Foundations of Classical Electrodynamics
Prof. Samudra Roy
Department of Physics
Indian Institute of Technology-Kharagpur

Lecture-60
Magnetic Materials

Hello student to the foundation of classical electrodynamics course under module 3 we have today lecture number 60. And in this lecture we will qualitatively discuss different kind of magnetic materials.

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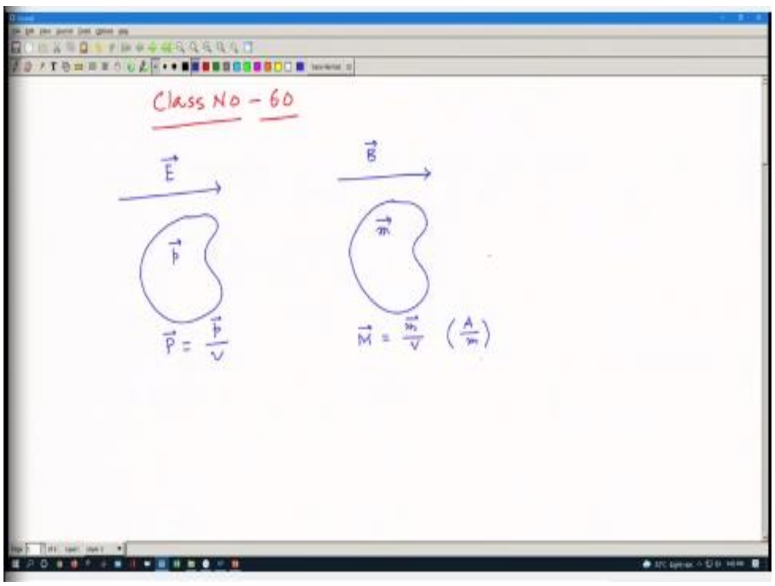

We have class number 60 today, so in electrostatic what we had let me remind that if I have an electric field, this is my electric field and if I placed a dielectric material it will give rise to something called polarization, $\vec{p}$ is an electric dipole moment and $\vec{P}$ is the electric dipole moment per unit volume, so roughly this. In a similar way, if I have a magnetic field here say $\vec{B}$ or $\vec{H}$ and if I placed a magnetic material here, this material is characterized by the magnetic dipole moment $\vec{m}$.

And magnetization will be like magnetic dipole moment per unit volume, this is Ampere per meter in terms of unit. So, both the cases what happened that in this case the dipole will try to align along the applied electric field. So, suppose this is the dipole it will try to align the applied electric field in magnetic case also similar phenomena happens. Now based on the alignment, so we can have suppose I have a magnetic field here $\vec{B}$.

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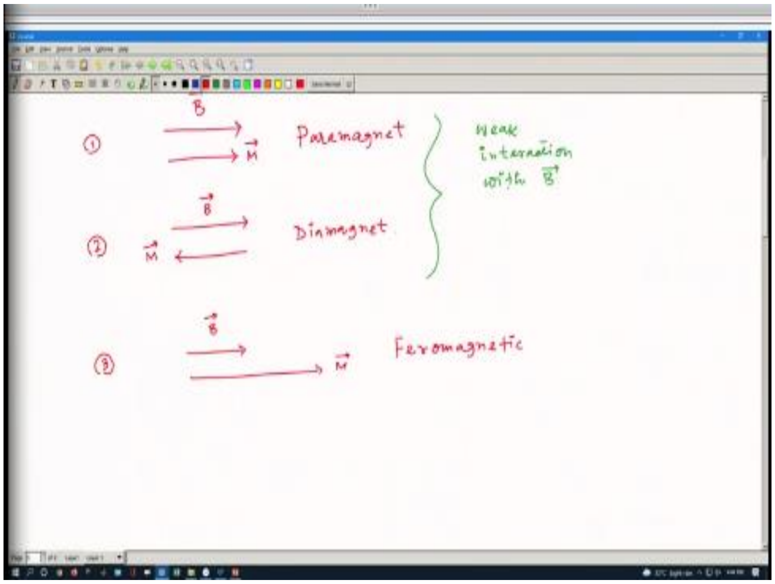

And if the alignment is in the same direction, this is my $\vec{M}$, then this is called the paramagnet, this is case 1. So, in paramagnet what happened that let me first define another then maybe. So, in second case I had an applied electric field say $\vec{B}$ but the response is like it is creating a magnetic moment in the opposite direction of the applied magnetic field, so this kind of material is diamagnetic.

Normally in paramagnet and diamagnet what happened that for these 2 cases, it is interact weekly with the applied electric field $\vec{B}$. So, weak interaction with the applied field $\vec{B}$. But there are third kind of important material that we had where if you apply the magnetic field $\vec{B}$, the magnetization will be in same direction but the effect will be much larger compared to the other 2, so this is called the ferromagnetic material. So, for ferromagnetic material the interaction with $\vec{B}$ is very strong.

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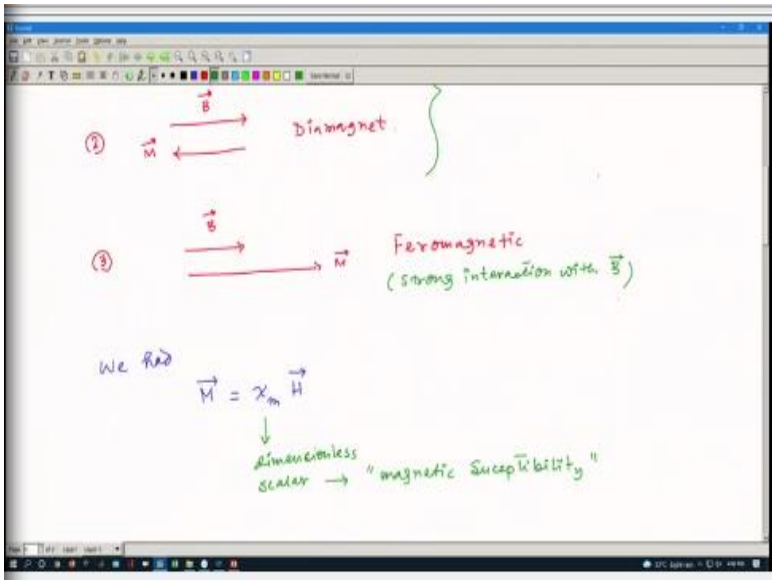

So, it is having a strong interaction with the applied field $\vec{B}$. So, these are normally the permanent magnet, so these are basically form a permanent magnet, so fine. So, so far what we have? So, let us try to understand in a more qualitative manner, more quantitative manner rather. So, we already had an expression where we had the relationship with the magnetic moment per unit volume that is magnetization with the magnetic field $\vec{H}$, that is the relation we derived couple of classes ago.

