Quantifying thermodynamic variables
Module α-1 : Magnetic Work.

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Objectives:

1. understand the thermodynamics of the magnetization process (work done by field to magnetize a material) and its relation to mechanical work,
2. understand the factors that can make it harder to magnetize some magnetic materials, and how these factors compare to those that influence mechanical hardness
3. gain an appreciation of the factors that can contribute to magnetic hysteresis
4. to gain an understanding of what factors make a given magnetic material suitable for certain applications

Summary of tasks:

A. Measure the magnetization process, M vs. H curve, for a soft magnetic alloy or amorphous alloy to show that the integral of HdM, the area to left of M-H curve, is positive on increasing field and exactly the same magnitude but negative on decreasing H. <u>Lessons to be learned</u>: Work is first done on the material by the field (dM is of same sign as H), then given back (dM is opposite to H); no significant loss of energy in the material, no hysteresis. These alloys are elastic or conservative in their magnetic response.

B. Measure the magnetization curve, M vs. H, for a hard magnetic material. Now the M-H curve is different on increasing and decreasing field; the magnetization process is no longer conservative. Calculate the energy per unit volume lost per cycle.

   <u>Lessons to be learned</u>: The area inside the M-H loop is the energy per unit volume that is lost per field cycle. The energy loss is due to the thermodynamically irreversible process of domain wall motion. The material is no longer magnetically elastic; its initial state of magnetization is not recovered after a field cycle.

Materials needed

Samples of soft magnetic alloys, soft and hard ferrites and amorphous metal.

Equipment to be used

Vibrating sample magnetometer (VSM), Rm. 4-055,

Background

<u>Power Transformers</u>

Magnetic materials are used every day in applications that are rarely considered. Electrical power is transmitted at high voltages and low currents over the power lines to minimize the energy loss. Transformers are used to step the voltage up and down, to and from the transmission lines, and in all sorts of power supplies. Transformers use magnetic cores with two sets of windings.

The ratio of the voltage in to the voltage out is proportional to the ratio of the number of turns on the coils. The input voltage generates an oscillating magnetic field in one of the coils, this magnetizes the magnetic core. The oscillating field in the core induces a voltage in the second coil. The electric work is converted into magnetic work, and than back into electric work. Soft and hard magnetic materials "loose" different amounts energy every time the direction of the magnetization is switched back and forth, this is related to the difference in the work done while magnetizing the material and the work returned by the material.

Magnetic materials

Magnetic materials derive their importance and usefulness from the fact that they have a property called the magnetization, $\boldsymbol{M} = N\mu\boldsymbol{m}/V$, i.e. $\boldsymbol{M}$ is the volume density of atomic magnetic moments, $\mu\boldsymbol{m}$. The magnetization can be changed by application of a magnetic field, $\boldsymbol{H}$. Applying a field tends to line up the magnetization with the field. The sum of the magnetization and the $\boldsymbol{H}$ field defines the flux density, $\boldsymbol{B}$: $\boldsymbol{B} = \mu_o(\boldsymbol{H} + \boldsymbol{M})$ (MKS) or $\boldsymbol{B} = \boldsymbol{H} + 4\pi\boldsymbol{M}$ (cgs).

Units:	**cgs**	**MKS**
Applied field:	H (Oersted)	H (Amperes /m)
Magnetic response:	M (emu/cm3) or 4πM (Gauss)	M (Amperes /m) or μ_oM (Tesla)
Total flux density:	$B = H + 4\pi M$ (Gauss)	$B=\mu_o(H + M)$ (Tesla)

Measuring M-H:

The M-H curves are measured with a vibrating sample magnetometer (VSM).
There are many instruments that can measure magnetization of a material. Most of them make use of Faraday's law of induction:

$$\oint E \cdot dl = -\frac{\partial}{\partial t}\oint B \cdot dA = -\frac{\partial \phi}{\partial t}$$

It says that a voltage, $\oint E \cdot dl$, is generated in a path that encloses a time-changing magnetic flux, $\frac{\partial \phi}{\partial t}$. The sense of the voltage is consistent with Lenz's law as shown in Fig. 1.

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Fig. 1 A decrease in flux through a coil results in a voltage in that coil whose sense is such that its current would create a field opposing the initial change. (From O'Handley, Modern Magnetic Materials)

The flux density or magnetic induction inside a sample depends on the applied field and the sample magnetization, $B = \frac{\phi}{A} = \mu_0 (H + M)$. Outside the sample (M=0) the induction, $B = \mu_0 H$ comes from the applied field and the H field due to the dipole moment of the sample. When the flux density around a magnetic sample is changed (by either moving the sample or the pickup coil, or by varying the sample magnetization with a small AC field), a voltage is induced in a nearby pickup coil. Integration of that voltage with time gives the flux change due to the sample.
The sample may be magnetized by an electromagnet, which generates a magnetic field by passing a current through a copper coil as shown in Fig. 2 and 3.

