Introduction to Magnetic Composites

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Abstract

This Module introduces basic concepts of magnetic composites and magnetic materials in both the traditional and in the rare-earth realm to students in high school and college technology courses. A brief review of magnetic materials and composites is provided; magnetic composites and rare-earths are explained. PowerPoint slides provide references and talking points/procedure to assist instructor in discussing the important points of the Module. A lab activity explores the composition, properties, and behavior of magnetic composites, their application, and how/why rare-earth elements can play an important role in the design of composites and their use in devices.

Module Objective

Recognize the applicability of magnetic composites and the role of rare-earth magnetic material properties/characteristics in magnetic composite composition.

Objectives/SLOs

- Identify differences between “hard” and “soft” magnetic materials
- Describe how a magnetic composite benefits from each of its constituents
- Discuss the behavior differences between a common ferromagnetic material (Fe) and a rare-earth ferromagnetic material (Gd or Nd)
- Explain the variables that affect the strength of a magnetic field
- Alter a magnetic composite material in response to a given design requirement/problem.

Introduction to Magnetic Composites

Module Data

Key words: magnetic composite, rare-earth elements, ferromagnetism, critical materials, magnetic domains, polymer chemistry

Pre-requisites: Knowledge of measurement of physical properties i.e. weight, mass, volume

Target Grade Level: Introductory level technical programs (grades 9 – 14)

Type of Module: Lecture with demonstrations and hands-on lab

Time required: One to two class periods depending on grade level, experience, and demonstrations/variations implemented

Accompanying material:

- Instructor Guide: Rare Earth Elements Activity (pdf)
- Student Guide: Rare Earth Elements Activity (pdf)
- Magnetics Composites – PPT available for download
- Magnetic Composites Lab Video (12:20 minutes) - https://youtu.be/KMagn5XBmJc

NGSS and Core Competencies for Engineers and Technicians

NGSS Alignment

HS. Structure and Properties of Matter

HS-PS1-1. Use the periodic table as a model to predict properties and patterns

HS-PS1-3. Plan and conduct investigations to gather evidence to compare bulk scale substances and infer strength of electrical forces between particles

HS-PS2-6. Communicate scientific and technical information about why molecular level structure is important in the functioning of designed materials

PRACTICES	DISCIPLINARY CORE IDEAS	CROSSCUTTING CONCEPTS
Planning and carrying out investigations	Structure and properties of matter Types of interactions	Patterns Energy and matter Structure and function

HS. Engineering Design

HS-ETS1-1. Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering

PRACTICES	DISCIPLINARY CORE IDEAS	CROSSCUTTING CONCEPTS
Asking questions defining problems Constructing explanations and designing solutions	Defining and delimiting engineering problems Develop possible solutions	Systems and models

HS. Energy

HS-PS3-5. Develop and use models interacting through electric or magnetic fields to illustrate forces between objects and the changes in energy of the objects due to the interaction

PRACTICES	DISCIPLINARY CORE IDEAS	CROSSCUTTING CONCEPTS
Planning and carrying out investigations Constructing explanations and designing solutions	Definitions of energy Relationship between energy and forces	Cause and effect Systems and models Energy and matter

Core Competencies for Technician Education addressed in this Module

0.B Prepare tests and analyze data

b2 Demonstrate good lab notebook skills

1.C Demonstrate laboratory skills

c1 Demonstrate familiarity with good laboratory practice

c3 Operate a digital camera to obtain high quality images of technical objects

c4 Select appropriate devices and instruments for measurement of physical phenomena

5.A Apply safe and environmentally appropriate methods to chemical handling

a3 Apply knowledge of chemical and environmental safety including waste disposal and recycling

5.B Demonstrate knowledge of chemistry fundamentals

b2 Demonstrate knowledge of chemical symbols and the periodic table of the elements

b5 Apply the scientific method in a laboratory

b10 Describe the chain structure of polymers

7.B Discuss the general nature of plastics and polymers

b1 Explain the general behavior of thermoplastic materials

b2 Describe the general behavior of thermoset plastics

7.J Demonstrate how material properties are used in engineering design

j3 Explain the process of designing materials for specific applications

j4 Explain how and why a designer chooses properties of materials

7.L Explain how plastics and polymers differ from other materials

8.A Demonstrate the planning and execution of materials experiments

a6 Demonstrate an understanding of experimental design

11A Describe the structure and advantages of composite materials

a1 Describe a composite material

a3 Identify common materials used for the matrix of composite materials

Background/Introduction (information sequenced with Slideshow as indicated)

An accompanying PowerPoint presentation, that duplicates the figures found in this Module text is provided for use with the students.

MAGNETIC COMPOSITES—Soft vs. Hard Magnetic Composites (Slides 2 and 3)

Definition: Magnetic particles dispersed in a polymeric binder/matrix.

In traditional composites, the main goal is to improve mechanical properties with reinforcements. Common examples include: rebar and concrete, synthetic fiber and glass, and steel in tires. With magnetic composites, the main goal is to introduce a magnetic field into a lightweight, durable, flexible material.

Magnetic composites are manufactured with two constituents: magnetic filler obtained by milling/atomization of a magnetic material and a dielectric binder material (a.k.a. polymer). The dielectric creates an insulating layer on the surface of the filler grains such that the resulting magnetism is only that of the filler (there is no interaction between the magnetic particles).

Designers of electric motors are researching dielectric materials that allow them to construct electronic devices with new, adaptable, durable structures and shapes. Magnetic composite design advantages include:

- The ability to: **tailor physical properties, produce products with complicated shapes**, and **mechanically form it into whatever shape is most advantageous.**
- When used in electronics: **volume is reduced** (lower winding volume), efficiency (fewer parts required), **complex part shaping**, **higher fill factor**, and **new design and production concepts** are possible such as reduction in parts.
- The main attributes of magnetic composites are their ability to be deformed, stretched, bent, and shape controlled.

Introduction to Magnetic Composites

When designing a magnetic composite you must consider both magnetic and physical properties. These properties can be tailored/engineered by the appropriate **selection of the composition and manufacturing parameters (processing).** Properties are dependent on:

- magnetic strength of the filler
- amount and type of binder
- processes used (e.g.: pressing vs. molding)
- curing temperature
- weight of materials used

In addition, the properties of magnetic composites allow the designers to develop new structures with their magnetic circuits/devices, which are better adapted to customer requirements such as to reduce size/weight, or to fit into a complex shape.

