Materials Chemistry

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Module - 4
Lecture - 3
Magnetic Materials II

In the previous lecture, we looked at some of the definitions of Magnetism, and how we measure magnetic response of a material and some of the parameters that we usually link to a magnetic property in a material. And we also looked at some of the basic definitions that categorize, magnetic materials into different categories and how we can ascertain those magnetic properties.

In continuation to the previous lecture, I would like to dwell little bit more on the classification of the magnetic property in a material and also I will try to attempt showing, some of the group of compounds, which really stand out in today's functional applications. The cartoon that I have put in this in introductory slide shows that, today the magnetic materials can be used in every other applications, including toys to very sophisticated applications in avionic tubes and in recording media. So, in today lecture, I will try to take you through different classification of these magnetic materials and show some example of how these materials can be used in applications.

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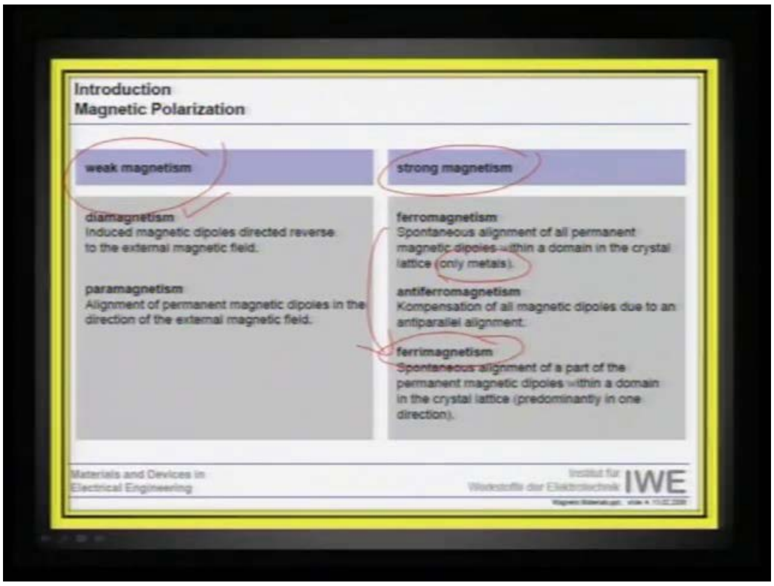

Introduction
Magnetic Polarization

weak magnetism	strong magnetism
diamagnetism Induced magnetic dipoles directed reverse to the external magnetic field. **paramagnetism** Alignment of permanent magnetic dipoles in the direction of the external magnetic field.	**ferromagnetism** Spontaneous alignment of all permanent magnetic dipoles within a domain in the crystal lattice (only metals). **antiferromagnetism** Kompensation of all magnetic dipoles due to an antiparallel alignment. **ferrimagnetism** Spontaneous alignment of a part of the permanent magnetic dipoles within a domain in the crystal lattice (predominantly in one direction).

Just to recall the 2 group of compounds that, we can easily categorize is based on the weak magnetic response and strong magnetic response that materials display. So, weak magnetic response, diamagnetism and paramagnetism, usually talks about influence of a external feet on the material, whereas in strong magnetism, it is a intrinsic response of a material in itself, when we say diamagnetism although, there is a very poor response from the material point of view, to a net magnetic movement, but the diamagnetism per say can be used for sophisticated applications, for example, magnetically levitating a train, magnetic materials are used. And those materials has to be diamagnetic, for magnetic levitation, therefore diamagnetism in essence is not a bad response, it is as much used and exploited like a strong ferromagnetic material.

So, this is one group called weak magnetic response and strong magnetic response, comes from ferromagnetism, antiferromagnetism or ferrimagnetism, we have already seen ferrimagnetism is nothing but, a ferromagnetism. But, then there are some antifferromagnetically aligned movements, which although is present, it is compensated by a strong ferromagnetic response, therefore, ferrimagnetism is a special case of ferromagnetism.

And ferromagnetism in essence is mainly seen evidently in metals and there are very few other compounds, which can be called as a ferromagnetic material, whereas in ferrimagnetism, you can actually look at examples other than metals, which show ferrimagnetic response and we will look at some of the categories in the next few slides.

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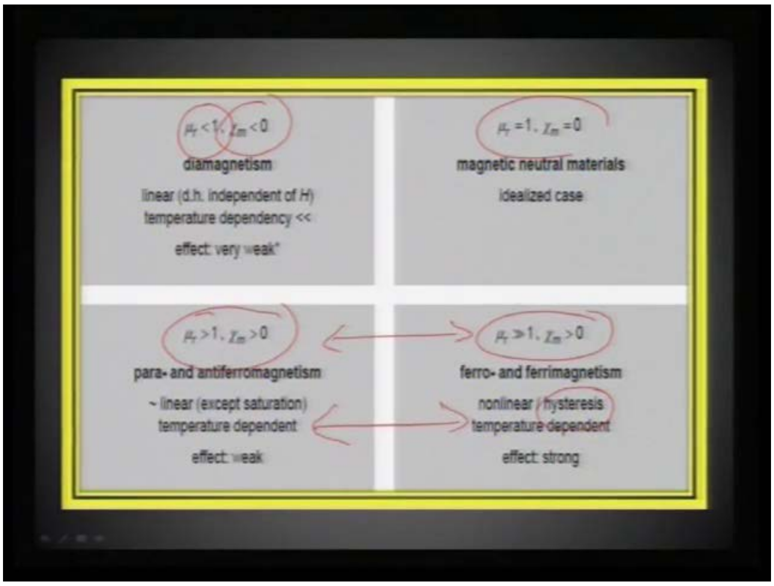

$\mu_r < 1, \chi_m < 0$

diamagnetism

linear (d.h. independent of *H*)
temperature dependency <<

effect: very weak*

$\mu_r = 1, \chi_m = 0$

magnetic neutral materials

idealized case

$\mu_r > 1, \chi_m > 0$

para- and antiferromagnetism

~ linear (except saturation)
temperature dependent

effect: weak

$\mu_r \gg 1, \chi_m > 0$

ferro- and ferrimagnetism

nonlinear / hysteresis
temperature dependent

effect: strong

Also to just group, this weak and strong magnetic material, those which are weak, the diamagnetic materials or paramagnetic materials, can be categorized from the others on 2 counts. One you talk about the susceptibility value and you talk about the permeability value, both are a good measure of whether the material is good or not in terms of its magnetic response.

Usually, if you look at the permeability for a diamagnetic material, it is going to be less than 1 and susceptibility is definitely less than 0, where as paramagnetic and antiferromagnetic ones have permeability greater than 1 and susceptibility greater than 0.

But, for neutral materials in ideal case permeability has to be 1 and chi m has to be 0, in case of ferromagnetic and ferrimagnetic materials, your permeability is far greater than 1 and definitely the susceptibility has to be greater than 0. And what is the response between these 2 or what really makes them candidly different is the hysteresis, that emerges out in the case of ferro or ferrimagnetic materials, which is absent in the case of paramagnetic materials.

Therefore there is a clear divide between these 2 compounds and therefore, it is very easy to understand, how a ferromagnetic material would respond against a antiferromagnetic material. Now, the main thing that governs all this 3 group of compounds, ferro, ferri and antiferromagnetic material is the presence of a magnetic domain. Which is not a crystallite or it is not a structural domain, that we are talking about it is the magnetic correlation, that is present within the material that makes these materials very rich in it is chemistry.

Temperatures above a material dependent limit thermal vibrations leads to disalignment of the magnetic moments, the materials becomes paramagnetic therefore, in ferro ferri or antiferromagnetic material. We usually talk about a antiferromagnetic to paramagnetic situation or antiferromagnetic sorry, ferromagnetic to paramagnetic situation. So, the transitions are always to a totally disordered alignment of spins to a ordered or to a antiferromagnetically ordered spins sticks.

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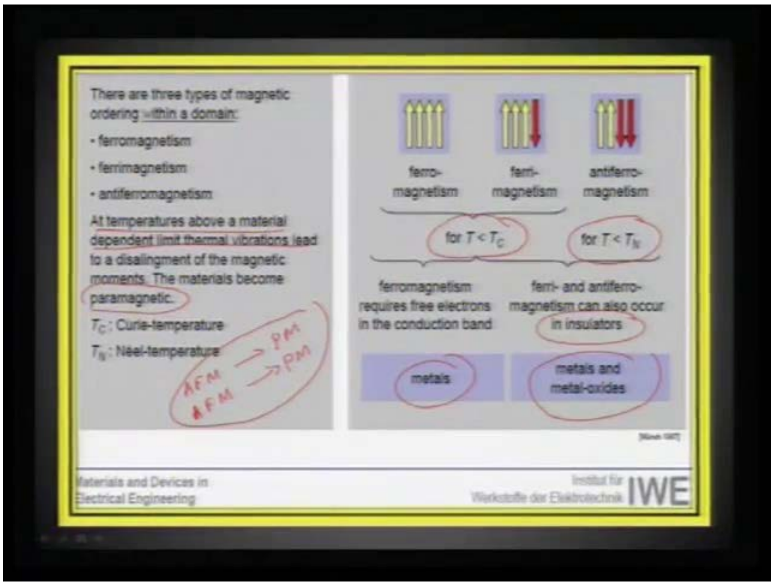

There are three types of magnetic ordering within a domain:

- ferromagnetism
- ferrimagnetism
- antiferromagnetism

At temperatures above a material dependent limit thermal vibrations lead to a disalingment of the magnetic moments. The materials become paramagnetic.

T_C: Curie-temperature

T_N: Neel-temperature

AFM → PM

AFM → PM

ferro-magnetism | ferri-magnetism | antiferro-magnetism

for $T < T_C$

for $T < T_N$

ferromagnetism requires free electrons in the conduction band

ferri- and antiferro-magnetism can also occur in insulators

metals

metals and metal-oxides

Materials and Devices in Electrical Engineering

Institut für Werkstoffe der Elektrotechnik IWE

So, this is exactly, what we see, in ferro and ferrimagnetism, usually for temperature greater temperature less than T C, you see a very strong magnetic response and this is usually present in the case of metals. Whereas, in the case of antiferromagnetism for temperature less than T N, that is Neel temperature ferro and ferrimagnetism can occur in insulators. And this is more prevalent in some of the selected metals and also in metal oxides.

So, what really is a common understanding about metal oxides, transition metal oxides is that, they are mostly antiferromagnetic, but what you would see, in today's application or the new generation compounds, what is understood to be a antiferromagnetic compound transience to become a very strong ferromagnet and metal. And that is the beauty of chemistry, because the substitutional chemistry or materials chemistry totally puts the landscape of transition metal oxides into a different perspective altogether, because of the ease with which, we can engineer the materials.

So, if you know for sure for example, lanthanum cuprate L a 2 C o 4, which is a antiferromagnetic oxide, you can actually make it metallic and you can make it semiconducting by just substituting with strontium, at the lanthanum site. Similarly another very important compound, which I will be discussing in module 4 and 5 is lanthanum manganite, which is a perovskite.

And this lanthanum manganite, actually is a antiferromagnetic insulator, because the in the a b plane, the manganese oxygen sheets are antiferromagnetically aligned along the c axis whereas, they are ferromagnetically confined in the a b plane. But, when you try to disturb this manganese oxygen manganese alignment by substituting with the strontium for lanthanum, you can actually bring about a collinear ferromagnetism where. you try to introduce a ferromagnetic exchange between neighboring manganese via oxygen 2 p.

And therefore, a radically antiferromagnetic insulator is transformed into a ferromagnetic metal, which is very very astonishing phenomena, in the case of oxides. So, when you look at metal oxides most of them are antiferromagnetic oxides, but you can easily translate them into ferromagnetic oxides. And there by effect the conductivity by mere chemistry and that is the specialty of materials chemistry in these oxides.