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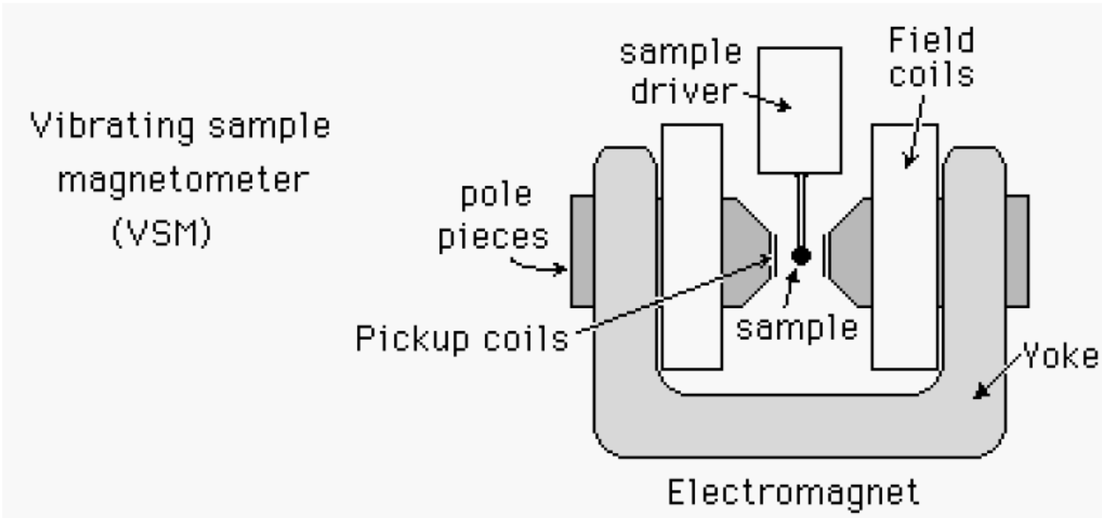
Fig. 2. Direction of magnetic B field about a current-carrying solenoid is given by the right-hand rule. (From O'Handley, Modern Magnetic Materials)

We will use a vibrating sample magnetometer in which a sample is vibrated (± 1 mm at about 75 Hz) to induce a voltage in a set of carefully designed pickup coils. The sample is magnetized by the field of the electromagnet. The magnetic flux forms a circuit through the magnet yoke; the sample sits in an open part of that magnetic circuit as shown in Fig. 3.



Courtesy of R. C. O'Handley. Used with permission.

Fig. 3. Schematic of a vibrating sample magnetometer in which a sample is driven orthogonal to the field of an electromagnet. A set of pickup coils attached to the faces of the pole pieces of the electromagnet detects the magnitude of the magnetic moment of the oscillating sample. (Courtesy of R. C. O'Handley).

The signal generated in the pickup coils of the VSM depends on several factors:
1. the number of turns in each coil as well as the coil orientation and geometry,
2. the amplitude and frequency of the sample vibration, and
3. the size of the magnetic moment, MV, of the sample.

Factors 1 and 2 are instrumental parameters that can be accounted for by calibration. The size of the magnetic moment depends upon the sample volume and its magnetization density, which in turn is a function of field and temperature. Hence the VSM signal depends on the state of magnetization of the sample, M, through H and T. The VSM output is a plot of M vs. H at constant temperature (which we're interested in) or M vs. T at constant field.

Reading list

1. Lectures on the Electrical Properties of Materials, L. Solymar and D. Walsh, (Cambride Univ. Press, 1988) Sections 11.4 , pages 298 - 306.
2. "Magnetic Materials", R. C. O'Handley, entry in Encyclopedia of Physical Science and Technology, Third Edition, ed. R.A. Myers (Academic Press, 2001).
3. “Modern Magnetic Materails” R. C. O’Handley, (Willey Inter-Science, 1999)