Types of magnetic composites depend on the magnetic component and can be classified as either:

- Soft magnetic composites usually iron-based, are obtained by pressing soft magnetic powder with a dielectric binder.
- Hard magnetic composites usually Nd-Fe-B (a neodymium, iron, boron compound), are obtained by bonding hard magnetic powder with a dielectric binder, e.g.: epoxy resin.

The use of “soft” and “hard” in this Module refer to magnetic properties, never to mechanical hardness, for example. Soft magnetic materials easily magnetize and demagnetize where as permanent, or “hard”, magnetic material maintains its magnetization. This makes soft magnetic material very useful in situations where you want to switch the magnetic field quickly and easily such as in motors. Hard magnets require too much current to do that.

Mechanical properties are defined as those material properties that measure a material's reaction to applied force such as: tensile strength, elongation, Young's modulus, elasticity, and fatigue strength. These are sometimes referred to as physical properties, but not in this Module.

A physical property is a characteristic of material that can be observed or measured without changing it. Examples of physical properties include color, weight, volume, density, thermal and electrical conductivity.

ENGINEERING COMPOSITES (Slide 4 - 6)

Definition: Combine properties of two different materials to form one material with properties superior to its individual constituents.

The "sandwich panel" a stiffer, stronger, lightweight composite structure made up of a core material with bonded layers has been the basis for composites since the 1960s.

Today, composite manufacture includes a binder and adding reinforcements/fillers such as fibers to form a matrix. Each composite takes advantage of its matrix properties.

- Reinforcement material, (a fiber or particle such as a powder) is embedded into a binder material. The most common types of reinforcements are: fiberglass and carbon and most commonly used to add strength to the matrix.
- The most common binder is a polymer. Polymers are long-chain molecules made of many repeating units called "mers." Binder material "glues" the filler materials in the matrix.

ROLE OF POLYMERS (Slide 5)

The most common polymer composite is the Polymer Matrix Composites (PMC). PMCs are classified as:

- **Thermosets** start off as a liquid and then through and chemical process called cross-linking, become a solid. Once "cured" through cross-linking it cannot be converted back to a liquid and it cannot be melted. Examples include: epoxy, cushioning material, polyester fabric, etc. Thermosets are typically much more rigid than thermoplastics.

- **Thermoplastics** do not cross-link and can be melted, formed, re-melted and re-formed. Examples included: grocery bags, plastic cases, etc.

Examples of common types and varieties of polymers (also called plastics):

- Polyethylene low density (LDPE): Grocery bags
- Polyethylene high density (HDPE): Detergent bottles, toys
- Poly (vinyl acetate) (PVA): Paints, adhesives

Polymer properties when applied to magnetic composites make a most versatile material with the desired properties that can be formed as needed for almost any application. Polymer properties such as ductility and flexibility are what make the magnetic composite so versatile and adaptable.

MAGNETS AND RARE EARTHS ELEMENTS (Slides 6 - 8)

Magnets can be made from only a select set if elements.

Rare Earth Elements (REEs) or Rare Earth Metals (REMs) are seventeen chemical elements found on the periodic table and fall in the Lanthanide family, plus two elements commonly found with REEs, scandium and yttrium. Looking at the Periodic Table (slide 8) you can discover that most REEs have a valance of three. Lanthanides have very similar physical and chemical properties including high electrical conductivity yet also posses other far ranging properties such as melting points e.g.: Lanthanum (918ºC or 1,684ºF) vs. Lutetium (1,663ºC, 3,025ºF).

"*Rare earth elements perplex us in our researches, baffle us in our speculations and haunt us in our dreams."* –Sir William Crookes, 19th Century British Chemist

Rare-earths have given us lasers that can cut out cancer and optical fibers that carry the World's information (Erbium), light that puts the color in our TV and LEDs

(Europium), energy saving car batteries (Lanthanum), and the ability to miniaturize the electronic devices that we enjoy and depend on (Neodymium).

Rare-earth magnetic properties are being exploited in many ways. There are four main types of magnets:

- Neodymium, Iron, Boron (NdFeB) doped with Dysprosium to improve coercivity is a chemical compound with a complex crystal structure. Due to its high coercivity and very strong magnetic field generated in a very small volume, it has been explored as an alternative to bulkier electromagnets since the 1980s. NdFeB magnets are most commonly being used in electronic motors/devices.
- Samarium Cobalt (SmCo) metallic alloys, developed in the 1970s for aerospace applications, withstand higher temps than NdFeB without suffering demagnetization (high coercivity).
- Ferrite magnets are ceramic compounds that have been used since the 1950s. Strong magnetic ferrites are manufactured from iron oxide combined with Strontium, Barium or Cobalt, Lanthanum. Coercivity is one fifth that of NdFeB. Weak magnetic ferrites are iron oxide combined with Mn or Ni, usually combined with Zinc, and is commonly used in transformer cores.
- Aluminum, Nickle, Cobalt (AlNiCo) is a metallic alloy of aluminum, nickel and cobalt, sometimes with other elements to give it specific properties. AlNiCo magnets were the strongest magnets known before the advent of rare earth magnets.

Introduction to Magnetic Composites

MAGNETIC MATERIALS AND MAGNETISM (Slides 9 – 13)

Since the discovery that iron was attracted to Lodestone, the era of magnetism and magnetic devices was born. The earliest known device was the compass. Today ferromagnetic devices dominate the telecommunications, energy and transportation industries, and more are emerging in medical and other areas. There are several elements that are ferromagnetic (here we use the abbreviation, “magnetic”)

- Iron and steel are the best known and most widely used; steel is an alloy of iron with a small amount of carbon.
- Other elements such as Cobalt, Nickel and rare-earths: Gd, Tb, Dy and Nd.
- Alloys and compounds including these magnetic elements can also be ferromagnetic.

Why iron attracts

- Relates to the electron spin in the unfilled valence shells and distance.
- Dipoles/domains: Unmagnetized iron has magnetic domains aligned such that they cancel one another out—no net magnetism.
- Unpaired electron spin in iron aligns with one another in small areas in material (microscopic).
- Iron is divided into magnetic domains (macroscopically).
- When magnetic field is added: domains move to align iron specimen and “stick” to the magnet (electric motors work this way).