So, this χ_m we mentioned that again I am writing this is a dimensionless scalar quantity, which we call the magnetic susceptibility. Now from this figure we can say that for paramagnet and diamagnet the value of the susceptibility, the sign of the susceptibility is different. So, for paramagnet what we have?

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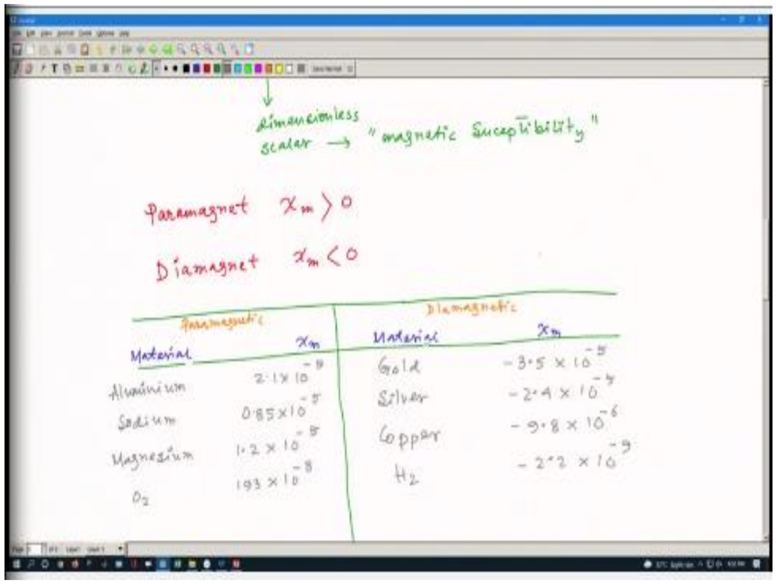

We have susceptibility greater than 0 and for diamagnetic the susceptibility is less than 0. So, if I make a quick chart to understand what is the typical value of the paramagnet and diamagnet material then let me do that first. So, let us make a table here to just give a rough idea. So, this is the table and here we have say paramagnet material, magnetic and these are the diamagnetic. And this is material, so I have 2 columns here.

So, one is material and the corresponding χ_m value or the magnetic susceptibility value. Here we have again like a material and we have some susceptibility value here. So, let us give some example. So, for example here the first thing I can write is aluminum, aluminum is one kind of paramagnetic material and if I want to know what is the value of this χ_m it is around 2.1×10^{-5}, just see the order here.

Another example I can put is sodium and for sodium this is 0.85×10^{-5}. Then magnesium is another example whose value is around 1.2×10^{-5}. Then we have like oxygen O_2, the typical value is 193 $\times 10^{-8}$, these are few examples of the paramagnetic material and the corresponding χ_m values. In a similar way, for diamagnetic we can give some example like gold the typical value is - 3.5 because for diamagnet I mentioned that the χ_m should be negative.

So, it is -3.5×10^{-5}, then silver this is around $- 2.4 \times 10^{-5}$, the order is same but the value is different here. Then copper it is -9.8×10^{-6} and then we have hydrogen, which is $- 2.2 \times 10^{-9}$. So, just I listed few typical values, so that you can appreciate that the paramagnetic and diamagnetic what should be the value of the χ_m.

And why this value is positive and negative? I just mentioned this is just for qualitative understanding that how the materials, what is the value of the materials for paramagnetic and diamagnetic? Now we will concentrate more on the most important material here that is the ferromagnetic and we will discuss in detail about that. So, let us write it here.

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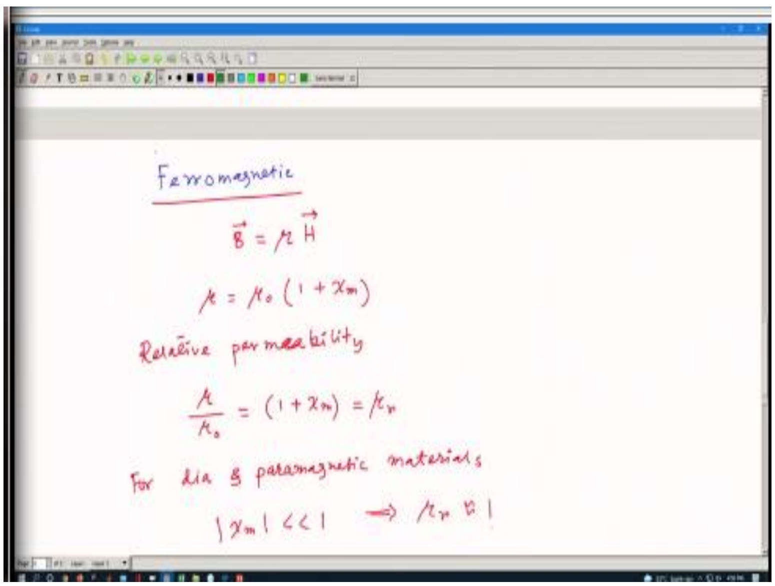

So, ferromagnetic is interesting material, so here I missed one r actually already I mention that the strong interaction. So, ferromagnet is a material where we had a strong interaction of the material with the applied external electric field. So, here for ferromagnetic material what happened? So, $\vec{B}$ we know, I can write it as $\mu\,\vec{H}$, this is the relationship with $\vec{B}$ and $\vec{H}$, where μ I can write as μ_0 (1 + the magnetic susceptibility, χ_m).

So, the relative permeability is $\frac{\mu}{\mu_0}$, which is 1 plus this quantity and normally we call it as μ_r. So, for dielectric and paramagnetic material I have already mentioned the value here χ_m. See we can see that the μ_r the relative permeability is very nearly equal to 1. So, for dia and paramagnetic materials, so the susceptibility value is very, very less than 1, which gives μ_r almost equal to 1.

For ferromagnetic on the other hand and also the response is a bit linear. So, if χ_m is small, so you can see that that means this relation, so μ can be replaced simply by μ_0, which is a constant and $\vec{B}$ and $\vec{H}$ it poses a linear relationship. But this is not the case for ferromagnetic material.