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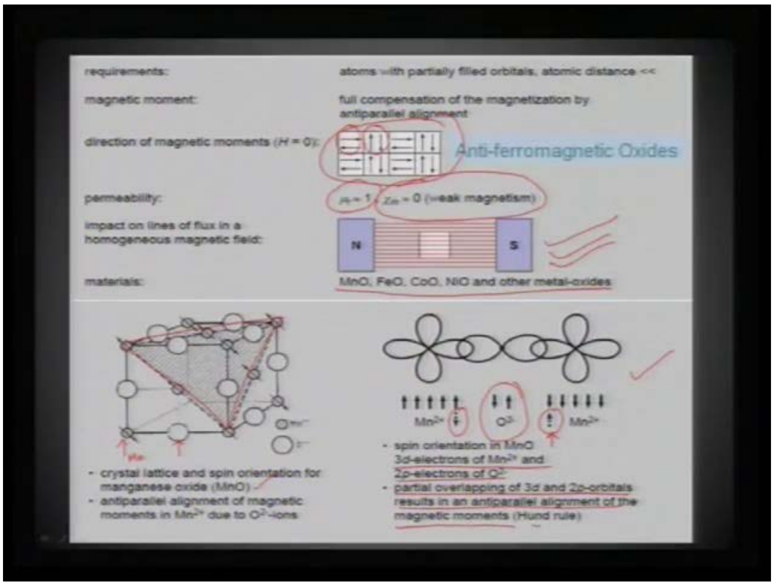

Anti-ferromagnetic Oxides

requirements:	atoms with partially filled orbitals, atomic distance <<
magnetic moment:	full compensation of the magnetization by antiparallel alignment
direction of magnetic moments ($H = 0$):	
permeability:	$\mu_r \approx 1$, $\chi_m \approx 0$ (weak magnetism)
impact on lines of flux in a homogeneous magnetic field:	
materials:	MnO, FeO, CoO, NiO and other metal-oxides

- crystal lattice and spin orientation for manganese oxide (MnO)
- antiparallel alignment of magnetic moments in Mn^{2+} due to O^{2-}-ions

- spin orientation in MnO 3d-electrons of Mn^{2+} and 2p-electrons of O^{2-}
- partial overlapping of 3d and 2p-orbitals results in an antiparallel alignment of the magnetic moments (Hund rule)

When you look at antiferromagnetic oxides typically, the domains are like this each one of this is domain in a antiferromagnetic oxide, which is antiferromagnetically coupled as result, your chi m. In that case is going to be nearly 0 whereas, your permeability is going to be approximately one and there is full compensation of the magnetization by the antiferromagnetic alignment.

And in such a situation in compounds like manganese oxide, iron oxide, cobalt oxide or nickel oxide, if you allow the external field to go through these oxides, you would see a situation like this where, there is no influence of the flux on the system. So, this is typical of a antiferromagnetic oxide, because the antiferromagnetic coupling is, so strong, that it cannot be removed by an external magnetic field. So, if you have a domain structure like this, the antiferromagnetic strength is of much higher order, that it cannot easily be removed by an external force and that is exactly what you see here.

But, if there is a antiferromagnetic interactions coming due to some impurity effect or defect effect, which is not intrinsic, but its extrinsic factor, then even with the little of external field strength, it is possible to remove those antiferromagnetic coupling. If possible, we will deal with this in the next lecture, one of the most important or well studied antiferromagnetic oxide is manganese oxide. And if you closely look at the manganese atom, these are the oxygen atoms and these are your manganese items.

Now, if you look at every alternate manganese atom you would see that, they are antiparallely align, in any direction, they are antiparallely aligned whereas, if you actually look at the 1 1 1 plane, then all the manganese are ferromagnetically aligned. But, in essence this is a antiferromagnetic coupling mainly, because the electron here, which is actually exchanging through the 2 p orbital of oxygen, to the neighboring oxygen, to the neighboring manganese site is antiferromagnetically coupled.

And this cannot be removed, because this is a supper exchange coupling, which is dynamic via the 2 p orbitals of oxygen and this cannot be removed at all. Therefore this is a very classic example of antiferromagnet, in this case the spin orientation is due to the 3 d electrons of manganese 2 plus and 2 p electrons of oxygen 2, which is antiferromagnetically aligned to the T 2 G orbitals of manganese 2 plus of the neighboring atom. Partial overlapping of 3 d and 2 p orbitals result in antiparallel alignment and this is actually dictated by the Hund’s coupling or Hund’s rule.

Now, in that situation, if it is a antiferromagnetic oxide, you would see a chi versus T plot to show something similar to this where, you have a almost a linear dependency in this high temperature scale. But at Neel temperature, the chi starts falling down. So, your susceptibility, drastically falls down at the Neel temperature, typically this should have actually increased in this fashion, but for a antiferromagnet, you would see this sort of a cross over and this is a very important signal for a antiferromagnetic oxide.

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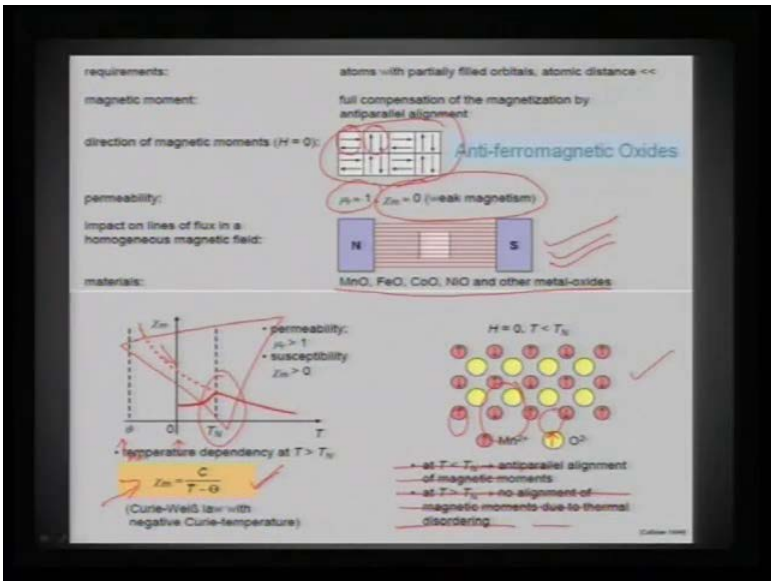

requirements: atoms with partially filled orbitals, atomic distance <<

magnetic moment: full compensation of the magnetization by antiparallel alignment

direction of magnetic moments ($H = 0$):

Anti-ferromagnetic Oxides

permeability: $\mu_r \approx 1$, $\chi_m \approx 0$ (weak magnetism)

impact on lines of flux in a homogeneous magnetic field:

materials: MnO, FeO, CoO, NiO and other metal-oxides

- permeability: $\mu_r > 1$
- susceptibility $\chi_m > 0$

- temperature dependency at $T > T_N$

$$\chi_m = \frac{C}{T - \Theta}$$

(Curie-Weiß law with negative Curie-temperature)

$H = 0$, $T < T_N$

- at $T < T_N$ → antiparallel alignment of magnetic moments
- at $T > T_N$ → no alignment of magnetic moments due to thermal disordering

And this is exactly what you see in this curve here, that all this manganese are aligned antiferromagnetically and they are mediated via this oxygen sites. And in such case the magnetic susceptibility is not governed by curie law rather, it is governed by curie-weiss law, which is dictated by this expression chi m. Therefore for antiferomagnetic oxides, your chi m will actually be related via curie-weiss law.

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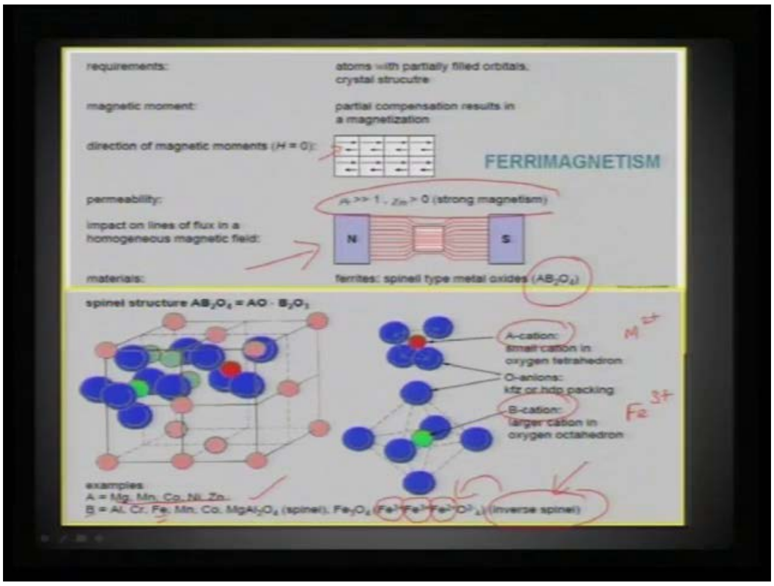

requirements: atoms with partially filled orbitals, crystal strucutre

magnetic moment: partial compensation results in a magnetization

direction of magnetic moments ($H = 0$):

FERRIMAGNETISM

permeability: $\mu_r >> 1$, $\chi_m > 0$ (strong magnetism)

impact on lines of flux in a homogeneous magnetic field:

materials: ferrites: spinell type metal oxides (AB_2O_4)

spinel structure $AB_2O_4 = AO \cdot B_2O_3$

A-cation: small cation in oxygen tetrahedron

O-anions: kfz or hdp packing

B-cation: larger cation in oxygen octahedron

examples

A = Mg, Mn, Co, Ni, Zn,

B = Al, Cr, Fe, Mn, Co, $MgAl_2O_4$ (spinel), Fe_3O_4 ($Fe^{3+}Fe^{3+}Fe^{2+}O^{2-}{}_4$) (inverse spinel)

Now when you come to ferrimagnetism, as we have already seen the partial compensation of the moments, actually results in a net magnetization, in this form and as a result each domain actually contributes to a net magnetization and this is possible only in metal oxides or any metals, which are partially filled. And it also depends on the crystal structure, which will see in some of the examples, what is that behavior of this ferrimagnetic 1, the permeability will be much stronger and your molar susceptibility will be greater than 0.

And if you look at the impact of the external flux line to these ferrimagnetic compounds, you would see that there is a strong correlation or there is a interaction with the external field strength. And as a result the domain will start getting influenced by the external magnetic fields, a classic example of a ferrimagnet is A B 2 O 4 type of metal oxides, which is called as Spinel metal oxides.

Spinel compounds usually ferrites show a very good response for ferrimagnetism and this is the unit cell for A B 2 O 4 type of oxide where, you have the a cations sitting in the tetrahedral sites and you have the b cation sitting in octahedral sites. In such case you can actually generate a variety of spinel compounds, this is a classic spinel, which is a naturally occurring mineral and we can actually try to make ferrites of this formula.

Where you can have a site occupied by divalent metal oxides metal ions and b side by trivalent metal ions, for ferrites b is always iron and you can generate magnesium ferrite, manganese ferrite, cobalt nickel or zinc ferrite. The well known spinel is inverse spinel that is iron oxide or magnetite where if you look at the occupation of the sites, you would see that, the these 2 ions are actually in b site and your F e 3 plus S is actually in a site.

So, because you have a mixed valency of both F e 2 plus and F e 3 plus in b site, this is actually called as a inverse spinel, otherwise in a normal spinel phase of ferrite, you will actually have always a F e 3 plus in b site and m 2 plus in a site. So, you would see, this discrepancy in most of the ferrites the occupation of the iron atoms sometimes will be between a and b site, so this categorizes a group of compounds like ferrites where, ferrimagnetism is very much operative.

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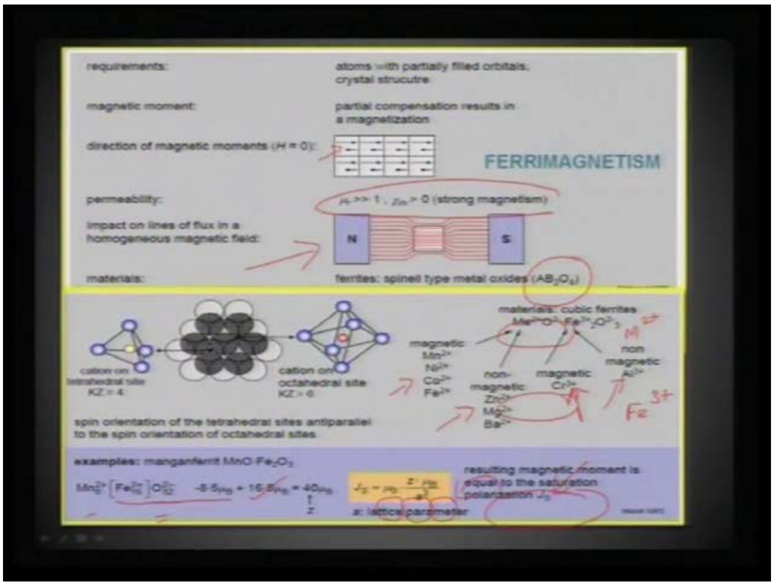

FERRIMAGNETISM

requirements: atoms with partially filled orbitals; crystal strucutre

magnetic moment: partial compensation results in a magnetization

direction of magnetic moments ($H = 0$):

permeability: $\mu_r >> 1$, $\chi_m > 0$ (strong magnetism)

impact on lines of flux in a homogeneous magnetic field:

materials: ferrites: spinell type metal oxides (AB_2O_4)

materials: cubic ferrites $Me^{2+}O^{2-}Fe^{3+}{}_2O^{2-}{}_3$

magnetic: Mn^{2+}, Ni^{2+}, Co^{2+}, Fe^{2+}

non-magnetic: Zn^{2+}, Mg^{2+}, Ba^{2+}

magnetic: Cr^{3+}

non magnetic: Al^{3+}

spin orientation of the tetrahedral sites antiparallel to the spin orientation of octahedral sites

examples: manganferrit $MnO \cdot Fe_2O_3$

$Mn^{2+}_8[Fe^{3+}_{16}]O^{2-}_{32}$ $-8 \cdot 5\mu_B + 16 \cdot 5\mu_B = 40\mu_B$ $\uparrow$ z

$J_S = \mu_0 \frac{z \cdot \mu_B}{a^3}$

a: lattice parameter

resulting magnetic moment is equal to the saturation polarization J_S

And in such cases, you can actually try to substitute with chromium, if it is chromium then we can still get a cubic ferrite, which is magnetic, suppose we substitute aluminum in the place of iron then it becomes a non magnetic ferrite. Similarly, a nonmagnetic ferrite, you will get if it is, if the a site is substituted with zinc magnesium or barium whereas, you get a magnetic ferrite, if it is manganese 2 plus nickel 2 plus cobalt 2 plus and F e 2 plus.