How magnetism happens—Dipoles and Domains

- A quantum mechanical “exchange interaction” between electron spins in ferromagnetic materials provides magnetic interaction:
  - Exchange interaction depends on distance between atoms.
  - Distance between atoms depends on material structure and temperature.

In local areas called “magnetic domains,” spins align (microscopic level). To reduce energy in the material, domains are aligned in different directions (macroscopic level) such that in equilibrium the materials appears not to be magnetized.

- Exposure to a magnetic field can cause the macroscopic material to become magnetized as the domains grow in the direction of an applied magnetic field.
  - External field can be from a permanent magnet or an electric field.
  - Extreme exposure can be used to create a “permanent magnet.”

Electric and magnetic fields interact (Slide 14)

- In a solenoid in which an electric current flow, a magnetic field is produced.
- In a transformer, the primary and secondary coils and inductors are not touching but induce a voltage through magnetism. This phenomenon is used to isolate a source of electric field from another. Current flowing in the primary coil (input) at voltage Vp, is transformed into a magnetic field through an iron core, which then creates an electric field that is induced into the secondary winding (the output coil) on the transformer core Vs. This is used, for example, to transform a 220 V current from an input power line to a 110 V current for household use.

CURIE TEMPERATURES (Slides 16-18)

Definition: Maximum temperature of magnetism for each specific material.

All magnetic materials have a Curie Temperature or Tc where the magnetic properties go away. This depends on temperature and can also be changed by changing the structure of the magnetic material by changing the distance between atoms:

- Heating the material causes atom vibrations:
  - The distance between atoms is expanded, increasing the distance between atoms such that ferromagnetism ceases.

- Add other elements to make a compound or alloy that will change the distance between atoms:
    - Adding carbon to iron makes steel; the change in distance is minimal and steel continues to be magnetic; same is true if adding chromium to steel to make standard "stainless steel."
    - Adding nickel and chromium to steel makes the highest quality stainless steel; however, adding nickel changes the structure and this type of stainless steel is NOT magnetic (used today on high-end refrigerators and for the most expensive stainless steel tableware).
    - The most powerful magnets are made of an iron/neodymium/boron compound.
- The Tc for Gadolinium is close to room temperature. See interesting video in slide 18.

COERCIVE FORCE (or Coercivity) (Slide 19)

Definition: Magnetic effort needed to demagnetize a magnet, or the ability to resist demagnetization.

- There are two ways to measure magnetic strength:
    - Remnance, measured by Flux density - the amount of force needed to pull it from steel or a similar-size magnet.
    - Coercive Force, Hc – the magnetic effort needed to demagnetize a magnet.
- Why some magnets are "super" magnets:
    - Temperature (depends on Curie Temperature).
    - Structure and distance of between atoms.
    - "Hard" magnetic materials have high Coercive Force.
      "Soft" magnetic materials have low Coercive Force.

High coercivity, high resistance; low coercivity, low resistance to demagnetization has a major impact on working conditions of permanent magnets at high temperatures.

ACTIVITY – DESIGN & CUSTOMIZE POLYMER MAGENTIC MATERIALS (Slides 20-23)

Introduction

This activity emulates a process of **dispersing magnetic particles into a dielectric polymer binder to create a magnetic composite**. Variations in the magnetic composite composition, processing, and composite behaviors are discussed. Observations are then applied to problem statements requiring use of data and research to explain. **Allow 1 hour for Station One and Two parts of the activity, allow an additional 15 minutes for observations and discussion.**

Background

Designers are researching flexible magnetic sheets that allow construction of electronic devices with new, adaptable, durable structures to improve both performance and efficiency. Magnetic sheets are a composite consisting of a magnetic material (usually a powder) and a polymer (such as silicone rubber).

In a real magnetic composite lab…

fine (often magnetite) particles (filler) are dispersed in water and networked with a poly vinyl alcohol (PVA) cross-linked aqueous solution/colloid (binder). Processes such as emulsification, in-situ precipitation, and atomization are used. The ferromagnetic particles actually attached to the flexible polymer chains by adhesive forces.

In our magnetic composite lab…

the polymer matrix (binder) is composed of a pre-formed polymer (PVA solution/glue) and magnetic particle filler (Fe filings and powder). PVA is a neutral polymer that acts when a cross-linking agent, Borax, is introduced. Result is a kind of magnetic “gel” that can be induced using a magnetic field – such as with a NdFeB permanent magnet.

While we are not creating and investigating a true, Nd-Fe-B magnetic composite, we are creating and investigating a magnetic filler-loaded polymer where filler particles have ferromagnetic behavior. Through this activity, learners can observe the effect of a magnetic field on the deformation (flexible behavior) and magnetic responsiveness of a magnetic composite. In the activity, magnetic strength and a shape change is induced (using a permanent magnet) to illustrate the composite’s physical properties. Also, the composite is processed in a variety of ways to demonstrate effects of the amount of Boron vs. the amount of the magnetic material.

Steps for instructor (see PTStudentGuide.pdf for lab activity procedures and accompanying videos.)

1. **Set up two stations** for each team/participant, one for designing and creating the magnetic composite and one for investigating the magnetic composite physical properties:
   - Magnetic attraction
   - Deformation and shaping
   - Magnetic strength

Station One: Design a Magnetic Composite

Supplies and Equipment		
Elmer’s Glue Borax Water Iron filings Iron oxide	150 mL Beaker or measuring cup/spoon Large wood craft sticks 9 oz plastic cups Small condiment cups	Disposable bowls Felt pen Paper towels Butcher paper Tape

Tape down the butcher paper. Provide plenty of craft sticks and paper towels. Depending on grade level/time measure out portions of glue, borax, water, and iron filing/oxide (see PTStudentGuide.pdf for exact amounts).