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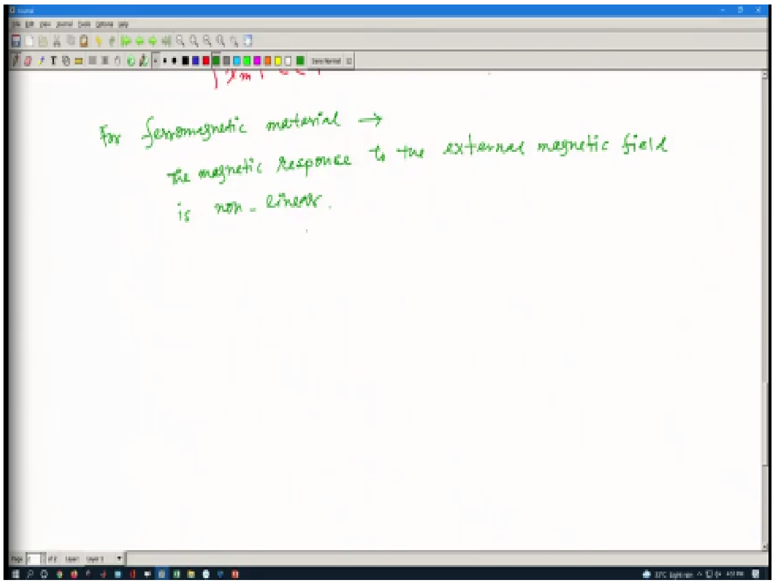

For ferromagnetic material what happened that the magnetic response to the external magnetic field is non-linear. Like the previous case we can see $\vec{B}$ is proportional to $\vec{H}$ but here we should not write $\vec{B}$ is proportional to $\vec{H}$ because the response is non-linear. So, few examples of the ferromagnetic material I should put here.

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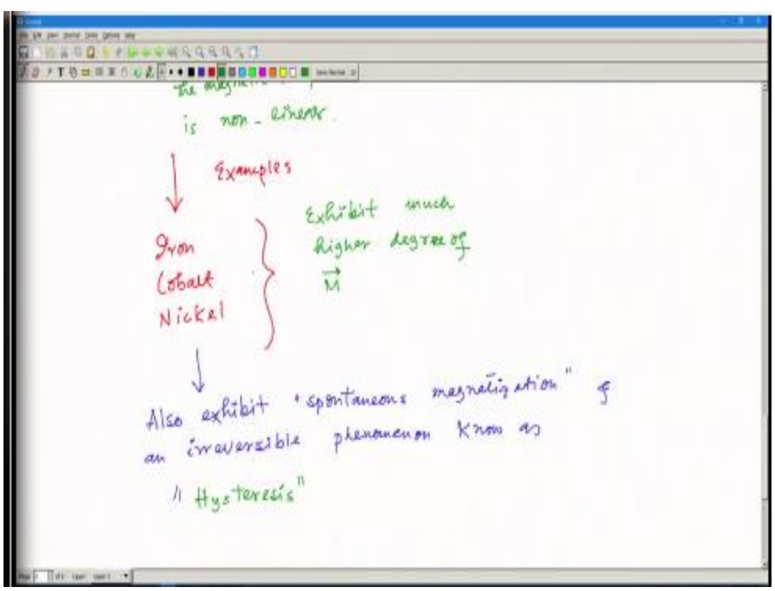

Examples like Iron or Cobalt, then Nickel, these are few example of the ferromagnetic material and they exhibit much higher degree of compared to the ferromagnetic and diamagnetic the magnitude of $\vec{M}$ the magnetization is much higher. And they also exhibit something very interesting here, so that maybe I should emphasis here. So, they also exhibit spontaneous magnetization and an irreversible, let me write it then I will be going to explain in detail.

Irreversible phenomenon known as hysteresis, a very important phenomena in ferromagnetic materials. So, we will be going to spend some time to understand this hysteresis. So, what is the meaning of that thus they have spontaneous magnetization and irreversible phenomena because if you apply the external electric field the magnetization will be there and if you reduce the corresponding electric field the reduction of the magnetization is not proportional.

So, there will be some lag and due to that some heat dissipation will occur, so that thing may create some sort of loss in the system and that we will be going to discuss. So, before going to the discussion of the hysteresis also I like to mention that there is for this kind of material we have something called Curie temperature or Curie point what is that?

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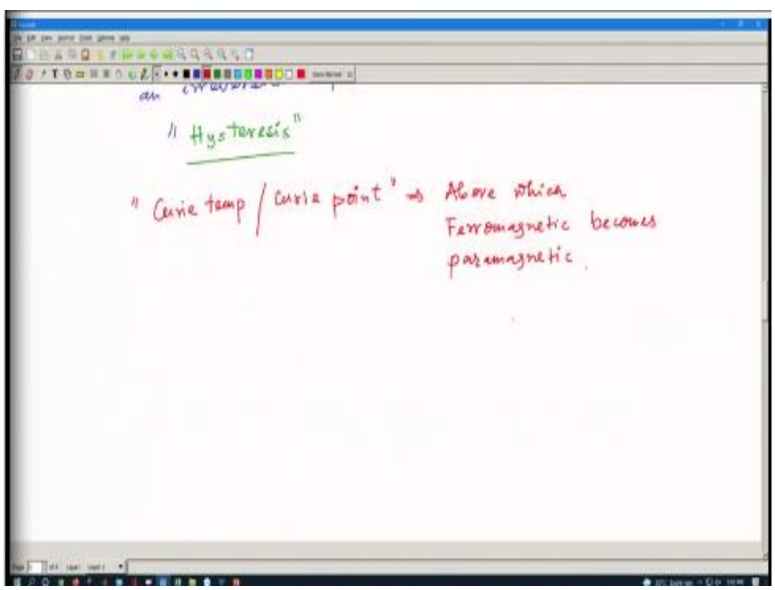

A temperature above which, so if I heat the material, so then there should be a specific temperature and if you go beyond that temperature if I heat the material beyond that temperature what happened that the ferromagnetic above which this ferromagnetic property will be lost, so ferromagnetic material becomes paramagnetic material. So, there is a transformation for ferromagnetic to paramagnetic.

If I heat this material up to a specific temperature called Curie temperature or Curie point that is another property that I should mention. Now for ferromagnetic let us see so if I plot that what is the meaning of this non-reversible thing and this stuff. So, here let me plot it.

