Quantifying thermodynamic variables

Module β-3 : Work derived from magnetic hysteresis curves.

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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 different recording media, Nickel disk and ferrite magnet disk

Equipment to be used

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

Background

<u>Magnetic recording materials</u>

Magnetic materials are used very frequently to store information. They are used because the information can be written and read with relative ease, and the information saved does not require a constant supply of power while stored. The use of magnetic materials to store information is not only limited to computer applications, it is used to store information on I.D. cards (like the MIT student I.D. card) or bank account numbers on credit cards. In all these applications the information is stored in a digital format, but magnetic storage was used to store information in an analog format even before computers became common use objects, magnetic tapes were for a long time the only way for the average person to record sound.

For this lab we will look at different magnetic storage materials, and we will try to relate the magnetic properties, like the amount of work needed to magnetize the material, to the applications where the magnetic materials are used.

For these experiments we will look at a 6 mm disk from a hard disk drive plate, a disk punched out of a 5.25 inch floppy disk, a disk punched from a 3.5 inch floppy disk, a disk punched from the magnetic strip of a credit card, a disk punched put of an audio tape, for reference we will look at a disk of pure nickel and a disk form a ferrite magnet.

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 + 4πM (Gauss)	B=μ_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.

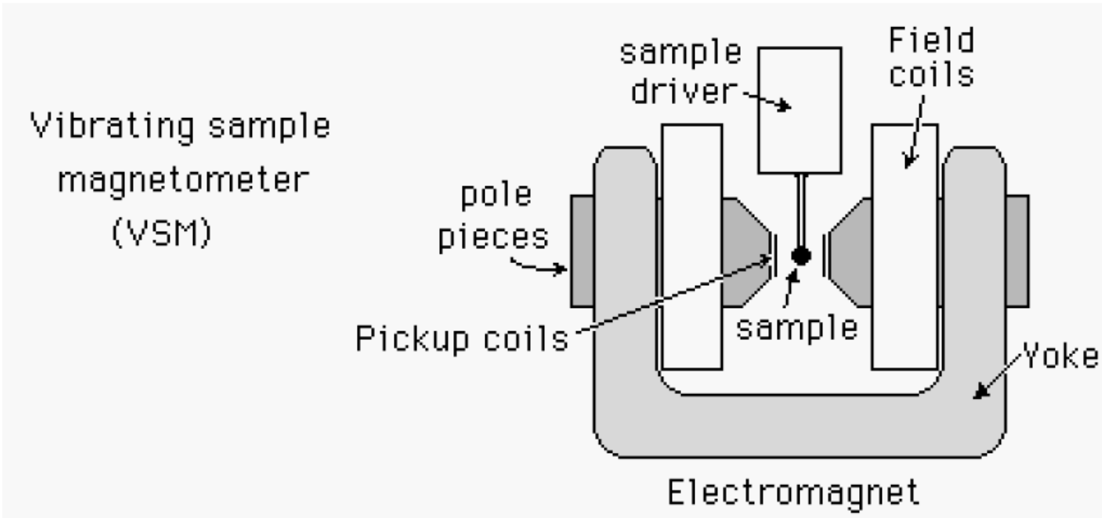


Fig. 3. Schematic of a vibrating sample magnetometer in which a sample is driven orthogonal to the field of an electromagnet. A set of pickup coils attached to the faces of the pole pieces of the electromagnet detects the magnitude of the magnetic moment of the oscillating sample. (Courtesy of R. C.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

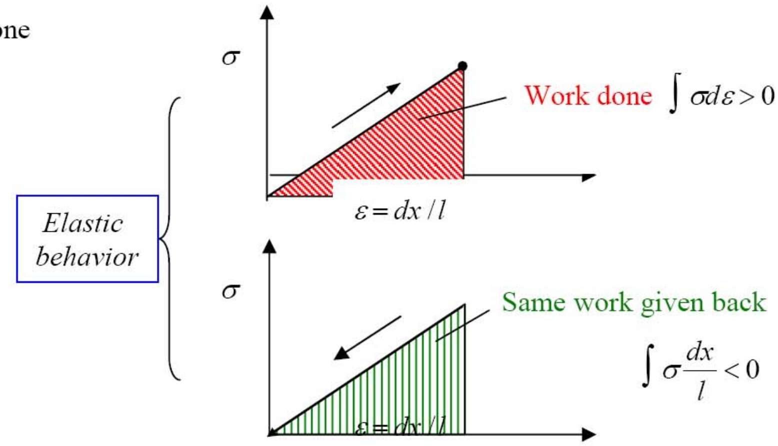
1. Lectures on the Electrical Properties of Materials, L. Solymar and D. Walsh, (Cambride Univ. Press, 1988) Sections 11.4 , pages 298 - 306.
2. "Magnetic Materials", R. C. O'Handley, entry in Encyclopedia of Physical Science and Technology, Third Edition, ed. R.A. Myers (Academic Press, 2001).
3. "Modern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

Useful concepts

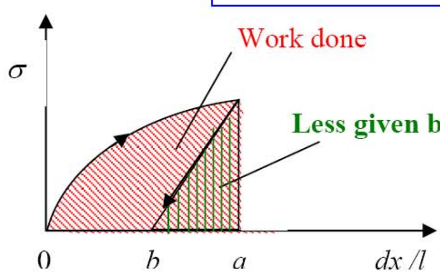
Mechanical work done

$= \int F dx$

Work / vol = $\int \sigma d\varepsilon$

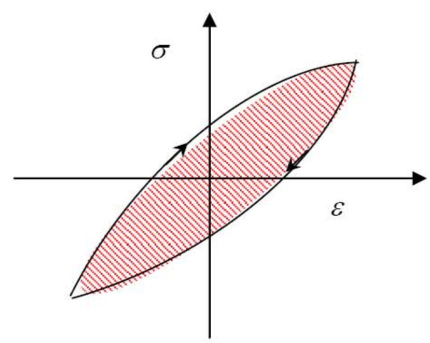


Plastic behavior



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.

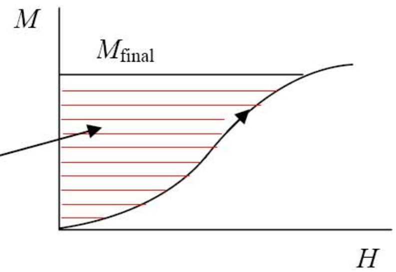
Similarly for magnetic systems

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: $B = \mu_o(H + M)$, $M = \chi H$, $dw = \mu_o HdM$

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



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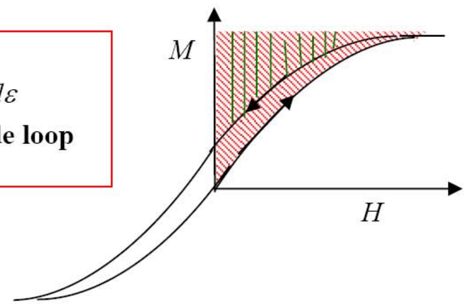

The area inside the hysteresis loop is the energy per unit volume of material that is lost per cycle. This lost energy is spent mostly moving domain walls over defects; some is lost in irreversible rotation of $\boldsymbol{M}$.

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 $\boldsymbol{M}$ being saturated in different directions is given by:

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

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.