

## Lab week 1

### Quantifying thermodynamic Properties of Materials

#### Module $\beta$ -3: Work derived from magnetic hysteresis curves

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#### Objectives:

- Understand the thermodynamics of the magnetization process (work done by field to magnetize a material) and its relation to mechanical work;
- Understand the factors that can make it harder to magnetize some magnetic materials, and how these factors compare to those that influence mechanical hardness;
- Gain an appreciation of the factors that can contribute to magnetic hysteresis.

#### Summary of tasks:

- 1) Measure the magnetization process,  $M$  vs.  $H$  curve, for an amorphous magnetic alloy to show that the integral of  $HdM$ , the area to left of  $M$ - $H$  curve, is positive on increasing field and (about) the same magnitude but negative on decreasing  $H$ .

Lessons to be learned: 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. The amorphous alloy is “*elastic*” or *conservative* in its magnetic response.

- 2) Heat-treat the amorphous material sufficiently to develop crystalline nuclei and possibly even grain boundaries that can pin domain walls. 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 for differently annealed material.

Lessons to be learned: 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

Four strips of  $\text{Co}_{83}\text{Nb}_{11}\text{B}_6$  metallic glass alloy: one strip as-cast, three annealed for 1h at 550°C, 700°C, and 850°C.

## Equipment to be used

Tube furnace and vibrating sample magnetometer (VSM).

## Background

### Amorphous magnetic alloys:

These unique materials have an atomic structure similar to that of the liquid state. That structure is retained at room temperature by rapidly quenching the alloy from its liquid state. The quench rate, of order  $10 \text{ Ks}^{-1}$ , has to be faster than the crystallization kinetics so that the structure of the liquid is essentially frozen into the room temperature solid. When the amorphous state is achieved, the alloy has a structure with no long-range atomic order; it is free from grains, grain boundaries, and segregation, and it is usually metastable (crystalline phases generally have lower *free energy* than liquid or amorphous phases at room temperature, but they are inaccessible, kinetically inhibited from transforming).

Amorphous metals are most often made near eutectic compositions. Heating a multi-component amorphous material can result in the nucleation and growth of one or more phases in the amorphous matrix. The crystalline phases are often the stable phases that bound the eutectic region of the phase diagram (or metastable ones not seen on the equilibrium phase diagram). The nucleation and growth rates of crystallites depend on the crystallization temperature, the composition of the phases nucleating and the diffusion kinetics.

### Magnetic materials

Magnetic materials derive their importance and usefulness from the fact that they have a property called the *magnetization*,  $\mathbf{M} = N\boldsymbol{\mu}_m / V$ , i.e.  $\mathbf{M}$  is the volume density of atomic magnetic moments,  $\boldsymbol{\mu}_m$ . The magnetization can be changed by application of a magnetic field,  $\mathbf{H}$ . Applying a field tends to line up the magnetization with the field. The sum of the magnetization and the  $\mathbf{H}$  field defines the flux density,  $\mathbf{B}$ :  $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$  (MKS) or  $\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$  (cgs). Table 1 gives some of the units used in magnetism.

<b>Units:</b>	<b>cgs</b>		<b>SI (MKS)</b>	
Magnetic field:	<b>H</b>	(Oersted)	<b>H</b>	(Amperes /m)
Magnetic response:	<b>M</b>	(emu/cm <sup>3</sup> )	<b>M</b>	(Amperes /m)
	or $4\pi\mathbf{M}$	(Gauss)	$\mu_0\mathbf{M}$	(Tesla)
Total flux density:	<b>B = H + 4πM</b> (Gauss)		<b>B=μ<sub>0</sub>(H + M)</b> (Tesla)	

**Table 1.** Some of the units used in magnetism for cgs and SI (MKS) systems.

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, and most of them make use of Faraday's law of induction:

$$\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \oint \mathbf{B} \cdot d\mathbf{A} = -\frac{\partial \phi}{\partial t} \quad (1)$$

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

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**Figure 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.