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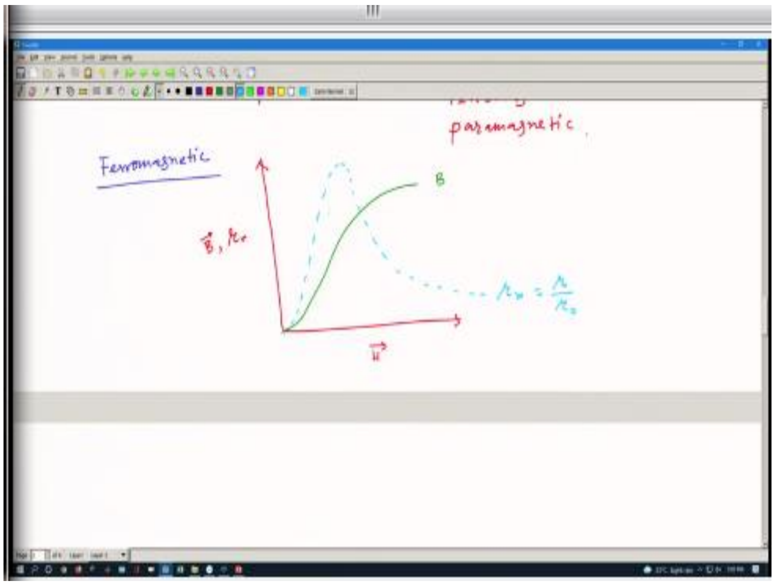

So, I have ferromagnetic material and I want to plot this, so here in the x axis I plot the field and y axis I plot $\vec{B}$ and also the relative permeability. So, this relative permeability is also function of $\vec{H}$ that is the important part here. So, the relationship with $\vec{H}$ and $\vec{B}$ is not linear because the response is non-linear. So, $\vec{B}$ and $\vec{H}$ normally this is a linear relationship for paramagnetic and diamagnetic but here we have a relationship like this.

It will increase and then gradually go to the saturation, so this is the $\vec{B}$ curve. What about the μ_r if I plot μ_r how the plot will look like? The plot is simply like this, so it will be going to increase, go to maxima and then decrease like this. So, this is μ_r and that is $\frac{\mu}{\mu_0}$, so the response of this relative permeability with respect to $\vec{H}$ is a typical response and we can understand that by the way.

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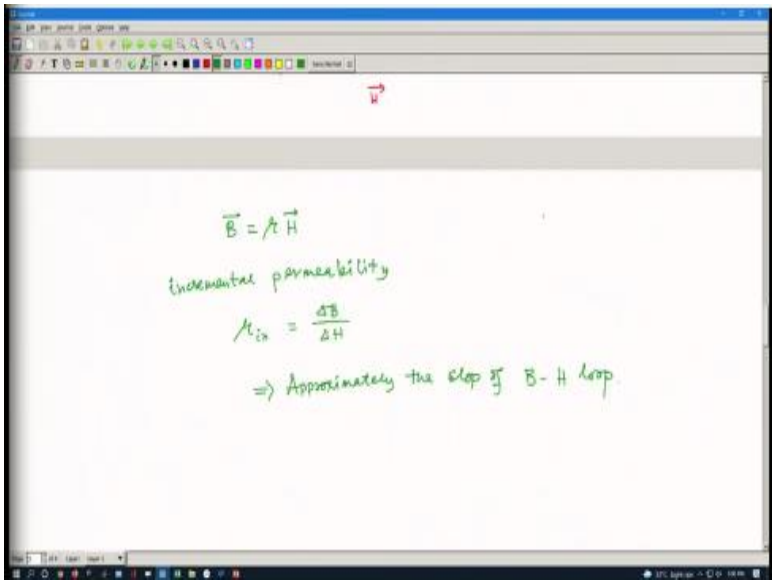

So, my $\vec{B}$ is simply $\mu\vec{H}$ and the incremental permeability if I want to find out. The incremental permeability that means what is the amount of the permeability by small change of $\vec{H}$, so this is this one that is roughly the ratio of the amount of $\vec{B}$ change with respect to the amount of the change of $\vec{H}$. That is nothing but this approximately the slope of the $\vec{B}$-$\vec{H}$ loop. So, that is why if you make a slope here you can see we have a steep slope here the value is high and then it goes to saturate and then the value drops radically but it goes to asymptotically like this. So, this is roughly following the slopes let us understand now the hysteresis in a more detailed manner.

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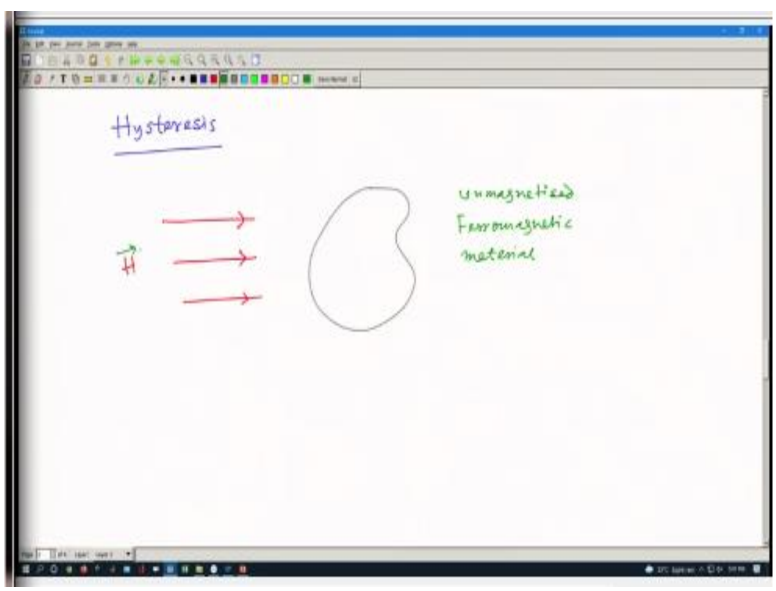

So, hysteresis, so what happened? That suppose I am applying some external magnetic field $\vec{H}$ and I placed a material here ferromagnetic material. So, this is say unmagnetized ferromagnetic material placed in the external magnetic field, this is unmagnetized. Now what happened?

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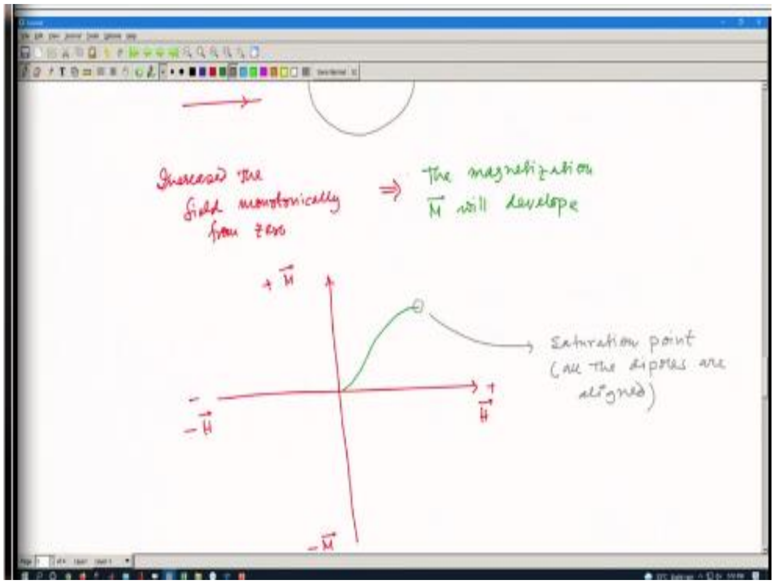

That if I increase the field monotonically from 0, so as a consequence what happened? That since I am increasing the field the magnetization $\vec{M}$ will develop, so this is my magnetization. So, this will also going to develop if I gradually increase the magnetic field. So, now if I plot that; that will have a very interesting plot. If I plot this stuff here, so let me first draw the axis. So, I have $\vec{H}$ here and this is my positive side and this is my negative side, this is negative $\vec{H}$.