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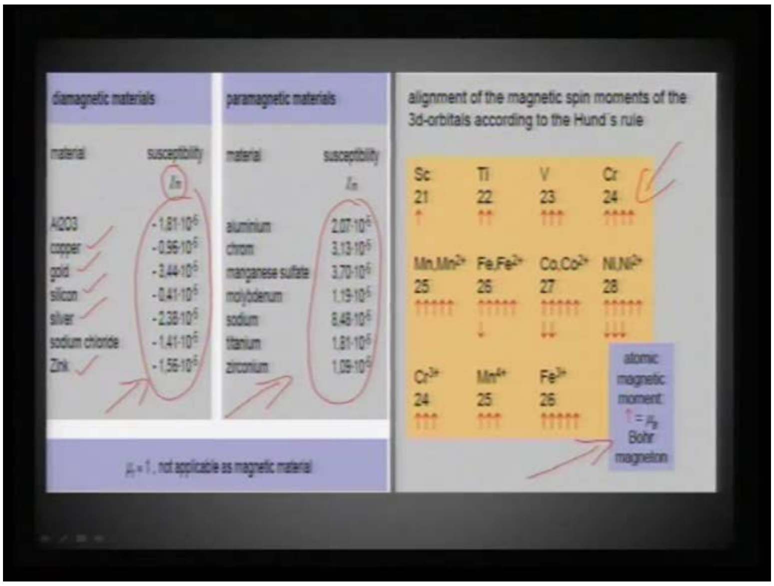

diamagnetic materials

material	susceptibility χ_m
Al2O3	$-1.81 \cdot 10^{-5}$
copper	$-0.96 \cdot 10^{-5}$
gold	$-3.44 \cdot 10^{-5}$
silicon	$-0.41 \cdot 10^{-5}$
silver	$-2.38 \cdot 10^{-5}$
sodium chloride	$-1.41 \cdot 10^{-5}$
Zink	$-1.56 \cdot 10^{-5}$

paramagnetic materials

material	susceptibility χ_m
aluminium	$2.07 \cdot 10^{-5}$
chrom	$3.13 \cdot 10^{-5}$
manganese sulfate	$3.70 \cdot 10^{-5}$
molybdenum	$1.19 \cdot 10^{-5}$
sodium	$8.48 \cdot 10^{-5}$
titanium	$1.81 \cdot 10^{-5}$
zirconium	$1.09 \cdot 10^{-5}$

$\mu_r \approx 1$, not applicable as magnetic material

alignment of the magnetic spin moments of the 3d-orbitals according to the Hund´s rule

atomic magnetic moment: ↑ = μ_B Bohr magneton

Some of the diamagnetic materials and paramagnetic materials are listed here and this also tells, why we use those materials for applications, for example copper gold silicon silver and zinc. These are very candid diamagnetic materials and when we look at the A C susceptibility or susceptibility chi value, you will always understand, that the susceptibility will be of the order of ten power minus 5 whereas, in the case of ferromagnetic materials, this will be of the order of minus 1 or it would be positive.

So, the chi value should exactly tell you, what sort of a material, you are talking about and most of these diamagnetic materials are in this range and also paramagnetic materials like, chrome chromium, zirconium, titanium, aluminum all these have a very low susceptibility value. And those, which are ferromagnetic the magnetic, spin moments are actually governed by the hund's rule and therefore, it is possible for us to calculate, how much of magnetic moment each of these transition metal ions can contribute and this is measured in terms of bohr magneton.

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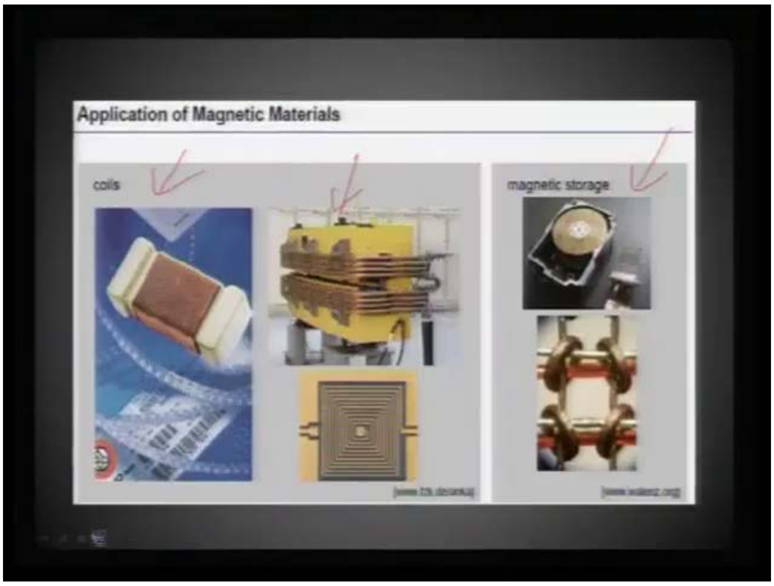

Application of Magnetic Materials

When we come to the range of compounds, we usually have an idea that magnetic materials are meant only for some sort of a magnetic force applications, like stickers or magnets for isolating some magnetic materials. And in today's application most of the time, we encountered only permanent magnets, used in household applications, but what we forget or what might slip out of attention is that the magnetic materials form a very solid application core.

And they are used in coils in transformers in transducers and not only that in power electronics, but also it finds a very important application in magnetic storage application. So, a range of applications are there, for magnetic materials, I will basically make a division between 2 types of materials before, I show some of the applications. One soft magnetic materials and the other one permanent magnetic materials or hard magnetic materials. Soft those, which show magnetic materials on application of a external magnetic field, permanent or hard magnetic materials are those inherently have a magnetic moment, you can kill the magnetic response only by applying a magnetic field.

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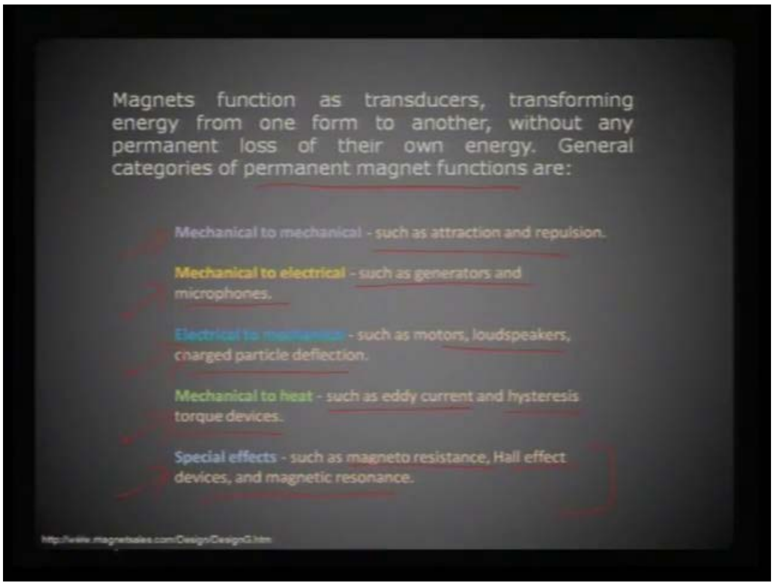

Magnets function as transducers, transforming energy from one form to another, without any permanent loss of their own energy. General categories of permanent magnet functions are:

- Mechanical to mechanical - such as attraction and repulsion.
- Mechanical to electrical - such as generators and microphones.
- Electrical to mechanical - such as motors, loudspeakers, charged particle deflection.
- Mechanical to heat - such as eddy current and hysteresis torque devices.
- Special effects - such as magneto resistance, Hall effect devices, and magnetic resonance.

http://www.magnetsales.com/Design/DesignG.htm

So, with this minimum distinction, let me just take you through some of the functional applications, that the magnetic materials hold, magnets function as transducers transforming energy from one form to the other, without any permanent loss, of their own energy. And for example, permanent magnets are used in a variety of applications, like they convert mechanical to mechanical energy, in other words just used for either repulsion or for attraction.

So, this is one application, but you can also use the mechanical to electrical conversion of energy, a as you see in generators and microphones, electrical to mechanical, in motors, loudspeakers and in charged particle deflection. We can also translate this mechanical energy into heat for example, in torque devices and in applications involving eddy currents. And more so in the recent past, special applications have emerged out of these materials, such as magneto resistance hall effect and magnetic resonance. I will not deal with these applications precisely, because I will be talking about this, when we discuss about electrical properties of materials, so I will try to show some example, on the other aspects.

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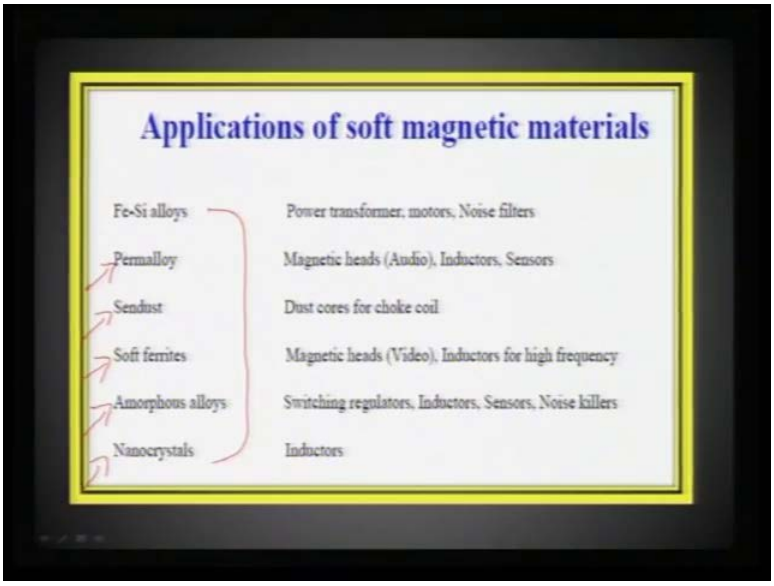

Applications of soft magnetic materials

Fe-Si alloys	Power transformer, motors, Noise filters
Permalloy	Magnetic heads (Audio), Inductors, Sensors
Sendust	Dust cores for choke coil
Soft ferrites	Magnetic heads (Video), Inductors for high frequency
Amorphous alloys	Switching regulators, Inductors, Sensors, Noise killers
Nanocrystals	Inductors

This is a one of the cartoon that gives some idea about, what sort of materials we characterize as soft magnetic materials, these are actually, a range of compounds, which stands out compared to all the other known soft magnetic material. So, I thought this would be, a good way to project some of the representative soft magnetic materials, what has emerged recent, past is nano crystals, which show soft magnetic response amorphous alloys are traditionally, soft magnetic.

And ferrites are mostly soft magnetic materials, but we also have bubbled memory materials, which are hard ferrites, there is another group of compound called sendust, then permalloy, which is used almost in every other applications. And then some of the alloys also show soft magnetic material compared to other alloys, which are usually hard in it is response.

When we talk about soft magnetic materials, we need to understand they have high permeability and very low coercivity, if coercive force is very less and permeability is very high, then you can categorize that to be a soft magnetic material, which is given by mu, mu is a equal to B by H. So, B is your magnetic induction and for obtaining soft magnetic materials, there are some clues one material with low magnetic anisotropy low magnetostriction and high saturation magnetization has to be there.

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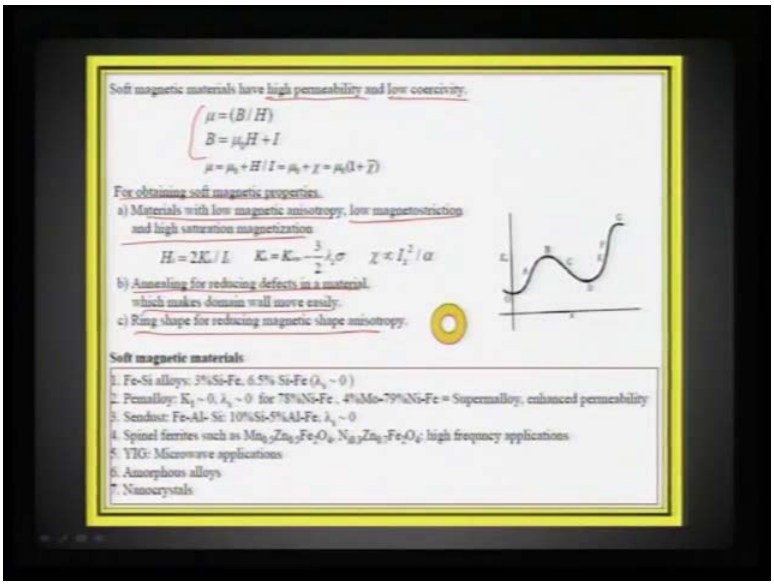

Soft magnetic materials have high permeability and low coercivity.