The *flux density* or *magnetic induction* inside a sample depends on the applied field and the sample magnetization,  $\mathbf{B} = \frac{\Phi}{A} = \mu_0(\mathbf{H} + \mathbf{M})$ . Outside the sample ( $\mathbf{M} = 0$ ) the induction,  $\mathbf{B} = \mu_0\mathbf{H}$ , comes from the applied field and the  $\mathbf{H}$  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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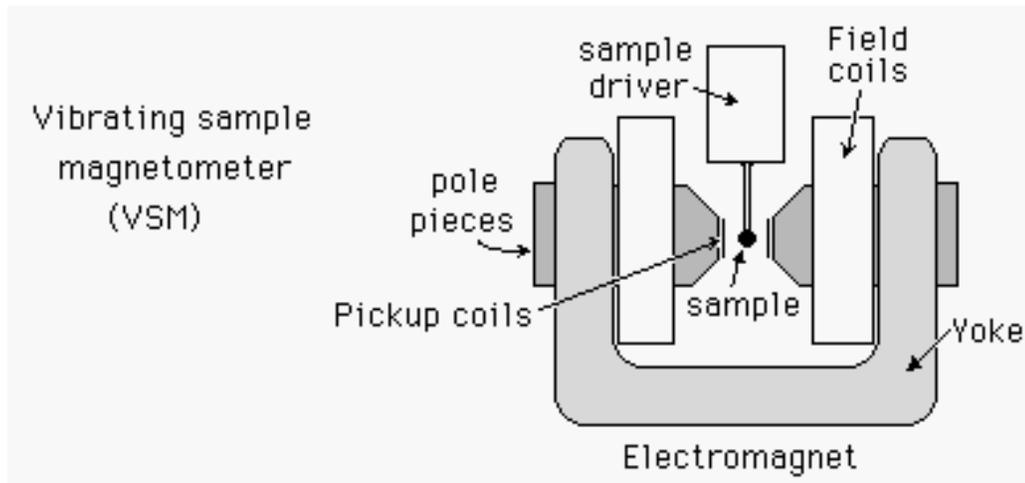
**Figure 2.** Direction of magnetic  $B$  field about a current-carrying solenoid is given by the right-hand rule.

We will use a *vibrating sample magnetometer* in which a sample is vibrated ( $\pm 1$  mm at about 88 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.

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 or  $M$  vs.  $T$  at constant field.



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**Figure 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.

### Reading list

1. *Lectures on the Electrical Properties of Materials*, L. Solymar and D. Walsh, (Cambridge 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. "Magnetic and Electronic Properties of Rapidly Quenched Metals" R. C. O'Handley and H. H. Liebermann, , *Elements of Rapid Solidification: Fundamentals and Applications*, ed. M.A. Otooni (Springer Series in Materials Science, Springer-Verlag, Berlin, 1998), pages 153 - 157, 163 - 165.
4. "Crystallization of Metallic Glasses", U. Koster and U. Herold, in *Glassy Metals*, Vol. I, (ed. H. J. Guntherodt, H. Beck, Springer Verlag, Berlin, 1981 ), pages 225 - 231, and 244 - 248.
5. "Magnetization process in devitrified glassy alloy", R. C. O'Handley, J. Megusar, S-W Sun, Y. Hara, and N. J. Grant, *J. Appl. Phys.* **57**, 3563 (1985).

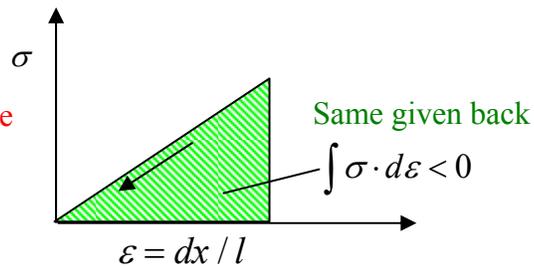
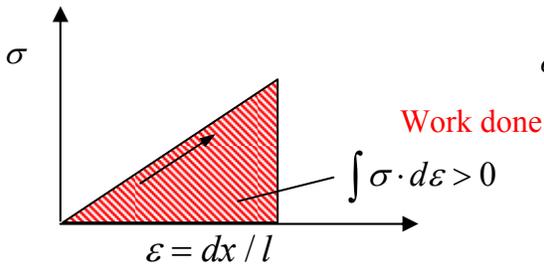
## Useful concepts

Mechanical work,  $W$ :

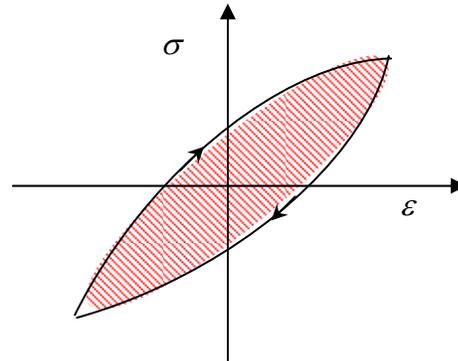
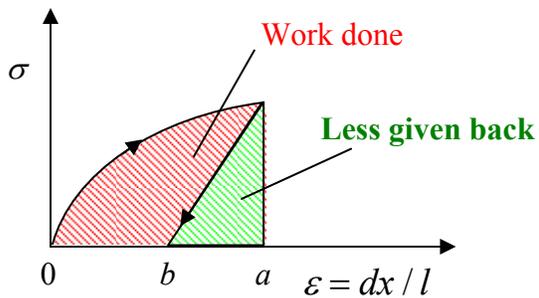
$$W = \int \mathbf{F} \cdot d\mathbf{x}$$