And if I plot in the y axis the magnetization, this is positive one and this side it is negative one. So, initially if I increase, so we will be going to get a response like this. And if I increase further the magnetization will not going to increase, so this point where it reaches to a saturation, this point we call this point as saturation point where all the dipoles are aligned. So, whatever the dipole we are having here inside the material, so they will be going to align.

So, we have different dipole and due to gradual increase, so they are now aligned. Now what happened that I will be going to decrease the $\vec{H}$ because they are saturated now I am going to decrease the $\vec{H}$? When I decrease the $\vec{H}$ the magnetization will reduce but it will not going to reduce in same path, it will be going to reduce in a different path, let us put this path.

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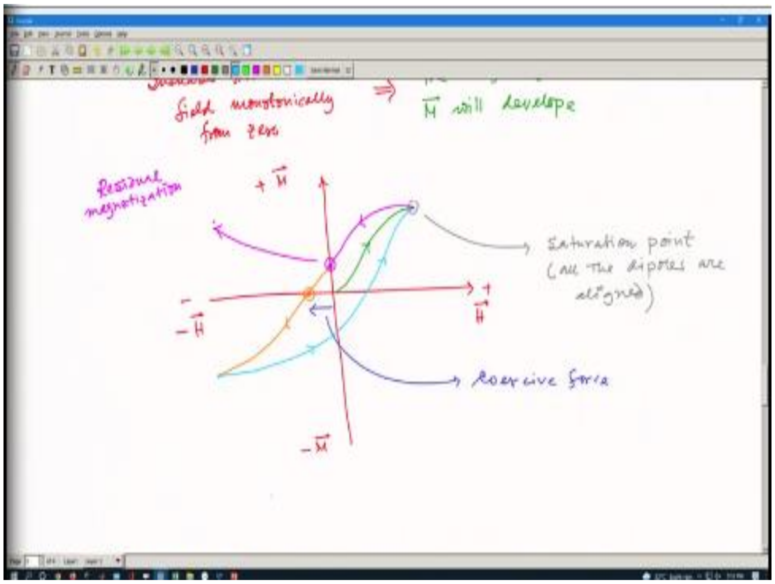

So, it will reduce in this way, so there is a gap here, so this point you can see that even though my magnetic field is 0, I should have some magnetization here still. So, this magnetization is called the residual magnetization. Why residual? Because even though I have my external field 0 the material is still having some sort of magnetization, then what happened? I further reduce, now I need to make it 0, so I further reduce my magnetic field in the opposite direction.

And if I go on to some that value so this will go on and reaches some value here. So, here again I can have a point where it will hit the 0 curve that means magnetization here vanishes. And that point, so this is the amount of the force that is required to make this magnetization 0, sometime it is called the cohesive force. Then again I gradually increase the value of $\vec{H}$ and you can see that if I increase the value of $\vec{H}$ then what happened that it will again not move to the to the direction in this direction rather it will follow a different curve.

And this curve will be something like this and eventually it will be going to meet here. So, this is the curve, which we called the hysteresis curve. And, so I first increase this direction and then I decrease further, then again I increase and it will form a closed loop kind of thing, this is the hysteresis curve. And this loop whatever the loop it is forming is called the hysteresis loop.

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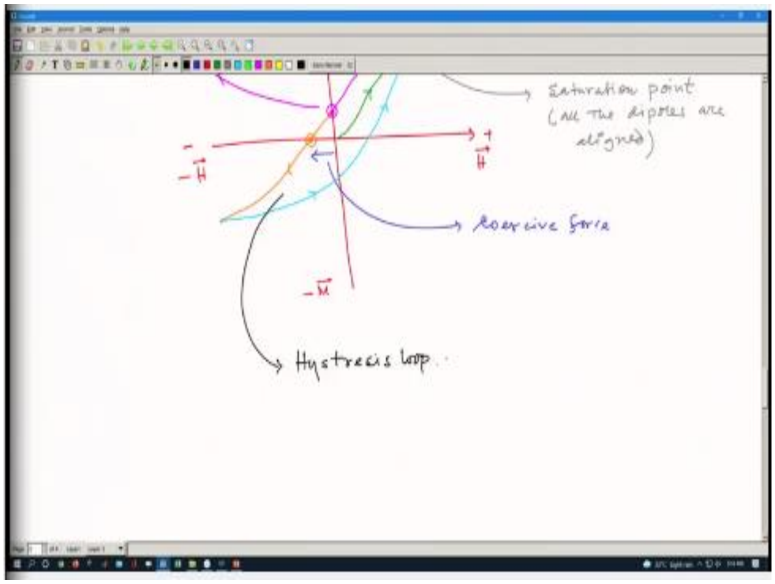

This loop is called the hysteresis loop.

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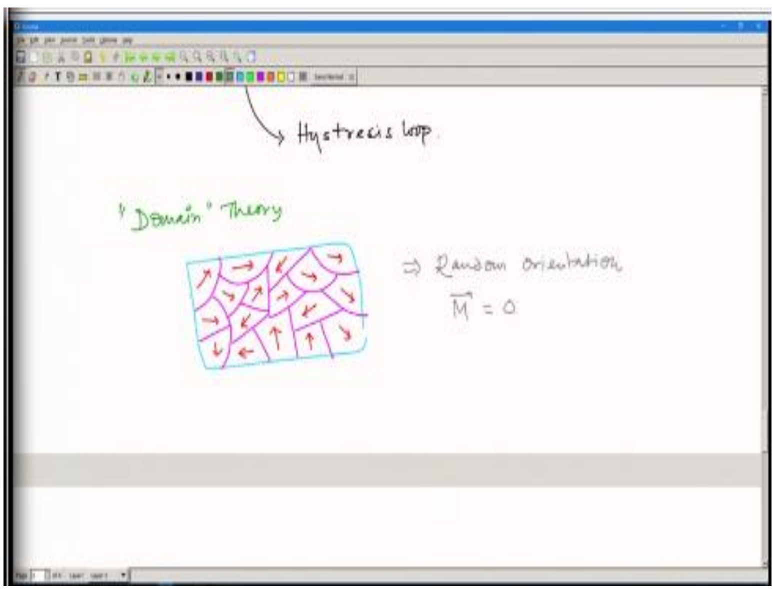

Now quickly understand something what is the reason behind this we called it domain theory, qualitative understanding of these things domain theory of the ferromagnetic. And it says that in the ferromagnetic, suppose we have a ferromagnetic material here, so in this ferromagnetic material we have several domains. Say I draw some arbitrary domain here, so these are the domains one can expect where?