$\mu = (B/H)$

$B = \mu_0 H + I$

$\mu = \mu_0 + H/I = \mu_0 + \chi = \mu_0(1+\bar{\chi})$

For obtaining soft magnetic properties.

a) Materials with low magnetic anisotropy, low magnetostriction and high saturation magnetization

$H_c = 2K_u/I_s \quad K_u = K_{u0} - \frac{3}{2}\lambda_s\sigma \quad \chi \propto I_s^2/a$

b) Annealing for reducing defects in a material, which makes domain wall move easily.

c) Ring shape for reducing magnetic shape anisotropy.

Soft magnetic materials

1. Fe-Si alloys: 3%Si-Fe, 6.5% Si-Fe ($\lambda_s \sim 0$)
2. Permalloy: $K_1 \sim 0$, $\lambda_s \sim 0$ for 78%Ni-Fe , 4%Mo-79%Ni-Fe = Supermalloy, enhanced permeability
3. Sendust: Fe-Al- Si: 10%Si-5%Al-Fe, $\lambda_s \sim 0$
4. Spinel ferrites such as $Mn_{0.5}Zn_{0.5}Fe_2O_4$, $Ni_{0.3}Zn_{0.7}Fe_2O_4$: high frequncy applications
5. YIG: Microwave applications
6. Amorphous alloys
7. Nanocrystals

In the previous lecture, I told you that when ferromagnetic or magnetic moments, they oscillate sometimes, they can dilate and bring about magnetostriction response and those materials cannot be a good, soft magnetic material therefore, it has to have a low magnetostriction. And how do we get this magnetic soft magnetic materials, we can engineer it by carefully annealing with the furnace or other annealing protocols where, we try to minimize on the defect, which can help the domain wall to move easily, so that, we can get this response.

Another way to get a soft magnetic responses to make a ring shape, so that you can minimize on the shape anisotropy, because shape anisotropy can influence your magneto crystalline anisotropy, as a result, it if you make a ring shaped one you can candidly minimize on the magnetic shape anisotropy. So, let me just take you through, some viewgraphs of each of this compound, just to show.

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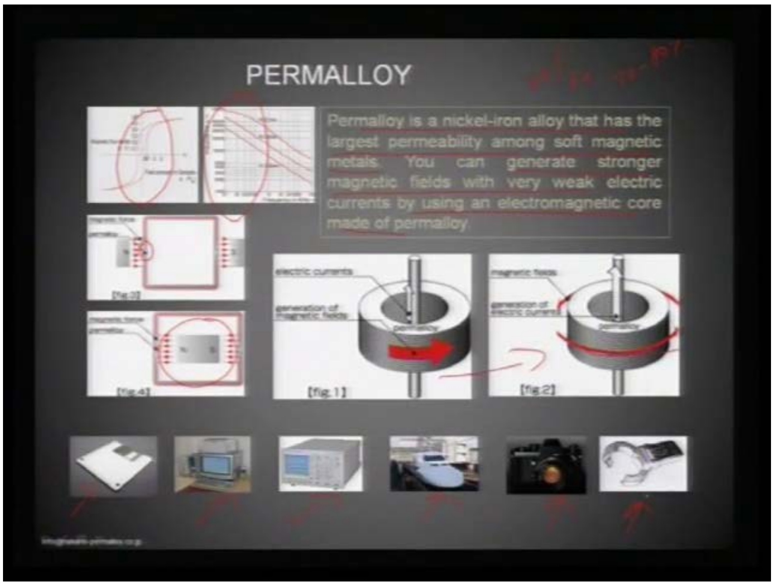

PERMALLOY

Permalloy is a nickel-iron alloy that has the largest permeability among soft magnetic metals. You can generate stronger magnetic fields with very weak electric currents by using an electromagnetic core made of permalloy.

What why, it is useful and how it is useful permalloy as you would see, to since we handle the floppy disc, it is important for us to understand, that permalloy is a material that, we use almost in everyday’s practical application. As you see here, this is a 3 and half inch floppy, which we no more use, we only use pen drives now, with much better storage density, but permalloys are actually used in magnetic applications mostly as shield.

And permalloy is nothing but, a nickel iron alloy where, 20 percent of iron and 70 to 80 percent nickel is used, permalloy is not the other way, usually we think that iron has to be more. But, it is the other way about 20 percent iron and up to 80 percent of nickel is there and what is important about, this it has largest permeability as you can see here. And it is soft magnetic metal, as you can see from this loop, it is a soft magnet and largest permeability. And what is the advantage, you can generate strong magnetic fields with very weak electric currents by using a electromagnetic core made of permalloy.

So, you can see here, this is your permalloy ring and using this with very small electric current, it is possible to generate or amplify the magnetic field and not only that, we can try to block the magnetic flux from entering. As a shield it can be used therefore, it can block the magnetic field, that is coming from outside or it can be used as a gate, where you can confined the magnetic flux to be confined to a particular place and that is why it is used in floppy’s in disc.

So, permalloy is actually a very very important alloy, soft magnetic alloy, used in magnetic storage, but conscious I am going to avoid this, because I will be discussing this example later, in module 5, where I, where permalloy is not only used as a magnetic shield, but is also being used for magnetic read write applications. And these are some of the cartoons, that you see here, permalloy is actually used as a magnetic shield in wide range of applications, including as a sensor in fast trains.

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Pemalloy processing

Permalloy processing is also very unique, because its alloy, it is malleable, therefore you can make it as a roll or as a sheet, in any form you can see this sort of big rolls of permalloys can be made for functional applications and as you can see here. These are all the permalloy applications, that you see in making disc and these are the magnetic recording heads, that you would see in tape recorders. Today, we do not see tape recorders or cassette players, but these are there head, that will actually read and help you play, the songs or lyrics that you want to hear. And permalloy is essentially, the head that reads the magnetic information.

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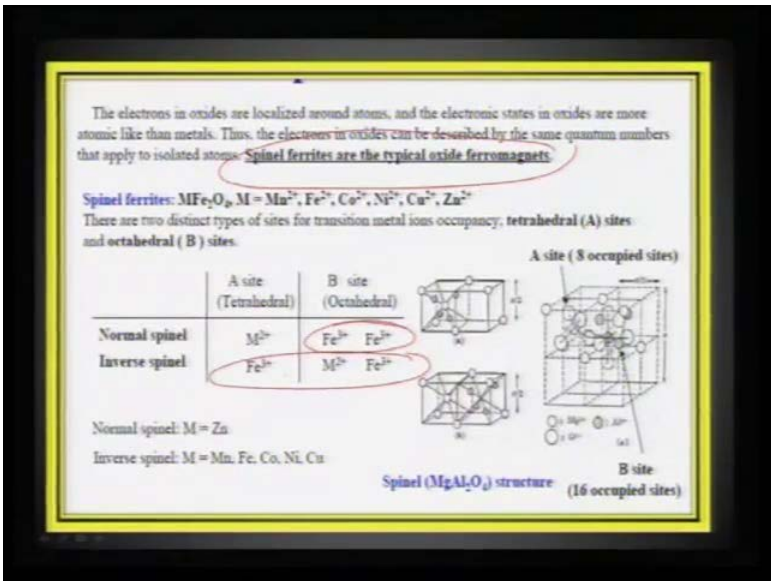

The electrons in oxides are localized around atoms, and the electronic states in oxides are more atomic like than metals. Thus, the electrons in oxides can be described by the same quantum numbers that apply to isolated atoms. **Spinel ferrites are the typical oxide ferromagnets**.

Spinel ferrites: MFe_2O_4, $M = Mn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}$

There are two distinct types of sites for transition metal ions occupancy; **tetrahedral (A) sites** and **octahedral (B) sites**.

	A site (Tetrahedral)	B site (Octahedral)
Normal spinel	M^{2+}	Fe^{3+} Fe^{3+}
Inverse spinel	Fe^{3+}	M^{2+} Fe^{3+}

Normal spinel: M = Zn

Inverse spinel: M = Mn, Fe, Co, Ni, Cu

Spinel ($MgAl_2O_4$) structure

This is one application of permalloy and then ferrites are also used systematically, in variety of applications, as I have already touched upon spinel ferrites are known ferromagnets, some are ferrimagnets. And mainly, because of their occupancy in the B site and the way they exchange between A and B site will tell, whether it is going to be a normal spinel or inverse spinel.

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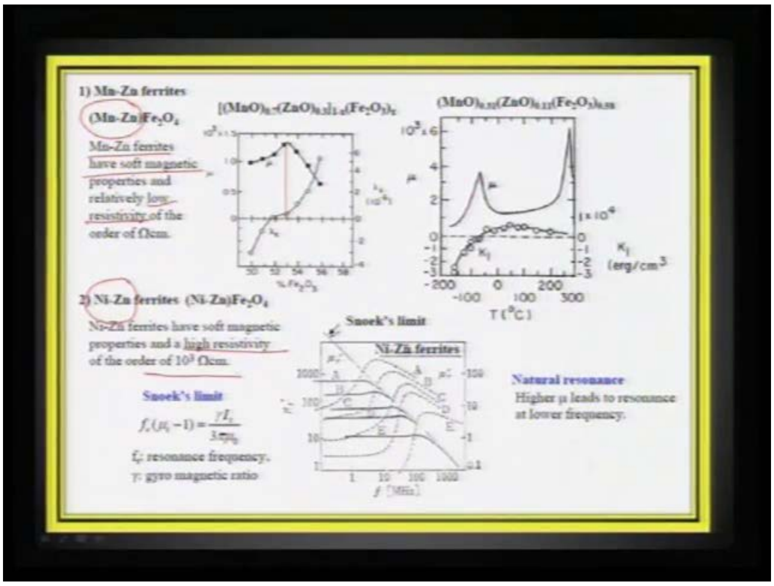

1) Mn-Zn ferrites

(Mn-Zn)Fe_2O_4

Mn-Zn ferrites have soft magnetic properties and relatively low resistivity of the order of Ωcm.

2) Ni-Zn ferrites (Ni-Zn)Fe_2O_4

Ni-Zn ferrites have soft magnetic properties and a high resistivity of the order of 10^3 Ωcm.

Snoek's limit

$$f_r(\mu_i - 1) = \frac{\gamma I_s}{3\pi\mu_0}$$

f_r: resonance frequency,

γ: gyro magnetic ratio

Natural resonance

Higher μ leads to resonance at lower frequency.

You can make any sort of ferrite, if you know how to play around with your A site combination, for example, you take manganese zinc ferrite and nickel zinc ferrite, you can candidly see, how you can affect the other properties, for example. Manganese ferrite have soft magnetic property, but they have very low resistivity of the order of ohm centimeter, whereas, if you gambled with nickel zinc ferrite, then you get resistivity of the order of ten power 3. And these 2 ferrites are incidentally used very much in storage density applications, manganese zinc ferrite and nickel zinc ferrite, both are by choice used for different applications, because one gives you a almost metallic behavior and the other one behaves more like a insulator.

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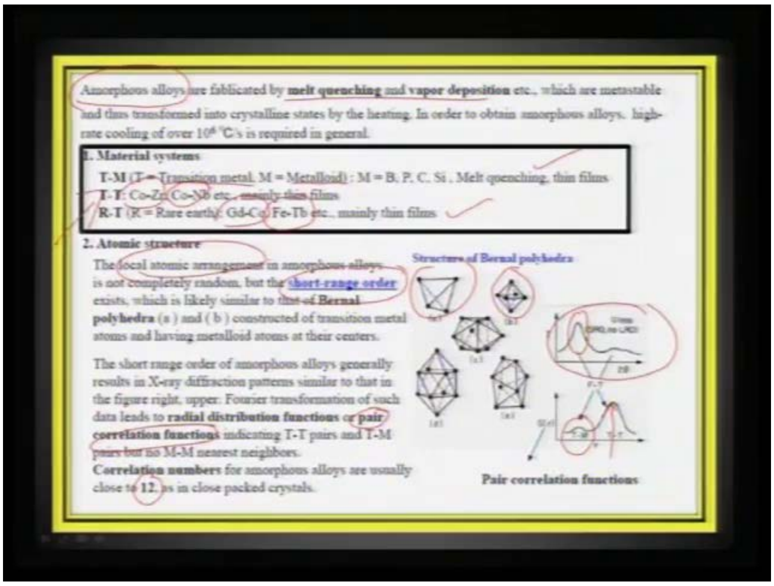

Amorphous alloys are fablicated by **melt quenching** and **vapor deposition** etc., which are metastable and thus transformed into crystalline states by the heating. In order to obtain amorphous alloys, high-rate cooling of over 10^6 °C/s is required in general.