$$W/V = \int \sigma \cdot d\varepsilon$$

*Elastic behavior*



*Plastic behavior*



Energy lost =  $\int_0^a \sigma d\varepsilon + \int_a^b \sigma d\varepsilon$

$< 0$

Over a full cycle:  
 Energy lost per cycle / V =  $\oint \sigma d\varepsilon$   
 = 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**

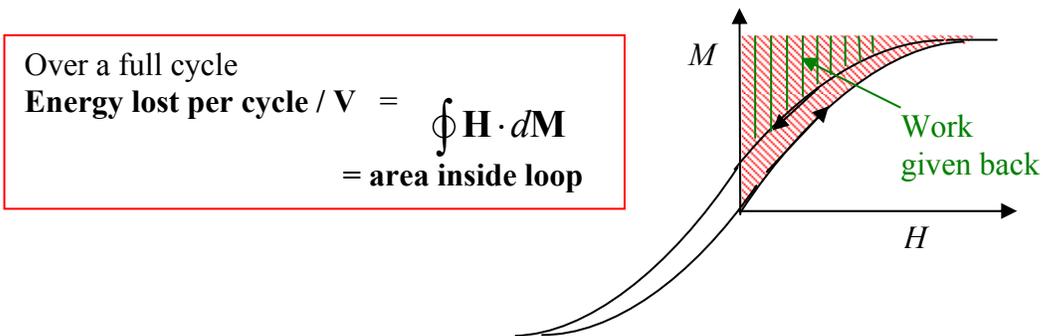
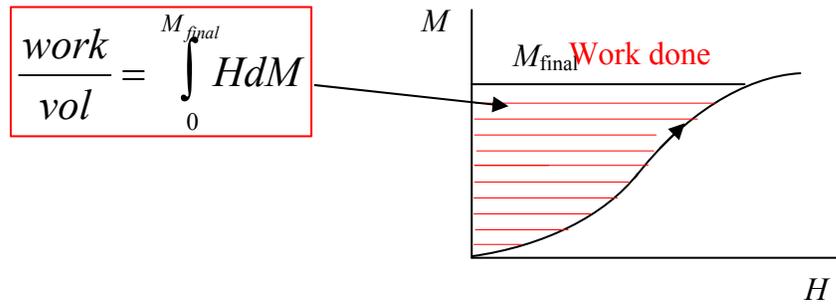
For magnetic work change variables:

$$F \rightarrow \sigma \rightarrow \mathbf{H} \quad (\text{intensive})$$

$$dx \rightarrow \varepsilon \rightarrow d\mathbf{M} \quad (\text{extensive})$$

**Magnetic variables:**

cgs:  $\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$ ,  $\mathbf{M} = \chi\mathbf{H}$ ,  $dw = \mathbf{H}d\mathbf{M}$   
 MKS:  $\mathbf{B} = \mu_o(\mathbf{H} + \mathbf{M})$ ,  $\mathbf{M} = \chi\mathbf{H}$ ,  $dw = \mu_o\mathbf{H}d\mathbf{M}$

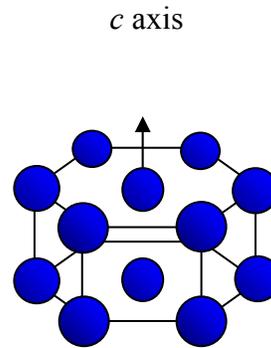
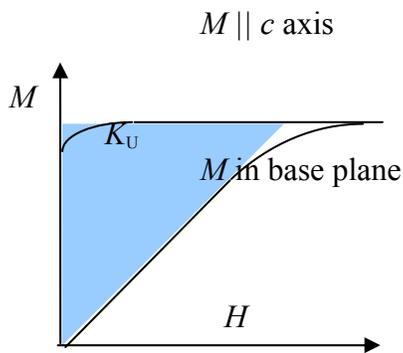


The area inside the hysteresis loop is the energy per unit volume of material that is lost per cycle. This lost energy is spent mostly moving domain walls over defects; some is lost in irreversible rotation of  $\mathbf{M}$ .

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  $\mathbf{M}$  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.



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