So, I just draw the domains here like this. So, in the domain we have the magnetization and they are oriented in a random way. So, these are the orientation of the corresponding magnetic moment per unit volume that is magnetization for this domain and they are oriented in a random way. So, I can say that random orientation makes the total $\vec{M}$ to be 0 but locally they are oriented in a particular direction.

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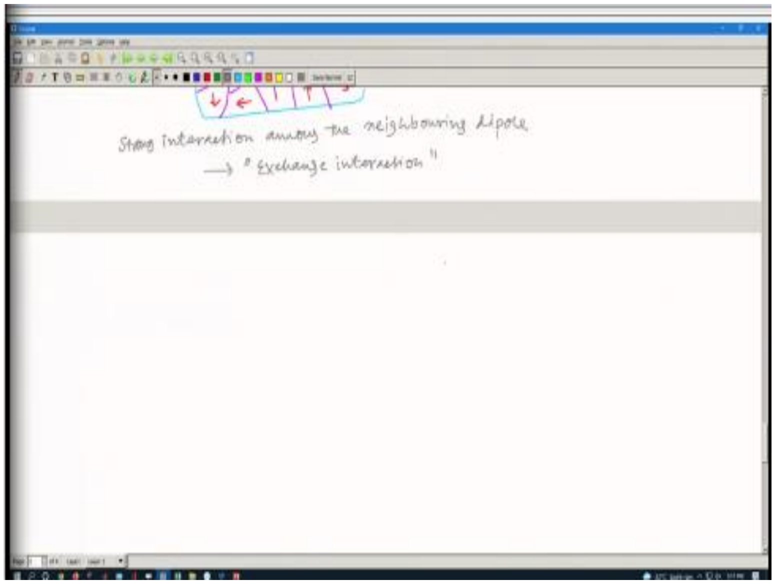

So, I can say that the strong interaction among the neighbouring dipole makes something called exchange interaction, a quantum mechanical process.

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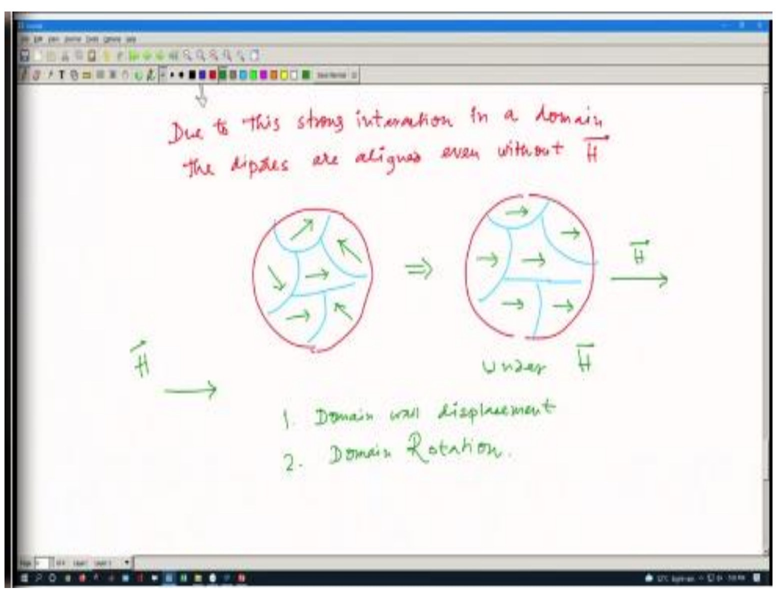

So, this exchange interaction leads to, so due to this strong exchange interaction in a domain what happened? The dipoles are aligned even without any applied field $\vec{H}$, so we have the domain here, so these are the domains. Suppose I am just drawing the domain here like this, so in this domain what happened? If I just highlight this domain, so due to the strong interaction even $\vec{H}$ is 0 the dipoles in these domains are already aligned but they aligned in such a way that the net thing is 0.

Now if I apply the external magnetic field here, so what happened that this domain, so they start align, so under these things will now aligned. So, suppose this was my domain and under the application of magnetic field these things are aligned. So, 2 ways, so this is under $\vec{H}$, so I have $\vec{H}$ here, so 2 ways it can align, one is called the domain wall displacement, domain wall are displaced to form this kind of alignment.

And another mechanism is called the domain rotation where the dipoles are rotate accordingly to align themselves along the applied magnetic field. So, this hysteresis loss you can understand under this let me do it quickly.

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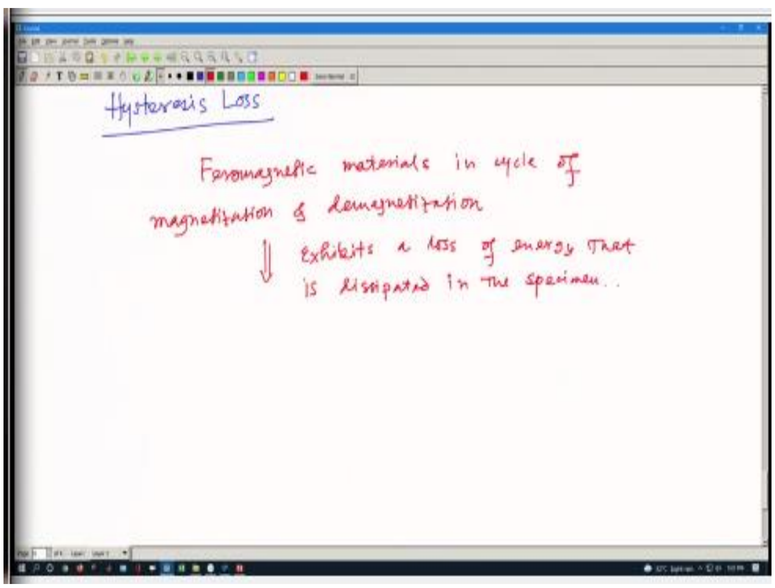

Hysteresis, so what happened that? Ferromagnetic materials in cycle of magnetization and demagnetization, so once it is magnetized and then again demagnetizes, during this process what happened? It exhibits a loss of energy that is dissipated in the specimen itself. So, this hysteresis loss I can calculate in this way.