1. Material systems

T-M (T = Transition metal, M = Metalloid) : M = B, P, C, Si , Melt quenching, thin films
T-T: Co-Zr, Co-Nb etc., mainly thin films
R-T (R = Rare earth): Gd-Co, Fe-Tb etc., mainly thin films

2. Atomic structure

The local atomic arrangement in amorphous alloys is not completely random, but the short-range order exists, which is likely similar to that of **Bernal polyhedra** (a) and (b) constructed of transition metal atoms and having metalloid atoms at their centers.

The short range order of amorphous alloys generally results in X-ray diffraction patterns similar to that in the figure right, upper. Fourier transformation of such data leads to **radial distribution functions** or **pair correlation functions** indicating T-T pairs and T-M pairs but no M-M nearest neighbors.
Correlation numbers for amorphous alloys are usually close to **12**, as in close packed crystals.

Structures of Bernal polyhedra

Pair correlation functions

And amorphous alloys are other group of compounds, which show soft magnetic response and usually amorphous alloys are fabricated by melt quenching or by vapor deposition. Because, you can deposit using a physical vapor deposition method at room temperature then whatever is crystalline will actually grow as amorphous compound. And then it is possible to characterize, the magnetic behavior of a amorphous alloy and since our course is designed more to materials chemistry, in the first module, I have increasingly stressed on the use of chemical approaches to make amorphous alloys.

I have discussed with you, based on sono chemistry, how we can make such amorphous alloys in nano scale and how the properties changes in one such example, I have mentioned. That what is usually conceived to be a magnetic compound can become a nonmagnetic compound, what is considered to be a nonmagnetic can transform into a magnetic compound. When you reduce the size to nano scale and that is possible using, simple chemical routes for preparing amorphous alloys.

This is the materials, which can be engineered as amorphous alloys are for example, a transition metal with a metalloid. So, you can actually make borides phosphites carbides a silicides and we can also make alloys of cobalt zirconium or niobium cobalt or we can make a rare earth manganites like gadolinium cobalt or iron terbium compounds as alloys. These are usually used, in thin film forms and when we try to do a casting or melt quenching, usually these are rendered in thin film form.

What is important about, this amorphous alloys is that, they have a very local atomic arrangement and this is what we call it as, short range order, because they are not totally disintegrated. They do have short range order, but they do not have a long range order usually, this sort of amorphous material will have x-ray pattern like this, where you have a hump at low angles, where as at higher angles, you do not see any reflection.

So, this low angle hump is a very clear indication, that it is not completely glassy, but it has short range orders, so if you actually look at the pair correlation functions, for such amorphous alloys. You would find out that, there is a reflection or a response for the transition metalloids or for alloys, which have, which gives an indication that, the pair correlation functions indicate small polyhedrons like this, of the order of say 4 to 12. They constitute a short range order as a result, you can get a very different magnetic phenomena compared to crystalline materials.

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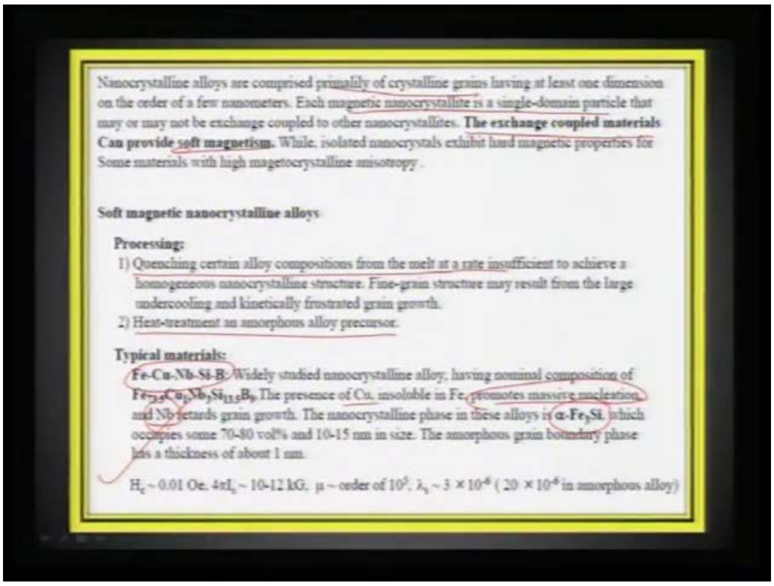

Nanocrystalline alloys are comprised primalily of crystalline grains having at least one dimension on the order of a few nanometers. Each magnetic nanocrystallite is a single-domain particle that may or may not be exchange coupled to other nanocrystallites. **The exchange coupled materials Can provide soft magnetism.** While, isolated nanocrystals exhibit hard magnetic properties for Some materials with high magetocrystalline anisotropy .

Soft magnetic nanocrystalline alloys

Processing:

1) Quenching certain alloy compositions from the melt at a rate insufficient to achieve a homogeneous nanocrystalline structure. Fine-grain structure may result from the large undercooling and kinetically frustrated grain growth.
2) Heat-treatment an amorphous alloy precursor.

Typical materials:

Fe-Cu-Nb-Si-B: Widely studied nanocrystalline alloy, having nominal composition of **$Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$**. The presence of Cu, insoluble in Fe, promotes massive nucleation, and Nb retards grain growth. The nanocrystalline phase in these alloys is **α-Fe_3Si**, which occupies some 70-80 vol% and 10-15 nm in size. The amorphous grain boundary phase has a thickness of about 1 nm.

$H_c \sim 0.01$ Oe, $4\pi I_s \sim 10\text{-}12$ kG, $\mu \sim$ order of 10^5, $\lambda_s \sim 3 \times 10^{-6}$ (20×10^{-6} in amorphous alloy)

Nano crystalline alloys, they are comprise primarily of crystalline grains, having at least 1 dimension, one interesting thing about this nanocrystalline alloys is that, they are usually considered to be a single domain size. In other words they are lesser than a single domain magnitude and most of this single domain particles are exchange couple materials, which can provide soft magnetism and the way we processes soft magnetic materials, specially the nano crystalline alloys is by sudden quenching.

So, quenching or by a preferred heat treatment of a amorphous alloy precursor, it is possible to get nano crystalline alloys for example, let us take the case of one composition. Before we look at the other examples, iron copper niobium silicon boride, actually has nano crystalline alloy of the composition alpha F e 3 S i where, additives like copper is added mainly to initiate nucleation, because iron and copper are immiscible.

Therefore, it will not form a alloy, therefore you will get a massive nucleation, which is promoted, when you put some copper into it and you can put some niobium in order to restrict the grain growth. So, to get a amorphous phase, you put this as a additive, but actually your compound is iron silicon. So, when you have such a composition, it is possible to realize nano crystalline alloys, one of the reasons why we look for a nano crystals, when we look for soft magnetic properties is that.

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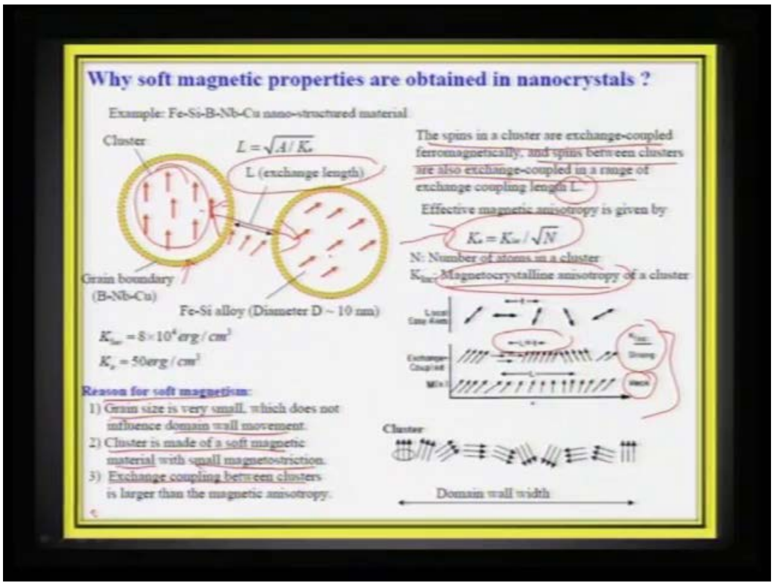

Why soft magnetic properties are obtained in nanocrystals ?

Example: Fe-Si-B-Nb-Cu nano-structured material

$L = \sqrt{A/K_e}$

The spins in a cluster are exchange-coupled ferromagnetically, and spins between clusters are also exchange-coupled in a range of exchange coupling length L.

Effective magnetic anisotropy is given by

$K_e = K_{loc}/\sqrt{N}$

N: Number of atoms in a cluster

K_{loc}: Magnetocrystalline anisotropy of a cluster

$K_{loc} = 8\times10^4 erg/cm^3$

$K_e = 50erg/cm^3$

Reason for soft magnetism:

1) Grain size is very small, which does not influence domain wall movement.
2) Cluster is made of a soft magnetic material with small magnetostriction.
3) Exchange coupling between clusters is larger than the magnetic anisotropy.

The spins in a cluster are exchange coupled ferro magnetically and the spins between the clusters are also exchange coupled in the range of coupling length called L and that is what we see here, in this cartoon. So, these 2 are clusters, but the clusters have a correlation within itself and between the crystals and both of these nano crystals will have some amount of a grain boundary influence.

And if this exchange can overcome the grain boundary influence and the exchange length, then they can be strongly coupled to the extent that, they show a net magnetization. And this is viewgraph, which tells how the exchange correlation or exchange length can influence the net magnetization, the effective magnetic anisotropy, which is actually contributed mostly by the magneto crystalline anisotropy is given by this expression where, your magneto crystalline anisotropy is actually governed by the correlation length.

If it is short then the crystalline anisotropy is going to be stronger whereas, if the correlation length is going to be larger, than your magneto crystalline anisotropy is going to be weak. And therefore, the reason for soft magnetism is coming from the grain size, which is very small, which does not influence the domain wall movement and the cluster is made of a soft magnetic material, with very small magneto striction or almost 0 magneto striction. And the reason for soft magnetism also is due to the exchange coupling between, clusters, which is larger than the magneto magnetic anisotropy, because you are minimizing on the magneto crystalline anisotropy, if your correlation length is going to be lesser.

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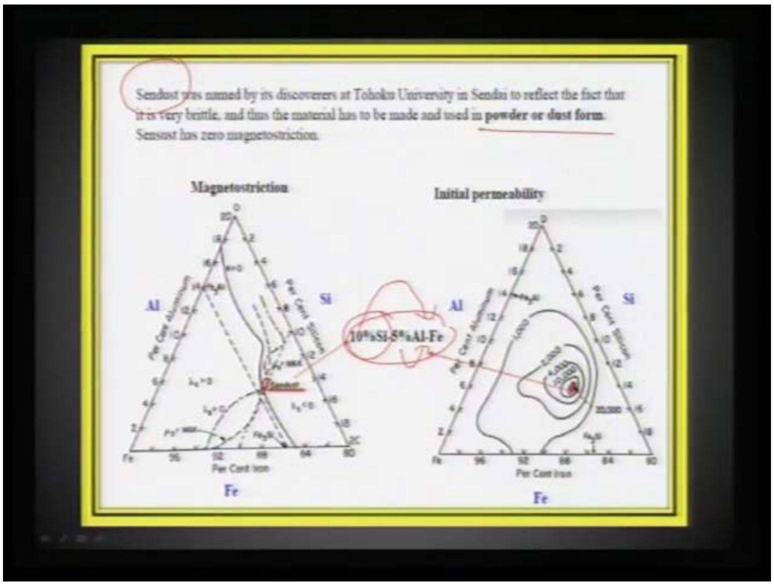

Sendust was named by its discoverers at Tohoku University in Sendai to reflect the fact that it is very brittle, and thus the material has to be made and used in **powder or dust form**. Sensust has zero magnetostriction.

This is another compound, which is used widely, it is called sendust, this is basically discovered by those researchers in sendai and this is actually a material, which is peculiar, because it is very very brittle therefore, it cannot be used in any other form, other than as a dust or as a powder. So, it is called as sendust, the reason sendust is interesting is that, you have a very very less magneto striction by the way, the composition for the sendust, varies in terms of its aluminium content and it can vary from 5 to 15 or so.

But, usually silicon 10 percent will affect the magnetic property of your B C C iron. So, doping iron and aluminum, can give you a special composition and you can see herem the magneto strictionm for a sendust is somewhere here. And it has a very high permeability for this particular composition, which is almost amounted to 20000 therefore, this is one compound.