Station Two: Investigate Composite Behavior

Supplies and Equipment

- 2 – Ferrite bar magnets: approximately 1-7/8" long x 7/8" wide x 3/8" tall with pulling capability, 3 lbs.
- 2 – Horseshoe magnets
- 10 – Rare-earth, Neodymium bar (not disk) magnets: approximately 2" long
- Gram scale
- Wood craft sticks
- Small condiment cups
- Small, plastic cookie cutter (shapes vary, stars/hearts work well)
- Funnel

2. **Introduce the activity:** You will be preparing a soft magnetic composite. First, a cross-linking agent (Borax) is added to a dielectric binder material (PVC liquid/glue). Next, a magnetic filler (Fe) is dispersed to alter the composite's magnetic attraction (material is no longer dielectric).

3. **Discuss Safety:**
    - Rare-earth magnets are extremely powerful and very brittle.
        - Handle with care to avoid injury to you or damage to the magnet.
        - Fingers can be pinched between attracting magnets and the magnets can "chip" if allowed to jump onto the surface of another.
        - Rare-earth magnets are very high energy as well and can damage any device that is sensitive to a magnetic field, e.g.: computer/TV.
    - LABEL ALL VESSELS e.g.: "water," "glue," etc.

- Wear nitrile gloves when handling the magnetic composite, it can irritate or stain the skin.
- Eye and clothing protection and other appropriate PPE are recommended.

4. Instruct students to follow procedures in the PTStudentGuide.pdf handout for Station One and Station Two.

5. Guide students in discussion/observations.

Tips for each station/step discussion:

Magnetic composite design:

- Transformation from a liquid state to a solid state of the polymer.
- Effect of cross-linking the molecules.
- Left over water could be explained by un-reacted material, this is common in the “real” process too.
- What makes this a composite? Composite is created that is flexible yet stronger than either of its constituents.
- Property differences between use of the different fillers (iron filings vs. oxide particles)

Magnetic attraction investigation:

- Random orientation of the magnetic filings in the absence of an applied field.
    - NOTE: There are no initial net magnetization/dipole moments, but as soon as an external field is applied, the magnetic/dipole moments tend to align with the field to produce a bulk magnetic moment; the particle align in the direction of the applied field.
- The magnetic field attracts particles and the dispersing liquid moves along with the particles.

- Effect of decreased particle size – Oxide vs. filings to magnetic and physical properties.
    - NOTE: Filings (typically the size in micrometer range) are ferromagnetic. vs. nano-sized oxides (typically the size range of 5–15 nm) are superparamagnetic, not ferromagnetic. It may be important to point out here that Loadstone is a crystalline structure. All of these particle shape/size affect magnetic attraction.
- Differences in type of magnet used: horseshoe, bar, Nd.
    - Which is the composite most sensitive to?
    - Relate magnetic composite attraction to the composition of the magnet and its Curie temperature.

Deformation and shape-ability investigation:

- Viscosity, how can it be tested, differences between filings and oxide?
- It can be segmented, what is the advantage?
- It can be pulled/stretched, what is the advantage? NOTE: if allowed enough time, the entire piece of composite should be sucked into the shape.
- Holding shape depends on what? Should be density of the composite composition, more binder. Also particle size, the smaller particle holds it's shape but is very stiff and hard. Maybe temperature?

Magnetic strength investigation:

- Main observation: pull of the magnet.
- What changes affect pull of the magnet most? Height of bridge, number of magnets used?

6. **Ask students to prove/explain the following by varying any one or more component/process (NOTE: this may require designing a completely new composite and testing it again or students may be doing this all along as they investigate).**

   - *For stiffer, harder shape-ability, what changes would you make to your magnetic composite composition?*

     ***Answer**: Increase binder (glue) content*

   - *What does your change in the magnetic composite composition do to its magnetic properties?*

     ***Answer**: It should decrease magnetic properties*

   - *What effect does "doping" with other non-magnetic filler, i.e. iron oxides have on the magnetic composite, on the magnetic attraction?*

     ***Answer:** It should have no effect on magnetic strength but physical properties like deformation should change. Shouldn't have an effect you are just diluting a paramagnetic fluid.*

4. **Ask students to reflect on the following problems/possibilities:**

   - *What would determine your selection of magnetic material to use in a composite? Where/when might a rare-earth material be used/needed as filler?*

     ***Answer**: temperature requirements, Curie temperature would be used to determine type of filler.*

Introduction to Magnetic Composites

- *The effective use of magnetic composites leads to the redesign of electric devices to take advantage of these materials. What redesign considerations are needed?*

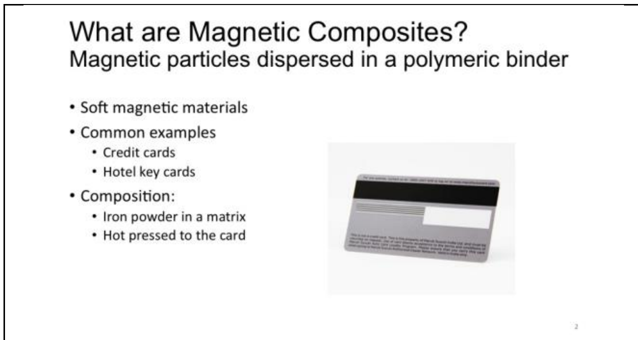
  Answer*: When redesigning, consider:*

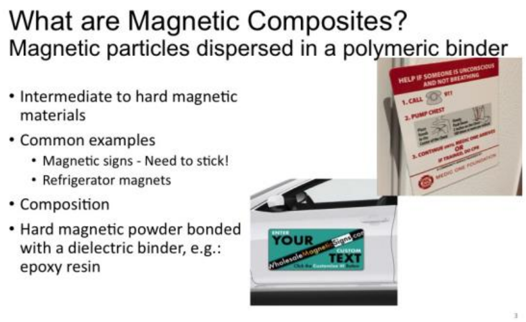
  - *Shape-ability*
  - *Curie temperature*
  - *Coercivity*
  - *Magnetic strength*
  - *Composite composition*
- *How might an electronic device (of your choice) be improved using a magnetic composite?*

  Answer (for a motor winding): replace the coils with the magnetic composite "sheet"

  Advantages: reduction of weight (mass), takes up less space (volume), fewer parts required (efficiency).