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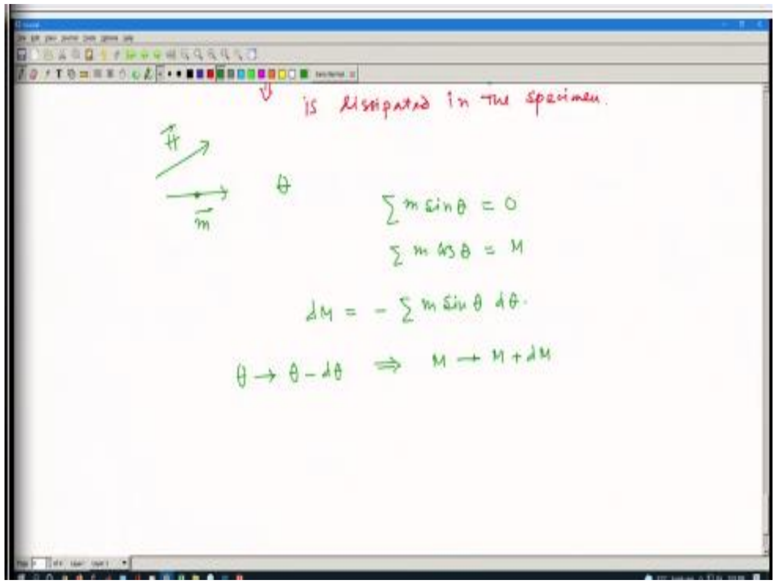

So, suppose I am applying the $\vec{H}$ here in this direction and this is my magnetic moment and the angle between these 2 is θ. Then if I calculate the total magnetization, so the sine component of all this magnetic moment perpendicular to the $\vec{H}$ should be 0, where when it is aligned the cos component of all these things should be the magnetization that we are looking for. So, from here we can calculate that dM should be - m sin θ dθ, why minus sign?

Because if θ, so I am making alignment, so if θ is reducing from θ to θ - dθ, so that eventually makes the M increasing M goes to M + dM. Because if the θ is 0 then we have a maximum magnetization because this is then $\vec{M}$ and $\vec{H}$ will be in the same direction. So, that is why the negative sign should appear.

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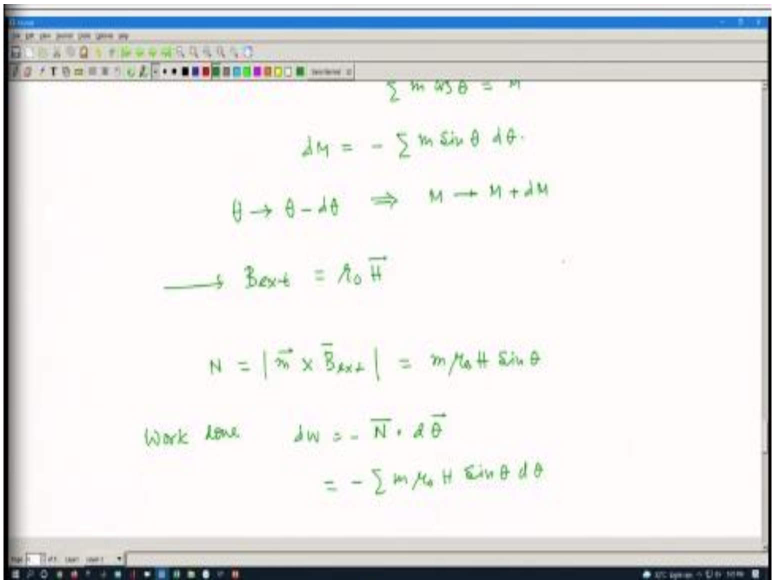

Now if I make an external field say $\vec{B}_{\text{external}}$ that is equal to μ_0 $\vec{H}$, so the torque we calculated last day the amount of this torque due to which there is alignment is this $\vec{B}_{\text{ext}}$, this is the expression we figure out. And that should be m μ_0 H and since it is a cross product we have a sin θ here. Then what happened? Then this is the amount of torque on the dipole moment, so the work done that we also calculated.

The work done is dw that should be $-\vec{N} \cdot \mathrm{d}\vec{\theta}$ because it is rotating the amount dθ. So, this value is simply -m μ_0 H and then sin θ dθ. So, now this dw I can write because already I figure out that μ_0 H is B_{ext} and I already calculated that dM = m sin θ dθ.

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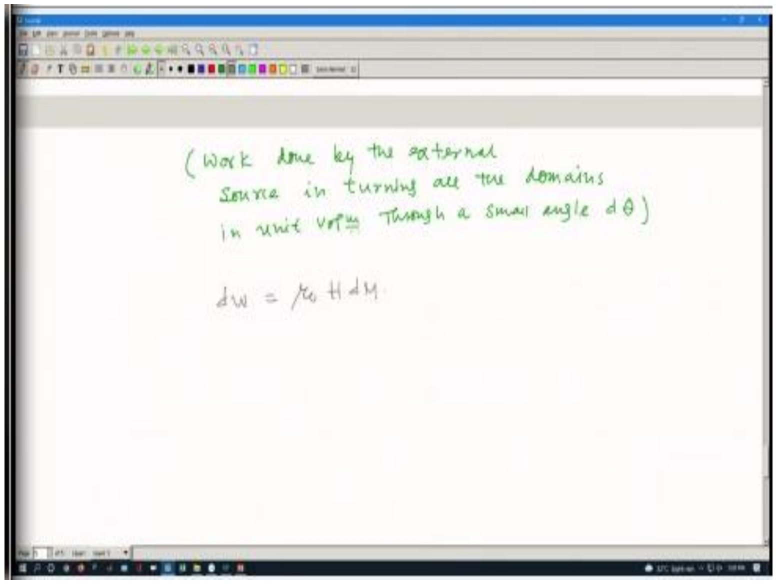

So, if I replace this value, so this is the amount let me write down. The work done by the external source in turning all the domains, whatever the domains we have, all the domains in unit volume because we are calculating magnetization through a small angle dθ. So, all the domains are tilted to the small angle dθ, so that amount is simply dw, if I put all this value comes to be H dM. Now if I want to find out what is the total amount of work then I need to integrate.