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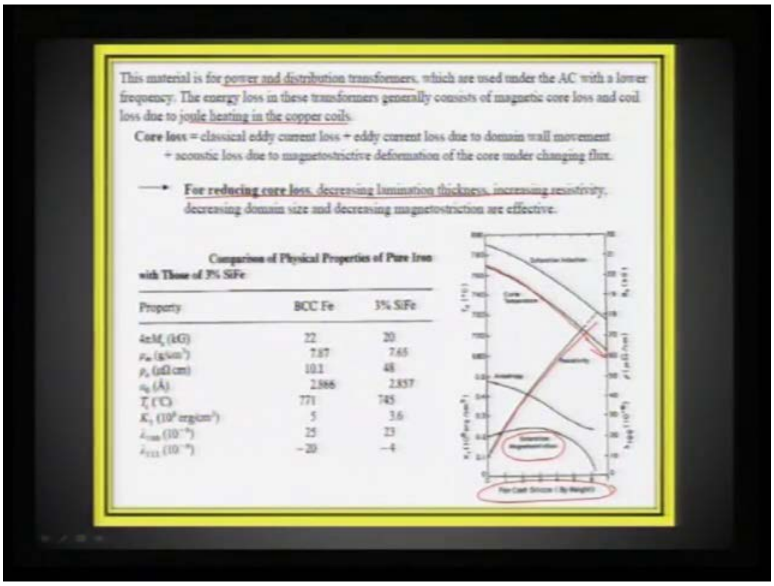

This material is for power and distribution transformers, which are used under the AC with a lower frequency. The energy loss in these transformers generally consists of magnetic core loss and coil loss due to joule heating in the copper coils.

Core loss = classical eddy current loss + eddy current loss due to domain wall movement + acoustic loss due to magnetostrictive deformation of the core under changing flux.

→ **For reducing core loss**, decreasing lamination thickness, increasing resistivity, decreasing domain size and decreasing magnetostriction are effective.

Comparison of Physical Properties of Pure Iron with Those of 3% SiFe

Property	BCC Fe	3% SiFe
$4\pi M_s$ (kG)	22	20
ρ_m (g/cm^3)	7.87	7.65
ρ_e (μΩ cm)	10.1	48
a_0 (Å)	2.866	2.857
T_c (°C)	771	745
K_1 (10^5 erg/cm^3)	5	3.6
λ_{100} (10^{-6})	25	23
λ_{111} (10^{-6})	−20	−4

Which is actually used for reducing core loss and what you do here is that, we this can be actually coated as a lamination in transformers, therefore, it can bring down the joule heating in copper coils. This material is for power and distribution transformers and the heating affect can be minimized, when you try to spray or laminated with this sendust.

And this particular cartoon gives you an idea, how little amount of silicon can rapidly alter some of the properties, for example saturation magneto striction or resistivity, you can see how the resistivity varies, just with very little amount of silicon, then the curie temperature also varies down, with the doping of silicon up to 5 to 10 percent.

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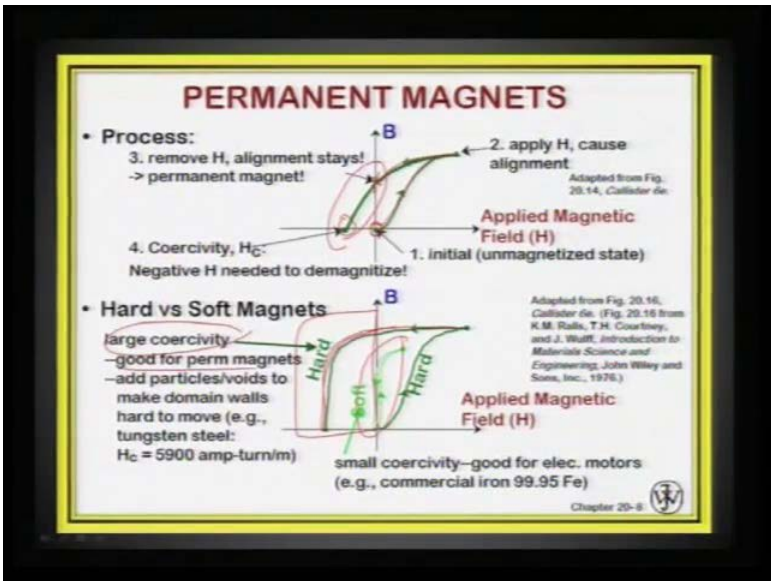

PERMANENT MAGNETS

- Process:
  - 1. initial (unmagnetized state)
  - 2. apply H, cause alignment
  - 3. remove H, alignment stays! -> permanent magnet!
  - 4. Coercivity, H_C: Negative H needed to demagnitize!

Applied Magnetic Field (H)

Adapted from Fig. 20.14, *Callister 6e.*

- Hard vs Soft Magnets
  - large coercivity
  - --good for perm magnets
  - --add particles/voids to make domain walls hard to move (e.g., tungsten steel: H_c = 5900 amp-turn/m)

Applied Magnetic Field (H)

small coercivity--good for elec. motors (e.g., commercial iron 99.95 Fe)

Adapted from Fig. 20.16, *Callister 6e.* (Fig. 20.16 from K.M. Ralls, T.H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*, John Wiley and Sons, Inc., 1976.)

Chapter 20-8

Now, we will take a quick look at some of the materials, which stands out as permanent magnets, just want to highlight that, the main divide between a hard magnet and a soft magnet comes, basically by looking at the hysteresis loop. As you know the hysteresis loop, tells us about a unmagnetised state or virgin state of a magnetic material on application of a magnetic field, it get saturated. And then when you remove or reverse the field it loses, it is saturation and this is the remanence that you get out of it. And then, you can completely remove the magnetization or demagnetize, when you reverse it.

Therefore you are response, in the second quadrant becomes very very important, for your permanent magnetic material and as you would see here, a permanent magnetic material, when you try to reverse the field. In the second quadrant here, whatever is happening here will tell, you the nature of your magnetic material or the strength of your magnetic material. So, compare to a soft ferrite, which is here a hard ferrite or a hard magnet will actually have a very high hysteresis and large coercivity and therefore, this can be used as a permanent magnet.

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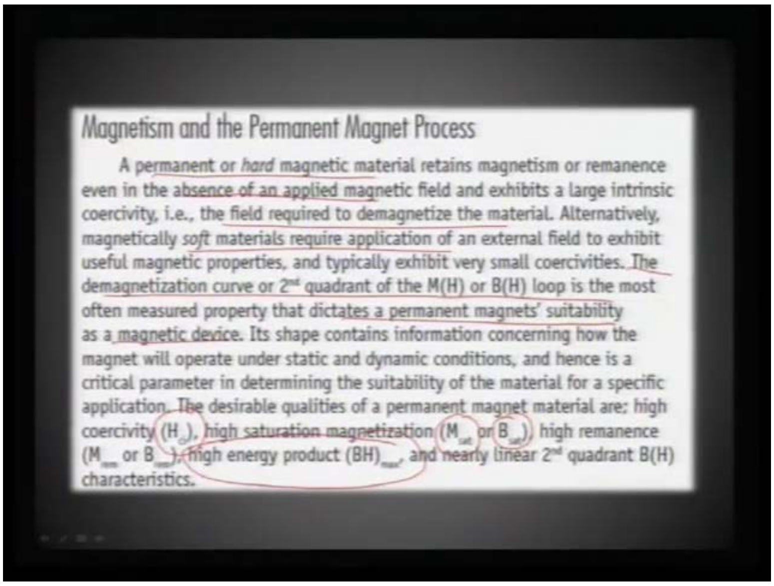

Magnetism and the Permanent Magnet Process

A permanent or *hard* magnetic material retains magnetism or remanence even in the absence of an applied magnetic field and exhibits a large intrinsic coercivity, i.e., the field required to demagnetize the material. Alternatively, magnetically *soft* materials require application of an external field to exhibit useful magnetic properties, and typically exhibit very small coercivities. The demagnetization curve or 2nd quadrant of the M(H) or B(H) loop is the most often measured property that dictates a permanent magnets' suitability as a magnetic device. Its shape contains information concerning how the magnet will operate under static and dynamic conditions, and hence is a critical parameter in determining the suitability of the material for a specific application. The desirable qualities of a permanent magnet material are: high coercivity (H_{ci}), high saturation magnetization (M_{sat} or B_{sat}), high remanence (M_{rem} or B_{rem}), high energy product $(BH)_{max}$, and nearly linear 2nd quadrant B(H) characteristics.

So, how does this affect or what is the parameter, that we use to ascertain for a permanent magnet, we can just look at it briefly, a permanent or a hard magnetic material is 1, which is having a remanence, even at 0 magnetic field or in the absence of magnetic field. And you need a very large field to demagnetize the material, soft magnetic material on the other hand requires application.

So, then demagnetization curve or the second quadrant of the magnetization or magnetic induction is the most preferred property that, dictates a permanent magnet suitability as a magnetic device. So, when you try to magnetize a compound and try to reverse the magnetization, the second quadrant behavior is very important, to measure the strength of a permanent magnet.

The notable parameters that, we use for judging is coercivity or you talk about magnetic saturation magnetization saturation or magnetic induction saturation B saturation and popularly, this B H max is what is used to ascertain the strength of a permanent magnet which is called energy product. If the energy product is very high, which is A factor of B cross H, then more the energy factor, more stronger the field strength as a result, it can be used as a magnetic material.

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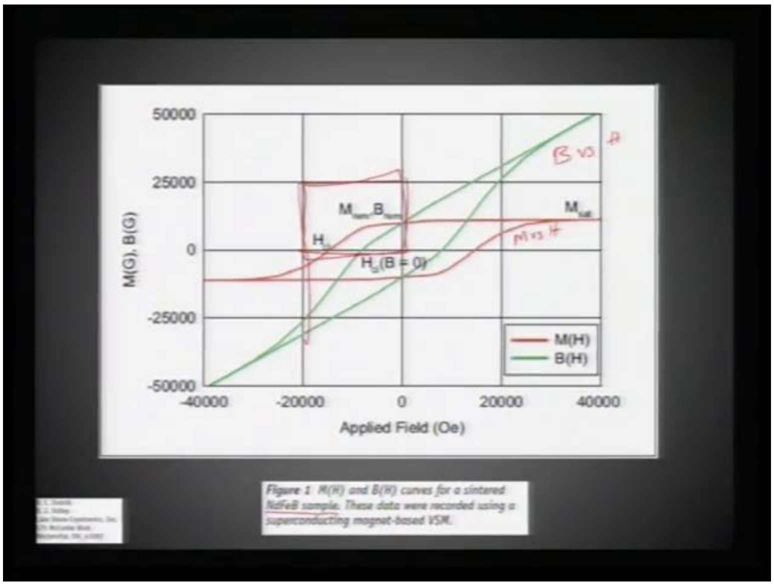

Figure 1 M(H) and B(H) curves for a sintered NdFeB sample. These data were recorded using a superconducting magnet-based VSM.

This is the plot for a neodymium iron boride, which is a permanent magnet and as you can see here, the width of the coercive field is very very high and this is typical of a hard magnet. And the behavior of your, B versus H and M versus H, usually is different and how they respond in this second quadrant is what is important for the permanent magnet.

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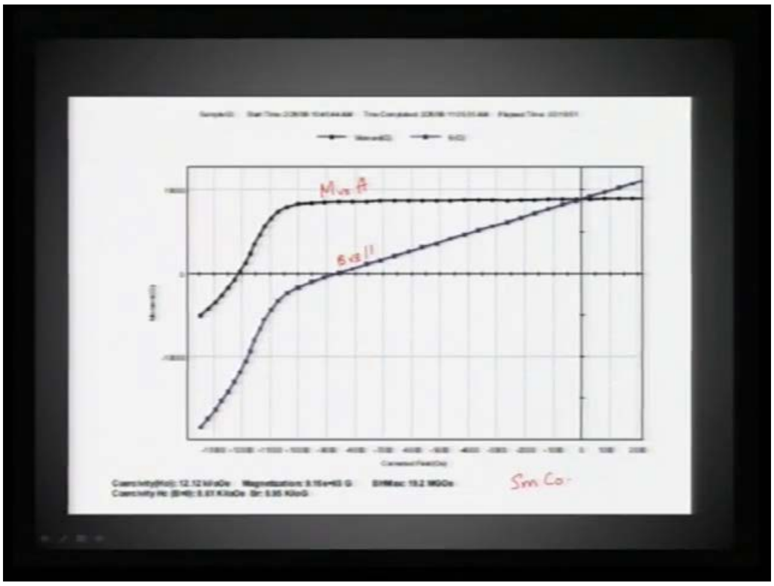

And this is how, we see a response for samarium cobalt compound, this is your M versus H and this is your B versus H plot for a samarium cobalt.