Curriculum Overview and Procedure Notes for Instructor

 	**Slide 2** **What are Magnetic Composites?** Definition: Magnetic particles dispersed in a polymeric binder Discuss every day examples of soft magnetic materials: ▪ Credit card example ○ Relatively soft magnetic material (iron filings in a polymer binder)

	○ Easy to magnetize/demag (hotel room cards) ○ Harder to magnetize/demag (credit cards)
	**Slide 3** **What are Magnetic Composites?** Discuss every day examples of harder magnetic materials: ▪ Refrigerator signs ▪ Signs for trucks, cars – need to be strong so they won't fall off ▪ Need to be flexible – fit the size/shape of the truck door etc.
	**Slide 4** **Engineering Composites** Definition: Combine properties of two different materials to form one material with properties superior to its individual constituents Discuss traditional examples on slide: sandwich panel and carbon fiber Ask: What's different about magnetic composites?

Introduction to Magnetic Composites

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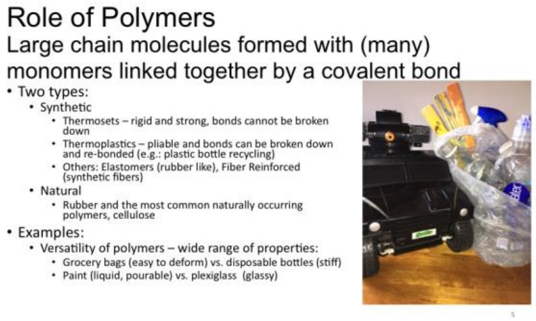

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Slide 5

Role of Polymers

- Review types (thermoset vs. thermoplastic)
  - Explain that one way to identify thermoplastic or thermoset. Press a heated stirring rod against it, if it melts, thermoplastic; if not, thermoset
- Show examples pictured & discuss properties and versitility
  - Grocery bags LDPE – demo deformation by pulling the bag in a couple of directions
  - Water bottles HDPE – demo stiffness by crushing/twisting
  - Paint and adhesives PVAs (fluid nature of polymer…)

Point out that due to its versatility, polymer is one of the constituents of magnetic composites

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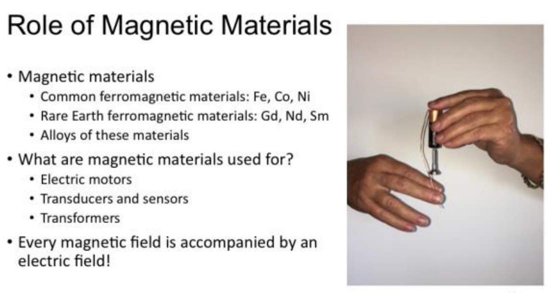

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Slide 6

Role of Magnetic Materials

Review list on slide

- Bar magnets—usually iron-based
- Used in compasses since the earth has a magnetic field!

Ask: How do magnets create an electro-current?

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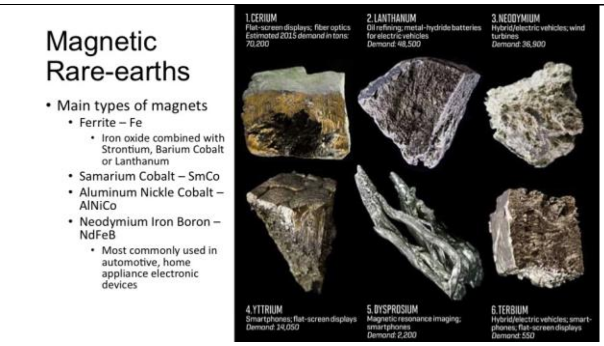
Demonstrate using the Screw Motor demo (see Appendix for directions)

Point out that magnetic material is one of the constituents of magnetic composites

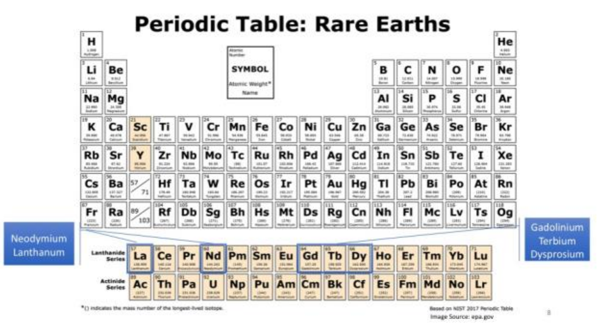


Slide 7

Rare-earths

Introduce the magnetic Rare-earths

- Discuss the terms: REE, REM, Critical Material



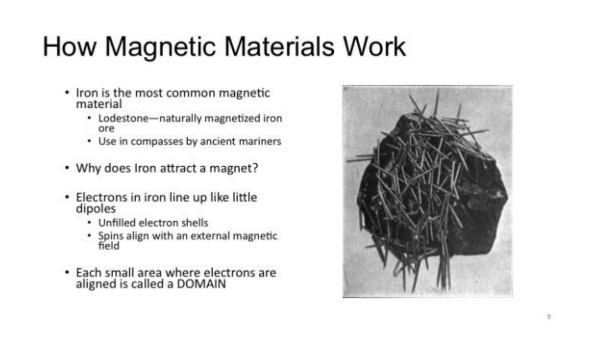
Slide 8

Periodic Table

Using Handout: PTStudentGuide.pdf,

PTInstructorGuide.pdf

- Point out Nd and Gd
- Discuss PT trends, listed on handout
- Introduce RE spelling i.e.: all REs end with "ium", etc., have some fun with it
- Review list of how REs are used in magnetic materials (table in handout)



Slide 9

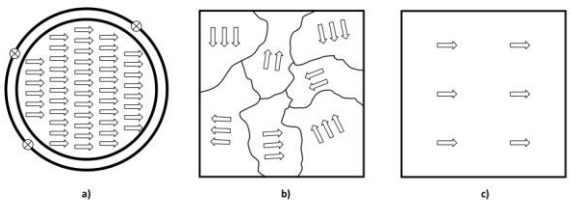
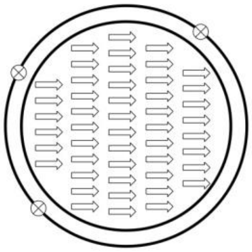
How Magnetic Materials Work