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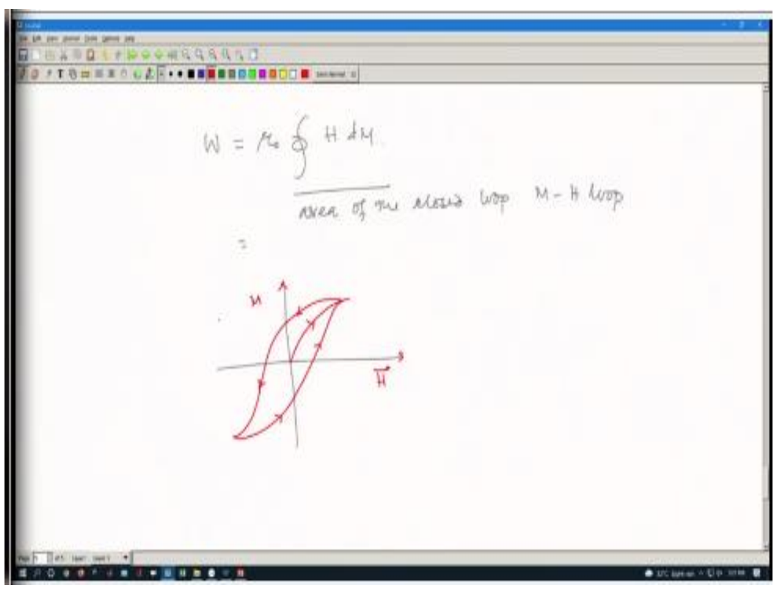

And if I integrate it should be $\oint H\, dM$. So, H dM close line integral is nothing but, so this is the area of the closed loop form or which is the M-H loop. So, the M-H loop already we have drawn, so this is the form of the loop. So, we plot it here $\vec{H}$ and $\vec{M}$ this side, so it should have an area and if I calculate this area closed area then that eventually gives me the amount of the loss. You can also calculate this loss in terms of $\vec{B}$ actually B-H loop and that calculation is like this.

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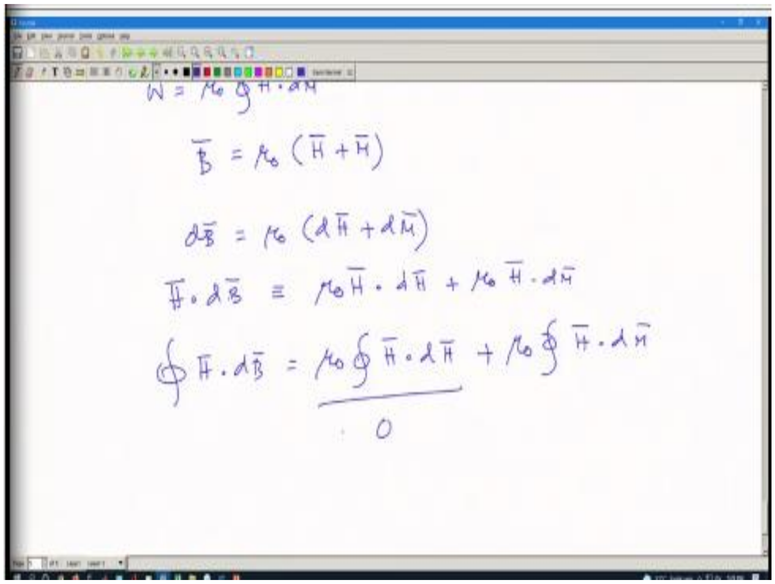

So, w is $\mu_0\ \vec{H} \bullet d\vec{M}$ and $\vec{B}$ I can have $\mu_0\ (\vec{H} + \vec{M})$, let me do it quickly. So, $d\vec{B} = \mu_0\ (d\vec{H} + d\vec{M})$ and if I calculate this quantity $d\vec{M}$. Now that will be μ_0 this is $\vec{H} \bullet d\vec{B}$ if I calculate, so what value we are getting $\mu_0\ \vec{H} \bullet d\vec{H} + \mu_0\ \vec{H} \bullet d\vec{M}$. Now if I integrate both the side $\vec{H} \bullet d\vec{B}$ it should be $\mu_0 \oint \vec{H} \bullet d\vec{H} + \mu_0 \oint \vec{H} \bullet d\vec{M}$. Now this quantity should be 0 because H dH if I plot, so it is forming a straight line.

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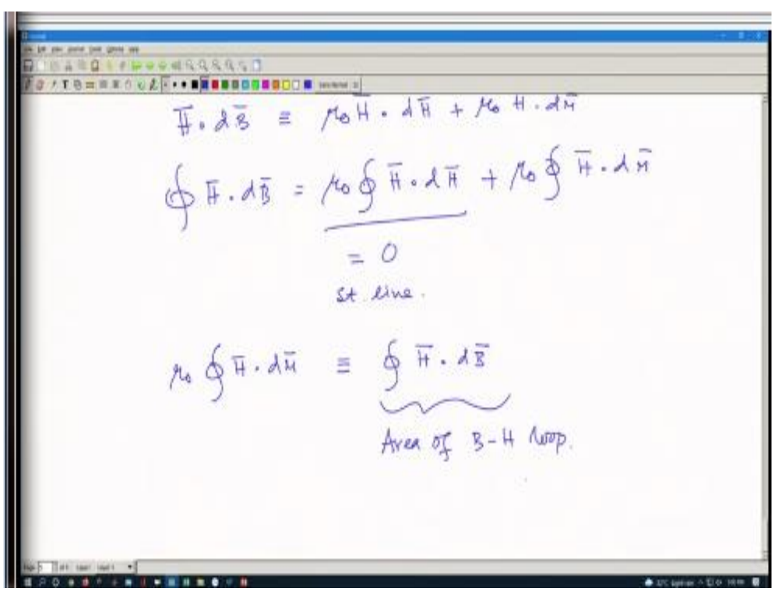

So, straight line should not have any area, so this is simply gives a 0. So, then we have whatever the value μ_0 H dM we are having that is equivalent to the closed and $\vec{H} \cdot d\vec{B}$, which is the area of the B-H loop. So, you can also calculate this is nothing but the area of B-H loop. So, you can also calculate the same thing by calculating the area of the B-H loop. In many cases it is written in this way, that is why I just simply calculate and show that both the cases you are calculating the same thing.

Well, I think I should conclude here, today we have a qualitative discussion of the different kind of magnetic material, so that basically ends our module 3. So, in the next class maybe we will continue more about the other modules and other problems, thank you for your attention and see you in the next class.