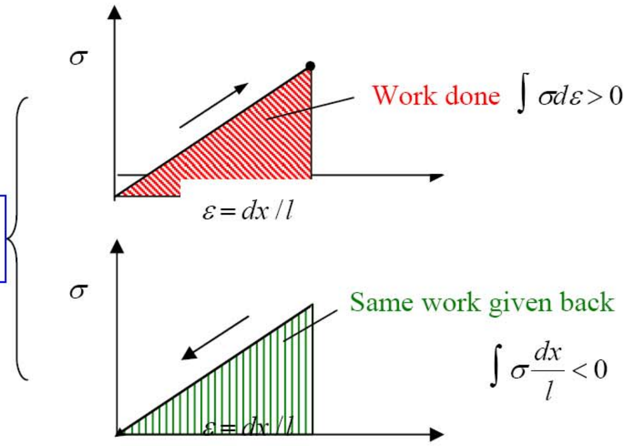
Useful concepts

Mechanical work done

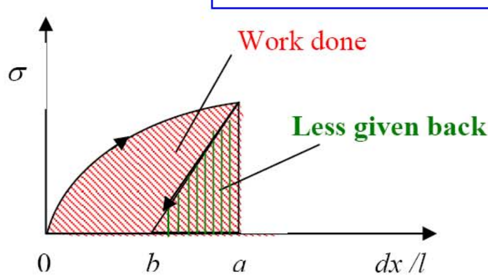
$$= \int F dx$$

$$\text{Work / vol} = \int \sigma d\varepsilon$$

Elastic behavior



Plastic behavior

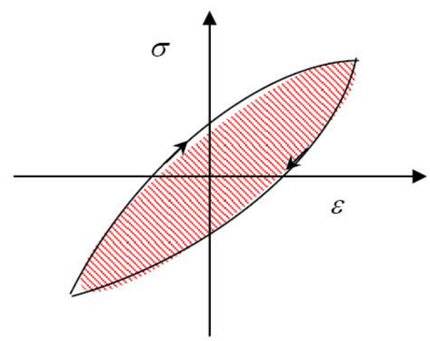


$$\text{Energy lost} = \int_0^a \sigma d\varepsilon + \underbrace{\int_a^b \sigma d\varepsilon}_{<\ 0}$$

Over a full cycle

Energy lost per cycle / vol $= \oint \sigma d\varepsilon$

= area inside loop



The convention in mechanical properties is to plot the *dependent* variable, strain, on the *x* axis. This was followed above. However, with magnetic properties, it is conventional to plot the magnetization or flux density (the dependent variable, the response to the applied field) as a function of the applied field. Keep this in mind when you compare the figures and integrals of mechanical and magnetic work.

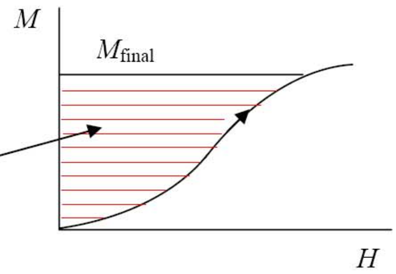
Similarly for magnetic systems

For magnetic work
change variables: $F \rightarrow \sigma \rightarrow \boldsymbol{H}$ (intensive)
$dx \rightarrow \varepsilon \rightarrow \boldsymbol{dM}$ (extensive)

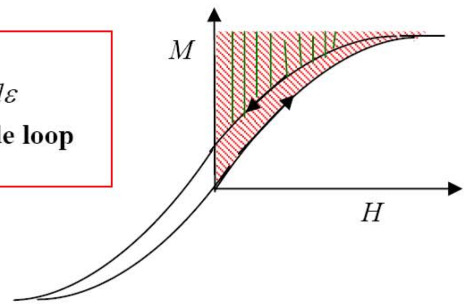
Magnetic variables:

Cgs: $B = H + 4\pi M$, $M = \chi H$, $dw = HdM$
MKS: $B = \mu_o(H + M)$, $M = \chi H$, $dw = \mu_o HdM$

$$\frac{work}{vol} = \int_0^{M_{final}} HdM$$



Over a full cycle
Energy lost per cycle / vol = $\oint \sigma d\varepsilon$
= area inside loop



The area inside the hysteresis loop is the energy per unit volume of material that is lost per cycle. This lost energy is spent mostly moving domain walls over defects; some is lost in irreversible rotation of ***M***.

The energy required to magnetize a crystal can be different along different crystal directions if the crystal symmetry is low. This is called the magnetocrystalline anisotropy. In a uniaxial material (such as hexagonal Co) the energy associated with ***M*** being saturated in different directions is given by:

$$g_{anis} = K_u \sin^2\theta.$$

The difference in energy for magnetizing along the *c* axis ($\theta = 0$) and orthogonal to the *c* axis is K_u. It is the shaded region between the two *M-H* curves. K_u is the energy expended in rotating the magnetization from its preferred direction along the *c* axis into a hard direction in the base plane.