Look at properties of magnetic materials

Review list on slide

- Iron is the most common magnetic material – Loadstone and history

Introduction to Magnetic Composites

	Magnet Field Demo (see Appendix for directions) Ask: What did you see in the demonstration?
 Fig X a) Looking microscopically, magnetic dipoles (unpaired electron spins) within a magnetic material have all electron spins aligned. This is the case in one magnetic domain. b) Macroscopically, a magnetic material has a large number of magnetic domains. Because the material wants to be at equilibrium, each of the many domains will be aligned in different directions to cancel out any net magnetic field. c). In the presence of an external magnetic field, domains aligned with the external field will grow and encompass the whole of the material. When the external magnetic field is removed, the domains re grow and the materials returns to equilibrium.	**Slide 10** **Dipoles and Domains** Slide for Instructor information only, skip and go to next 3 slides to illustrate How Magnetic Materials Work
	**Slide 11** Unpaired electron spins in iron align with one another in small areas in material (microscopic): ▪ Depends on a special quantum mechanical interaction (“exchange interaction”) ▪ Depends on the distance between atoms ▪ Also depends on the structure of the material ▪ Iron has the correct atomic structure such that the atoms are the correct distance apart for this interaction!

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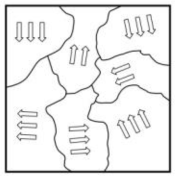
<td></td>
<td>Slide 12

Macroscopically iron is divided into magnetic domains:

▪ Unmagnetized iron has domains aligned such that they cancel one another out—no net magnetism)

Optional: show video, Magnetic Domains (see References for source)</td>
</tr>
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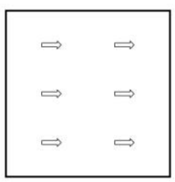
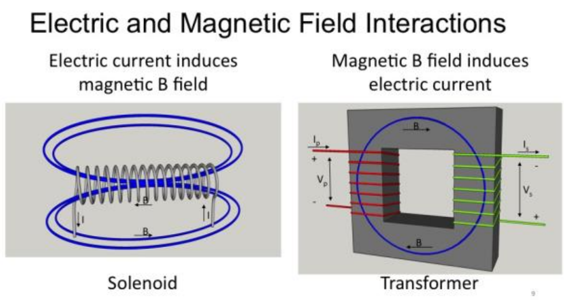
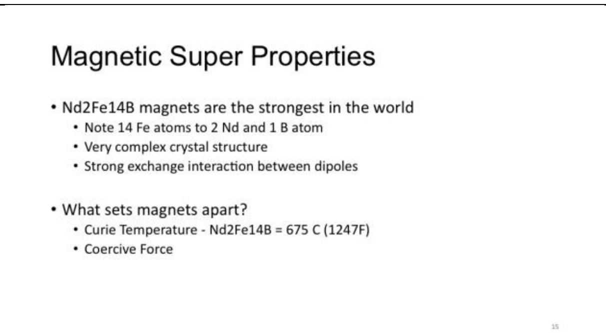
<td></td>
<td>Slide 13
When an external magnetic field is added:
▪ Domains move to align iron specimen
▪ Align and “stick” to the magnet</td>
</tr>
<tr>
<td>
</td>
<td>Slide 14

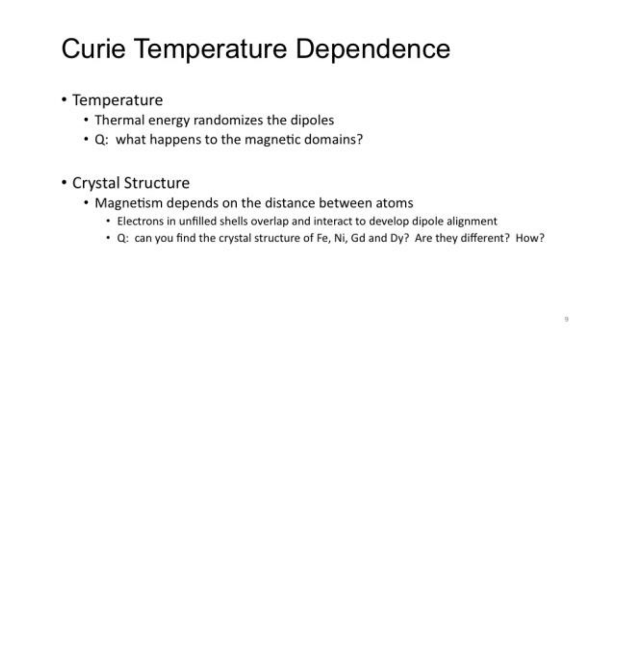
Electric and Magnetic Field Interactions

The solenoid and transformer are presented here as examples of the application of magnetic field to generate electricity.

Review for Solenoid: electric current flows, to induce magnetic field “B” shown in diagram</td>
</tr>
</table>

	Review for Transformer: magnetic field “B” induces electric current shown in diagram **Introduce homework problem:** **Look up how magnets are used in motors, sensors, transformers and how they work (see References for one source)** **Suggest breaking at this point, to be continued next class period**

	**Slide 15**
	
	Magnet Super Properties
	
	Discuss slide with class—get their ideas on why some magnets are stronger than others
	
	▪ Ask: Can you theorize as to why this compound would be such a great magnet?
	▪ Structure and distance between atoms
	  o NdFeB compound is a super magnet—“hard” mag material, why…
	    o Low Curie, etc.
	    o Look at Tc for each: Nd, Fe, B

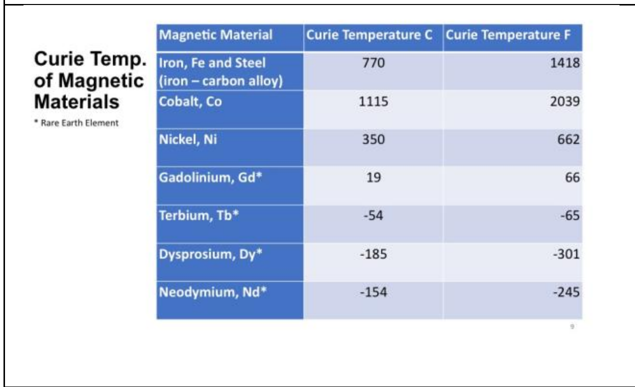


Slide 16

Curie Temperature Dependence

Definition: Maximum temperature of magnetism for each specific material

- Where magnetic properties go away with certain temperatures/maximum temperature, called the Curie Temperature or Tc
- Caused by atom vibrations which increase with temperature
- Atoms that are the right distance apart at low T; get farther apart at higher T