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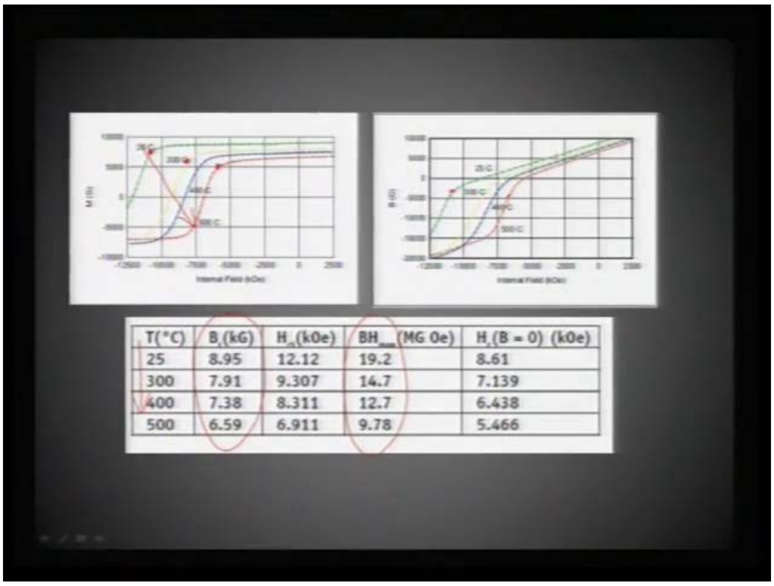

T(°C)	B_r(kG)	H_{ci}(kOe)	BH_{max}(MG Oe)	H_c(B = 0) (kOe)
25	8.95	12.12	19.2	8.61
300	7.91	9.307	14.7	7.139
400	7.38	8.311	12.7	6.438
500	6.59	6.911	9.78	5.466

And you can see that, the second quadrant is very clearly altered, when you try to increase the temperature and for example, the B r, B r is nothing but, your remanence induction, in this case or M R, that is your remanence magnetization, both changes distinctly. As you increase the temperature and you can see for B remanence, it drops down by at least 2000 Oersted and B H max is your energy products strength and significantly, it changes with temperature, that means, it loses it is magnetization with increase in temperature.

Therefore, you can decide, which sort of permanent magnet you can use for, what application. So, at high temperatures, if they are going to drastically drop the energy product, then you it put limits on its application. So, you can use this permanent magnets in, a variety of environment.

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And this is another viewgraph just to tell you, where all these permanent magnets are used, this is the neodymium iron boride and this is aluminum, cobalt, nickel called alnico, this is another permanent magnet. And these are ceramic magnets, usually made of ferrites and this is your samarium cobalt magnet and this one is new generation magnets, which is nothing, but a composite which are called flexible magnets.

Usually flexible magnets contain a polymer support where, these permanent magnets can be intersperse and rendered into tapes or any other flexible shapes. So, by and large when we think of permanent magnets, you have borides or alnico, which is a alloy or a rare earth alloy or ceramics, usually these are oxides and classifieds as ferrites, which are used for applications.

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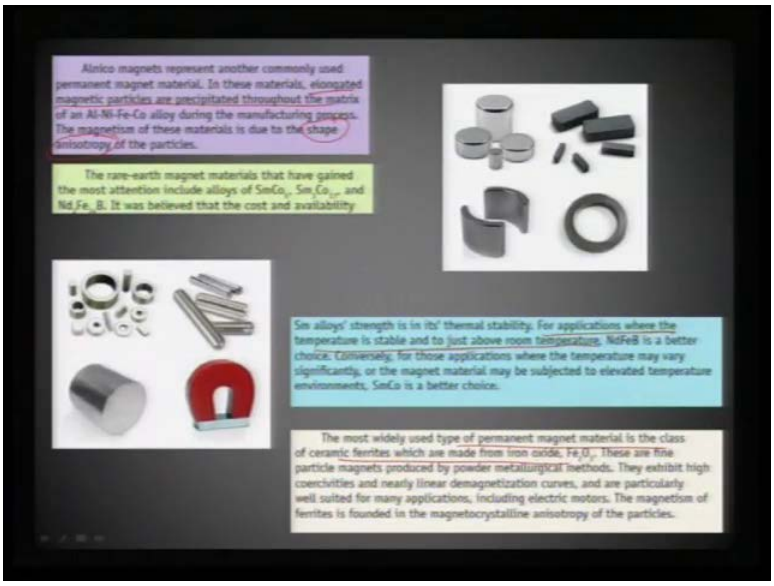

Alnico magnets represent another commonly used permanent magnet material. In these materials, elongated magnetic particles are precipitated throughout the matrix of an Al-Ni-Fe-Co alloy during the manufacturing process. The magnetism of these materials is due to the shape anisotropy of the particles.

The rare-earth magnet materials that have gained the most attention include alloys of $SmCo_5$, Sm_2Co_{17}, and $Nd_2Fe_{14}B$. It was believed that the cost and availability

Sm alloys' strength is in its' thermal stability. For applications where the temperature is stable and to just above room temperature, NdFeB is a better choice. Conversely, for those applications where the temperature may vary significantly, or the magnet material may be subjected to elevated temperature environments, SmCo is a better choice.

The most widely used type of permanent magnet material is the class of ceramic ferrites which are made from iron oxide, Fe_2O_3. These are fine particle magnets produced by powder metallurgical methods. They exhibit high coercivities and nearly linear demagnetization curves, and are particularly well suited for many applications, including electric motors. The magnetism of ferrites is founded in the magnetocrystalline anisotropy of the particles.

Alnico it is one of the magnet, which is used as a permanent magnetic material and in these materials elongated magnetic particles are precipitated throughout the matrix, during the manufacturing processes. And therefore, in the case of alnico, it is what is important is the shape anisotropy and this is usually spin cast into a particular form. Therefore the shape anisotropy is more important as far as alnico is concerned, the samarium cobaltite are preferred over borides, because of the processability, but both are essentially very good materials for alloys.

For applications where temperature is stable and it is just above room temperatures, samarium alloys are used whereas, borides usually used for, high temperature applications. And we have a range of applications coming from ceramic ferrites, the only permanent magnets, which are used from the oxides are mostly ferrites.

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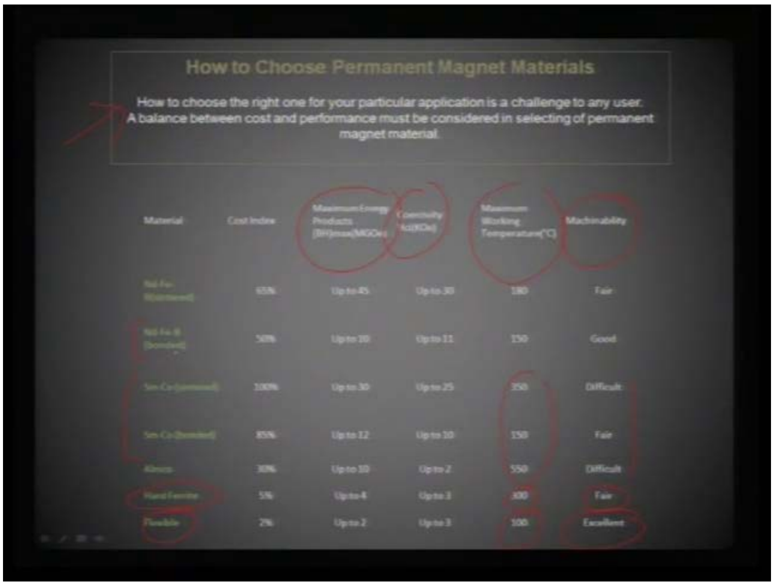

How to Choose Permanent Magnet Materials

How to choose the right one for your particular application is a challenge to any user. A balance between cost and performance must be considered in selecting of permanent magnet material.

Material	Cost Index	Maximum Energy Products (BH)max(MGOe)	Coercivity Hc(KOe)	Maximum Working Temperature(°C)	Machinability
Nd-Fe-B(sintered)	65%	Up to 45	Up to 30	180	Fair
Nd-Fe-B (bonded)	50%	Up to 10	Up to 11	150	Good
Sm-Co (sintered)	100%	Up to 30	Up to 25	350	Difficult
Sm-Co (bonded)	85%	Up to 12	Up to 10	150	Fair
Alnico	30%	Up to 10	Up to 2	550	Difficult
Hard Ferrite	5%	Up to 4	Up to 3	300	Fair
Flexible	2%	Up to 2	Up to 3	100	Excellent

And specifically, one particular compound its a hard ferrite, which is barium hexa ferrite, how to chose permanent magnet materials, we have a range of numbers, that will help you understand, what sort of materials, that you can use. We look at the maximum energy product value, we look at the coercivity and we also look at the machinability and the working temperature. All these 4 parameters decide, what sort of compound that, you want to chose for example, flexible materials, the limitation is you cannot go more than 100, but you can actually render it into any form.

Hard ferrites, you can play around up to 300, but processability machinability is very poor, there by that way, but if you look at the alloys and the borides alloys, you can use it in high temperature applications, whereas machinability is fairly decent and not very easy whereas, for borides, it is possible, for you to machine it, because it is a rugged material.

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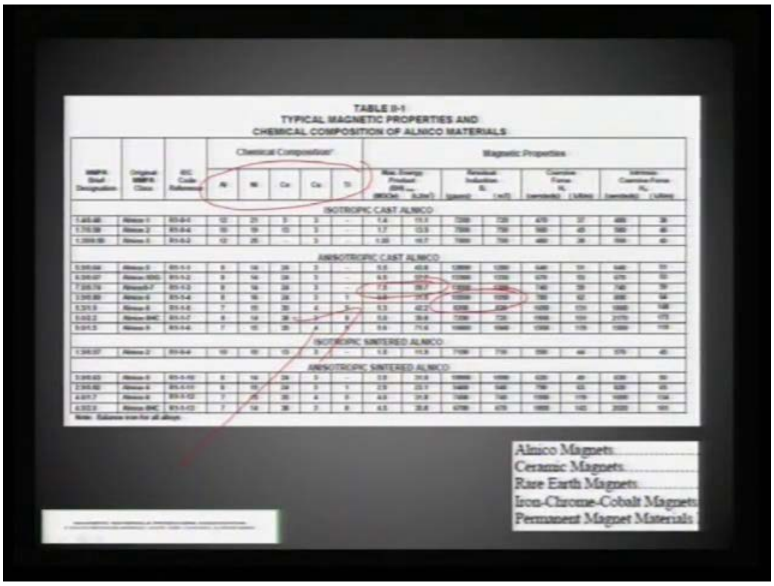

TABLE II-1
TYPICAL MAGNETIC PROPERTIES AND
CHEMICAL COMPOSITION OF ALNICO MATERIALS

ISOTROPIC CAST ALNICO

ANISOTROPIC CAST ALNICO

ISOTROPIC SINTERED ALNICO

ANISOTROPIC SINTERED ALNICO

Alnico Magnets
Ceramic Magnets
Rare Earth Magnets
Iron-Chrome-Cobalt Magnets
Permanent Magnet Materials

So, these are the some of the parameters, that will tell you, which one to use and alnico is one of the most popular material, I cannot run through all the datas, but we a preferred one is a composition, which will have maximum energy product up to 7.5 and your coercive force is up to nearly 1000 Oersted. So, there are various compositions of alnico, which will determine, what sort of energy product that, we are looking for the compositions are aluminum nickel cobalt with adhesions of copper and titanium.

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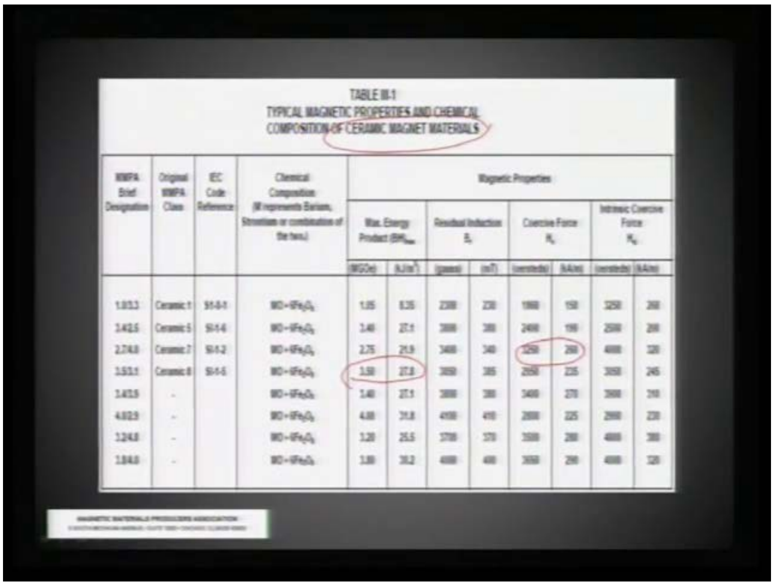

TABLE III-1
TYPICAL MAGNETIC PROPERTIES AND CHEMICAL
COMPOSITION OF CERAMIC MAGNET MATERIALS

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As far as the ceramic magnetic materials are concerned, we have barium hexaferrite or strontium hexaferrite, which does the job and as you would see here, maximum that, you can achieve, in the energy project product is of the order of 3.5 megagauss Oersted and coercive forces up to 3000 can be achieved in this barium hexaferrite.

