improve just you can see here you just here, the depth of field is improved by higher working distance. So, in order to take advantage of that, usually the fracture surface or fractographic that is what it is called. So, fracture surface examination under the scanning electron microscope usually it is done with a larger depth of with a larger working distance much larger working distance something like more than 10 millimetres usually.

But people can even go at 20 millimetre or even higher. So, that; but of course with a larger working distance you will be compromising on your beam diameter because if you remember the beam diameter is also related to working distance. So, if you are increasing the working distance or getting a higher depth of field, you will be losing in the resolution, because then your beam diameter will increase and you will not be able to get very good spatial resolution at higher magnification.

So, this trade off this kind of trade off one has to do when to work with an electron microscope and to in order to see it such tough surfaces you have to adjust it very suitably. You have to choose your beam diameter, you have to choose your working distance you have to choose your strength of your condenser lenses and all of this in order to get an aperture of course your aperture. So, these are the things which physically you can control the strength.

The focal length of a magnetic lens electromagnetic lenses, the aperture size, the working distance and so on. You have to adjust them in such a way that you could get the best resolution by controlling the pixel size as per the or rather by controlling the beam size as per your pixel as well as the good depth of field for examining for better view of your fracture surfaces. This is all you need to control you need to adjust such all those parameters in order to study this kind of fracture surface.

So, with this, I think we will stop here and we will continue in the next class about the minimum attainable beam size, probe size and so on and our ultimate resolution. Thank you.