Curie Temp. of Magnetic Materials

* Rare Earth Element

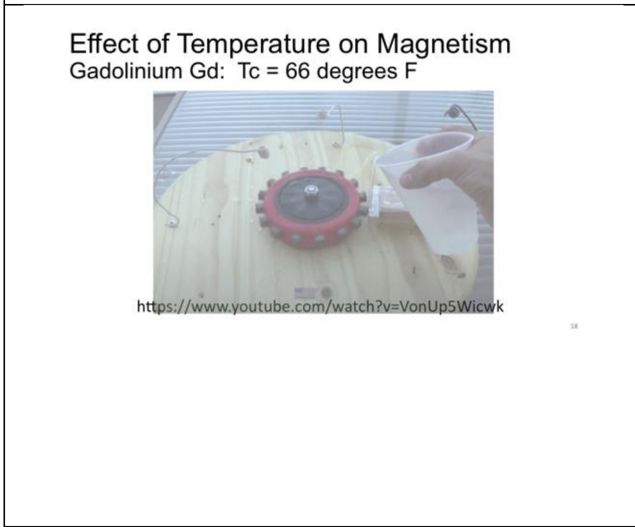
Magnetic Material	Curie Temperature C	Curie Temperature F
Iron, Fe and Steel (iron – carbon alloy)	770	1418
Cobalt, Co	1115	2039
Nickel, Ni	350	662
Gadolinium, Gd*	19	66
Terbium, Tb*	-54	-65
Dysprosium, Dy*	-185	-301
Neodymium, Nd*	-154	-245

Slide 17

Curie Temps

Review Tc values in the slide

- Compare values for iron with others



Slide 18

Effect of Temperature on Magnetism

Show video, Gd video demo (see References for source) and discuss:

- This video demonstrates the effect of temperature on magnetism
- Point out that Gd Tc = 66 degrees F
- What does this imply about application of Gd?

Coercive Force
Magnetic effort needed to demagnetize a magnet

	Coersive Force kA/m	Curie Temp °C
$Nd_2Fe_{14}B$	750-2000 (hard)	320
$SmCo_5$	600-2000 (hard)	720
AlNiCo	275 (intermed.	700-850
Sr ferrite $SrO.Fe_2O_3$	100-300 (intermed.)	450
Iron (bar magnet)	800 (Intermed.)	770
Annealed iron	1 (Soft)	770

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Slide 19

Coercive Force

Definition: Magnetic effort needed to demagnetize a magnet, ability to resist demagnetization

- Measure of how strong the magnet is – Hard vs. Soft
  - Super magnet (very "hard" mag material, high Coercive Force)
  - Intermediate strength materials like Sr Ferrite
  - Iron (soft mag material, low Coercive Force)
- Relate to previous demo of magnets, which magnets were hard to pull off/apart?

Design & Customize Polymer Magnetic Materials – Lab Activity

- Process a cross-linked polymer (thermoplastic)
- Create a magnetic composite with 2 constituents
- Investigate to observe composite behavior to magnetic (NdFeB) field
  - Magnetic attraction
  - Deformation and Shaping
  - Magnetic Strength
- Introduce variables in the magnetic composite composition
  - Composition (more binder vs. more magnetic material)
  - Particle size (iron filings vs. iron oxide)

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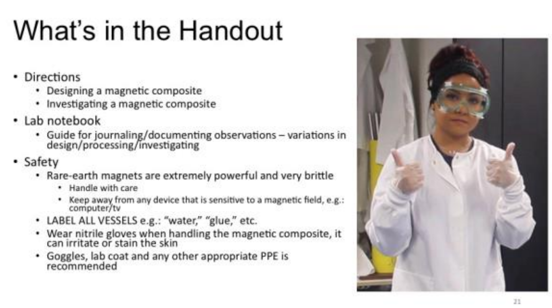
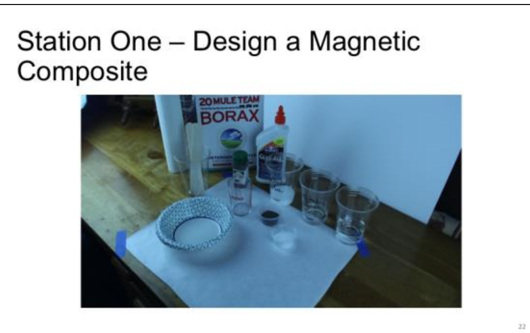
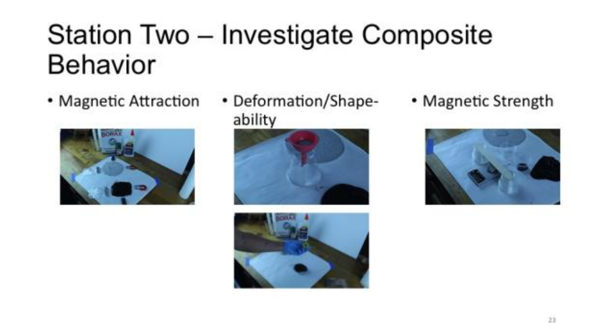
Slide 20

Design & Customize Polymer Magnetic Materials – Lab Activity

- Explain: We want a flexible magnetic composite material composed of 2 constituents:
  - Polymer binder
  - Filler – Magnetic material that will attract a magnet – Fe
- Review what learners will be doing (listed on the slide)
- Introduce activity: You will be preparing a soft magnetic composite. First, a cross-linking agent (Borax) is added to a dielectric binder material (PVC liquid/glue) that yields a polymer material that is flexible yet stronger

	than either of its components. Next the magnetic filler (Fe) is dispersed to alter the composite's magnetic attraction (material is no longer dielectric).
	**Slide 21** **What's in the Handout** **Using PTStudentGuide.pdf** Inform: Lab Directions and safety precautions are in the Student Guide Handout Guidance for maintaining a lab notebook is provided to answer questions about magnetic composite composition design and its applicability to new and better products NOTE: this is a reference to the Module Goal
	**Slide 22** **Station One – Design a Magnetic Composite** Explain the options: ▪ Iron filings ▪ Iron oxide ▪ Variations (e.g.: binder vs. filler, etc.) Discuss measurement and conversions if needed:

	60 mL – 4 Tbs – 2 oz 30 mL – 2 Tbs – 1 oz
	**Slide 23** **Station Two – Investigate Composite Behavior** Explain the suggested investigations: ▪ Magnetic Attraction ▪ Deformation/Shape-ability ▪ Magnetic Strength Show magnets provided, discuss handling

Acknowledgments

The authors thank Ms. Jean Frank for her contributions to our understanding of composite materials and her input on the Module. Development of this work was supported in part by the Joint Center for Deployment and Research in Earth Abundant Materials (JCDream), Everett, WA, and by NSF DUE Grant 2000347, Online Instructional Resources for Materials Science Technology Education.