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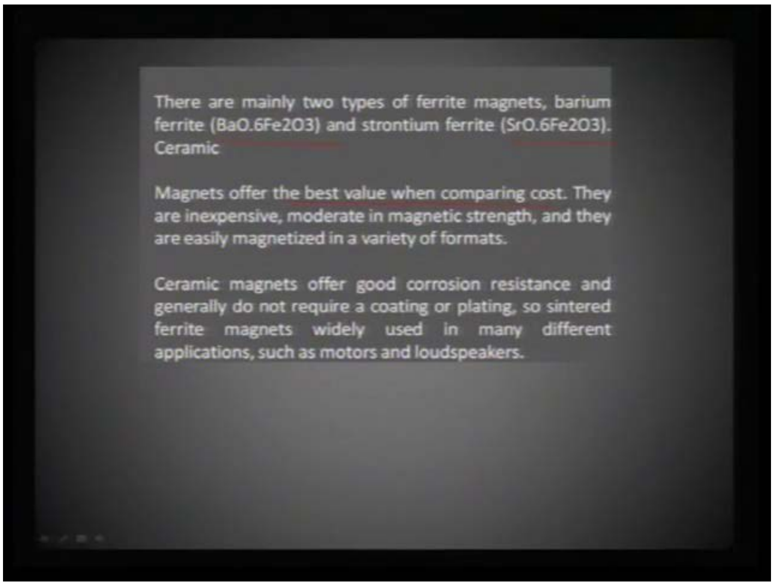

There are mainly two types of ferrite magnets, barium ferrite (BaO.6Fe2O3) and strontium ferrite (SrO.6Fe2O3). Ceramic

Magnets offer the best value when comparing cost. They are inexpensive, moderate in magnetic strength, and they are easily magnetized in a variety of formats.

Ceramic magnets offer good corrosion resistance and generally do not require a coating or plating, so sintered ferrite magnets widely used in many different applications, such as motors and loudspeakers.

Apart from barium hexaferrite, you also have strontium hexaferrite, which can do the job, as a permanent magnet these magnets offer, the best value when comparing the cost, because alloys are pretty much costlier, therefore ferrites are usually preferred.

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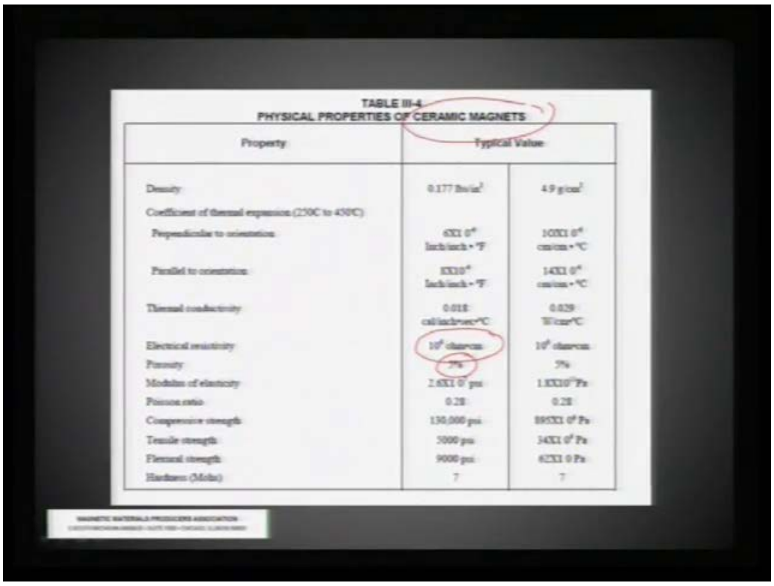

TABLE III-4
PHYSICAL PROPERTIES OF CERAMIC MAGNETS

Property	Typical Value	
Density	0.177 lbs/in^3	4.9 g/cm^3
Coefficient of thermal expansion (250C to 450C)		
Perpendicular to orientation	6X10^{-6} Inch/inch • °F	10X10^{-6} cm/cm • °C
Parallel to orientation	8X10^{-6} Inch/inch • °F	14X10^{-6} cm/cm • °C
Thermal conductivity	0.018 cal/inch•sec•°C	0.029 W/cm°C
Electrical resistivity	10^6 ohm-cm	10^6 ohm-cm
Porosity	5%	5%
Modulus of elasticity	2.6X10^7 psi	1.8X10^{11} Pa
Poisson ratio	0.28	0.28
Compressive strength	130,000 psi	895X10^6 Pa
Tensile strength	5000 psi	34X10^6 Pa
Flexural strength	9000 psi	62X10^6 Pa
Hardness (Mohs)	7	7

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And one important thing about these ceramic oxides is that, you can actually make very dense compact to the extent that, the porosity can be minimized less than 5 percent, that is the essential beauty of this barium hexaferrite and they are also highly resistive. So, this can be used for specific applications, because you can sinter it, to near to theoretical density.

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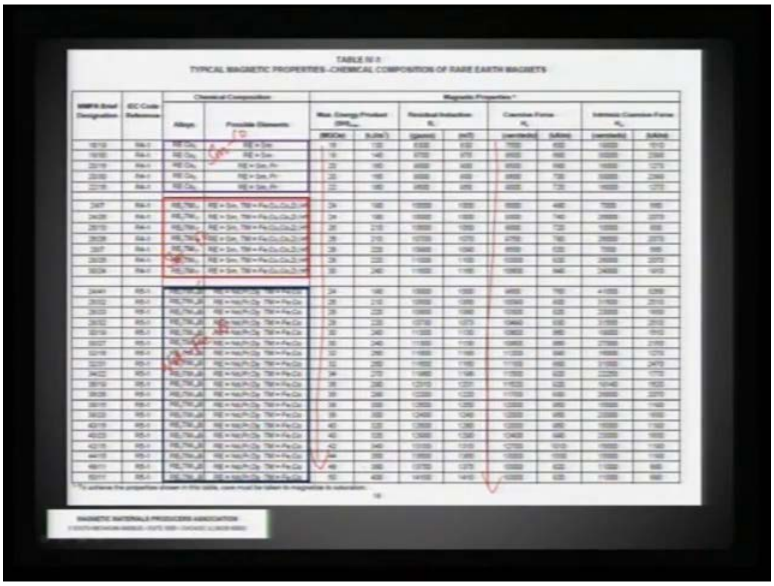

And rare earth manganites, there are 3 particular compositions, which I want to touch upon number 1 is the cobaltite, usually it is samarium cobalt, which is very useful material. As you would see here, in this particular viewgraph, the energy product keeps on increasing from 16 to 50 and you can tailor based on, the composition that, you are using. And the coercive forces can touch up to 10000 Oersted, if you can chose the right rare earth material.

So, the first one is usually samarium cobalt based compounds and the maximum that, you can achieve is 9000 Oersted and your energy product is up to 22 mega gauss Oersted. Whereas, when you go to, the next batch of compounds, these are usually a transition metal and samarium base ones, instead of cobalt samarium, if you go for samarium iron copper cobalt, then you can increase on the energy product or we can go for another batch of compounds, which are usually borides. These are neodymium iron boride based compounds and these are samarium iron base compounds, as would you see here, as you go down this list, the energy product can improve and mostly it is the borides, which take edge over samarium cobalt. And these are a range of iron chromium cobalt magnets that are available

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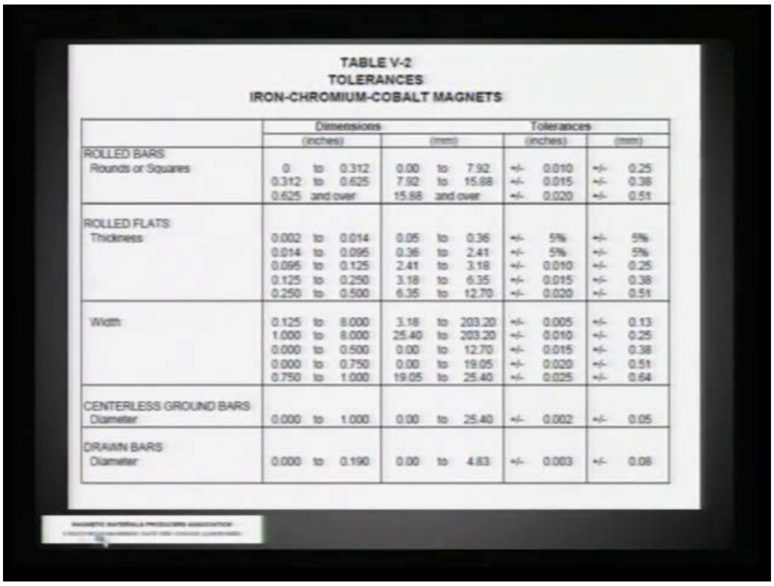

TABLE V-2
TOLERANCES
IRON-CHROMIUM-COBALT MAGNETS

	Dimensions		Tolerances	
	(inches)	(mm)	(inches)	(mm)
ROLLED BARS Rounds or Squares	0 to 0.312	0.00 to 7.92	+/- 0.010	+/- 0.25
	0.312 to 0.625	7.92 to 15.88	+/- 0.015	+/- 0.38
	0.625 and over	15.88 and over	+/- 0.020	+/- 0.51
ROLLED FLATS Thickness	0.002 to 0.014	0.05 to 0.36	+/- 5%	+/- 5%
	0.014 to 0.095	0.36 to 2.41	+/- 5%	+/- 5%
	0.095 to 0.125	2.41 to 3.18	+/- 0.010	+/- 0.25
	0.125 to 0.250	3.18 to 6.35	+/- 0.015	+/- 0.38
	0.250 to 0.500	6.35 to 12.70	+/- 0.020	+/- 0.51
Width	0.125 to 8.000	3.18 to 203.20	+/- 0.005	+/- 0.13
	1.000 to 8.000	25.40 to 203.20	+/- 0.010	+/- 0.25
	0.000 to 0.500	0.00 to 12.70	+/- 0.015	+/- 0.38
	0.000 to 0.750	0.00 to 19.05	+/- 0.020	+/- 0.51
	0.750 to 1.000	19.05 to 25.40	+/- 0.025	+/- 0.64
CENTERLESS GROUND BARS Diameter	0.000 to 1.000	0.00 to 25.40	+/- 0.002	+/- 0.05
DRAWN BARS Diameter	0.000 to 0.190	0.00 to 4.83	+/- 0.003	+/- 0.08

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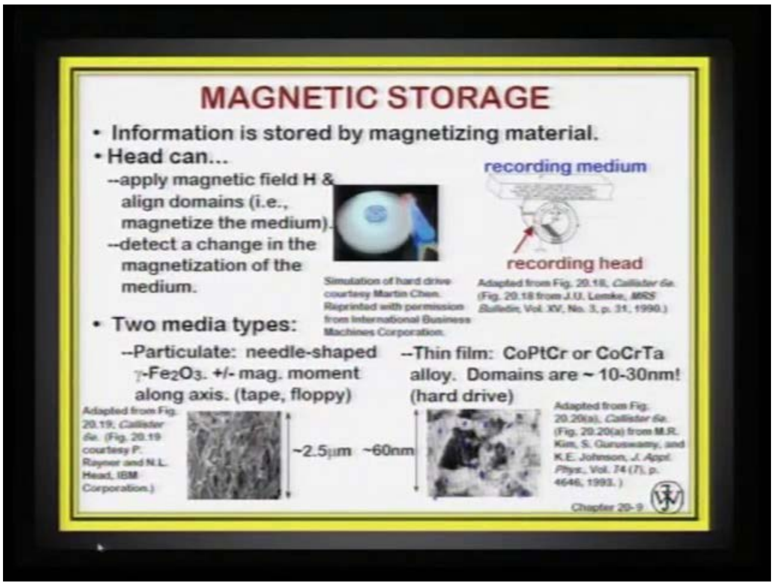

MAGNETIC STORAGE

- Information is stored by magnetizing material.
- Head can...
  - --apply magnetic field H & align domains (i.e., magnetize the medium).
  - --detect a change in the magnetization of the medium.
- Two media types:
  - --Particulate: needle-shaped γ-Fe_2O_3. +/- mag. moment along axis. (tape, floppy)
  - --Thin film: CoPtCr or CoCrTa alloy. Domains are ~ 10-30nm! (hard drive)

Simulation of hard drive courtesy Martin Chen. Reprinted with permission from International Business Machines Corporation.

Adapted from Fig. 20.18, *Callister 6e.* (Fig. 20.18 from J.U. Lemke, *MRS Bulletin*, Vol. XV, No. 3, p. 31, 1990.)

Adapted from Fig. 20.19, *Callister 6e.* (Fig. 20.19 courtesy P. Rayner and N.L. Head, IBM Corporation.)

Adapted from Fig. 20.20(a), *Callister 6e.* (Fig. 20.20(a) from M.R. Kim, S. Guruswamy, and K.E. Johnson, *J. Appl. Phys.*, Vol. 74 (7), p. 4646, 1993.)

Chapter 20-9

And the next important application of this magnetic materials is in the area of magnetic storage, which I will continue in the next lecture and also I will try to discuss what are all the magnetic phenomenas, that are involved when we try to look at these magnetic materials. So, in the next lecture, I will give some examples of a materials, that are used for magnetic storage and I will also discuss with you about some of the magnetic phenomena, that happens, which we can suitably minimize or enhance, if we get to know what is the application, that we are looking for.