Appendix

Slide #6 – Magnetic Screw Demonstration – How do magnets create an electro-current?

What you need:

- 1.5V AA Battery

- Short (1”) magnetizable screw
- 6” copper wire, if wire is coated, bare the ends using a blade and gently scraping
- Small NdFeB magnet, round works best, debris/coating on the magnet will block spinning

Directions: Referring to the picture on Slide 6

- Put the magnet on the head of the screw (this magnetizes the screw)
- Dangle screw bit end from the – end of the battery, if the screw will not dangle, use a shorter screw or more powerful magnet
- Hold one end of the copper wire on the + end of the battery
- Let the other end of the wire touch the magnet
- Holding it still, watch the screw spin, it will start slow and increase, you may see some sparks, the wire can get hot the longer you spin

Explanation: Magnets create a magnetic field; electrons in the conductor (copper wire) move and generate electricity.

Slide #8 – Periodic Table and Lab Handout

- PTStudentGuide.pdf
- PTInstructorGuide.pdf

Slide #12 – Magnetic Field Demonstration (suggestions/guide) – Magnetic strength

- Take a large magnet and stick it to something iron or steel
  - Leg of a chair or table
  - If students have magnets, have them check it out
- TIPS: Best to use magnets that are not too strong
  - There are lots of Nd magnets on the market—these are very strong
  - Better to find simple bar magnets

    - “Button” size magnets are dangerous as they can be swallowed
- Observation/discussion
    - Explain that the magnetic dipoles are re-aligning with the magnet!

References

Core Competencies for Technicians (who use materials in their work). Last visited August, 2020. http://materialseducation.org/educators/core-competencies/

Interactive Periodic Table from the RSC

https://www.rsc.org/periodic-table/

National High Magnetic Field Laboratory, facilities at Florida State University, University of Florida and Los Alamos National Laboratory. MagLab is the largest and highest-powered magnet lab in the world. Last visited August, 2020.

https://nationalmaglab.org

Magnetic Domains – Denise Kay. Last visited August, 2020.

https://www.youtube.com/playlist?list=PLjwmswMcfyhjTpDh9nXaMb_vL1tjkzXvt

Rare-earth Element, Encyclopedia Britannica. Last visited August, 2020.

https://www.britannica.com/science/rare-earth-element/Electronic-structure-and-ionic-radius

Rare-earth Element, Encyclopedia Britannica. Last visited August, 2020.

https://www.britannica.com/science/rare-earth-element/Minerals-and-ores

Gd video demo. Last visited August, 2020.

https://www.youtube.com/watch?v=VonUp5Wicwk

How motors work. Last visited August, 2020.

https://www.explainthatstuff.com/electricmotors.html

General Introduction to Critical Materials (download, 10 pages):
https://www.worldscientific.com/doi/pdf/10.1142/9789813271050_0001

Explanation of REE atomic structure, it's what makes REEs so special:
https://phys.org/news/2018-08-rare-earth-elements.html

The following articles form the basis for the concepts and investigation of magnetic composites suggested in this Module:

Ferrogel: a new magneto-controlled elastic medium. M. Zrínyi, L. Barsi, A. Büki Elsevier Bolue 5, Issue 5, 1997, Pages 415-427.

Last retrieved from:

https://doi.org/10.1016/S0966-7822(97)00010-5

Magnetic Composites in Electric Motors. Najgebauer, Mariusz & Szczyglowski, Jan & Ślusarek, Barbara & Przybylski, Marek & Kaplon, Andrzej & Rolek, Jaroslaw. (2018). Magnetic Composites in Electric Motors. 10.1007/978-3-319-63949-9_2.

Last retrieved from:

https://www.researchgate.net/publication/320549494_Magnetic_Composites_in_Electric_Motors

New Polymers for Polymer Magnetic Devices. James Masi and Christopher Gorrie. EME/EIC Conference. Indianapolis, IN, October, 2005. EME/IEEE 2005.

Last retrieved from:

https://www.researchgate.net/publication/4208101_New_polymers_for_polymer_magnetic_devices

Student Evaluation

1. What is the composition of a magnetic composite?

   Answer: Magnetic composite includes magnetic particles in a polymer matrix.

2. What is the structure of the matrix material of the composite?

   Answer: polymer chains, usually cross-linked.

3. What is a hard magnetic composite? How is it different from a "soft" magnetic material?

   Answer: a hard magnetic material that keeps its magnetic properties—difficult to demagnetize; soft magnetic materials are easy to demagnetize.

4. What are the various behavior/property differences between a common ferromagnetic material and a rare-earth ferromagnetic material?

   Answer: Curie Temp is different for each element (RE magnetic elements have a low Curie Temp); Coercivity or Coercive Force depends on the elements involved and mixtures of elements in compounds.

5. What variables in magnetic composite composition affect the strength of its magnetic field?

   Answer: depends on the magnetic material used but can be:

   - amount of magnetic material used
   - size of particles
   - the polymer volume.

6. How does a magnetic composite benefit from each of its constituents?

   Answer: Two individual materials, a dielectric and a magnetic material, are combined to make one material with better (or more desired) properties of flexibility and magnetism (2 together is better than either component alone).

7. How might you use a magnetic composite to re-design an electronic motor that is operable in a refrigerator?

Answer: Investigate relative Curie Temperatures of rare-earth magnetic materials, identify one with a lower Curie Temp and consider how this element could be used with a polymer matrix binder to run a motor with low temperature operating ability.