Information from magnetisation curves

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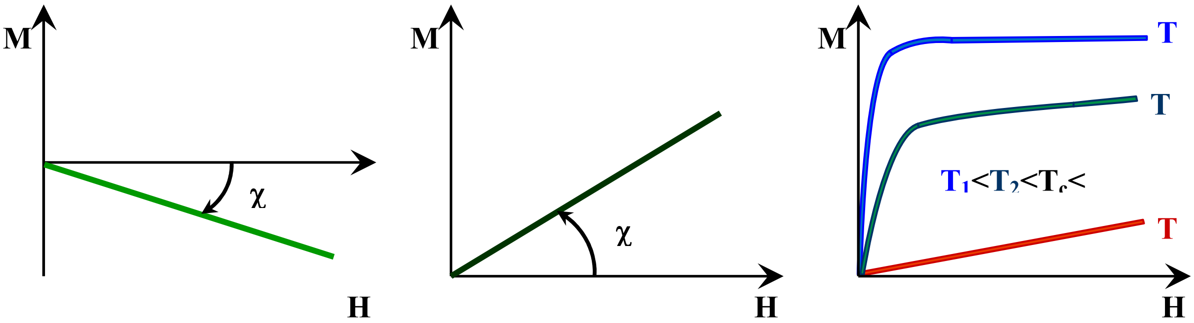
The observation and the study of magnetic properties of substances and materials have been a subject of interest since the early days of human civilisation. Nowadays they aroused a huge interest from both fundamental and application point of view. The starting point in the study of magnetic materials can either be the theoretical speculations or the experimental measurements such as: magnetic curves, magnetic susceptibility, neutron diffraction, electron microscopy, spectroscopic studies, magneto-optic measurements, etc. The magnetic curves obtained in different types of magnetic materials, figure 1, represent one of the most used and convenient methods of characterisation in magnetic studies.



(a (b (c

Figure 1. a) diamagnetic materials, b) paramagnetic materials, c) magnetically ordered (ferromagnetic or ferrimagnetic) materials.

We will present some of the scientific information which can be obtained from the study of magnetic curves. In the case of diamagnetic and paramagnetic materials, from the relation (1), the magnetic susceptibility, χ, can be obtained directly from the magnetisation curves, shown in figure 1.

$$\chi = \frac{M}{H} \tag{1}$$

where M is the magnetisation and H is the intensity of the magnetic field.

In the case of paramagnetic materials, the Curie constant, C, can be obtained from the temperature dependence of the magnetic susceptibility, relations (2). By using (3) it is possible to determine the kinetic moment of the magnetic atoms.

$$\chi = \frac{C}{T} \tag{2}$$

$$C = \frac{N\mu_0}{3k_B} g^2 \mu_B^2 J(J+1) = \frac{N\mu_0}{3k_B} \mu e f^{\,2} \tag{3}$$

where N is the number of magnetic atoms per volume unit, μ_0 is the vacuum permeability, g is known as the Lande factor, μ_B is the Bohr magneton, k_B is the Boltzmann constant and by μ_{eff} we denote the effective magnetic moment.

For ferromagnetic or ferrimagnetic materials, at temperatures smaller than the Curie temperature, T_c, the magnetic curves (figure 2) give information about the following: initial susceptibility χ_i, maximum susceptibility χ_m, field independent susceptibility χ_0, spontaneous magnetisation M_s, saturation field H_{st} and saturation magnetisation M_{st}.

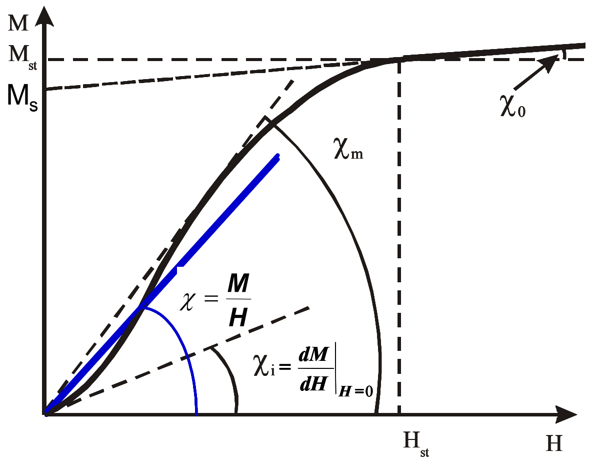


Figure 2 Magnetisation curve.

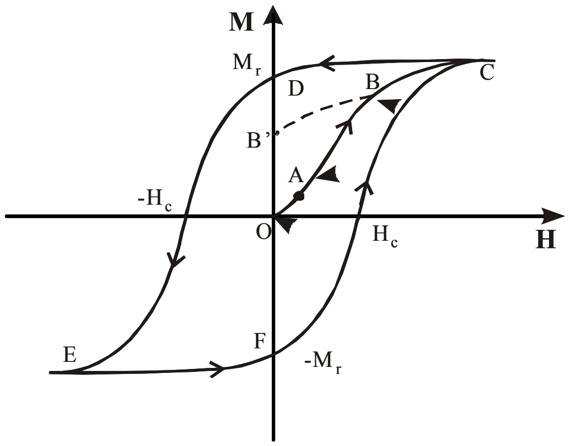


Figure 3. Hysteresis curve

As in the paramagnetic case, from the Curie Weiss (ferromagnetism) or the Néel type (ferrimagnetism) behaviours of magnetic susceptibility vs. temperature at T>Tc, we can obtain the effective magnetic moment and the kinetic moment of magnetic atoms, [1-8]. The remanence and coercivity can be studied from hysteresis curves, figure 3. Notice that the surface of the hysteresis loop is a measure of the magnetic energy stocked in to the hard magnetic materials or a measure of the hysteresis losses in soft magnetic materials.

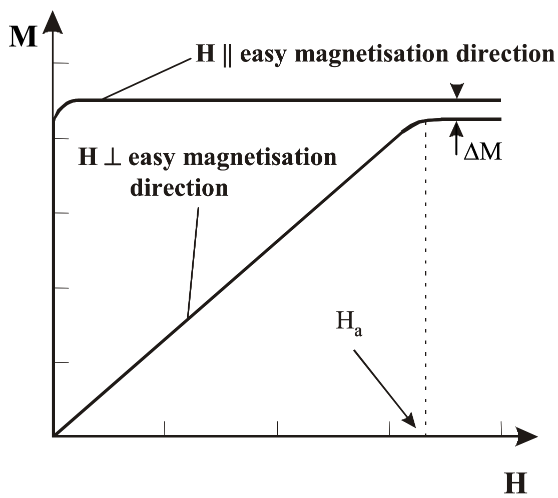
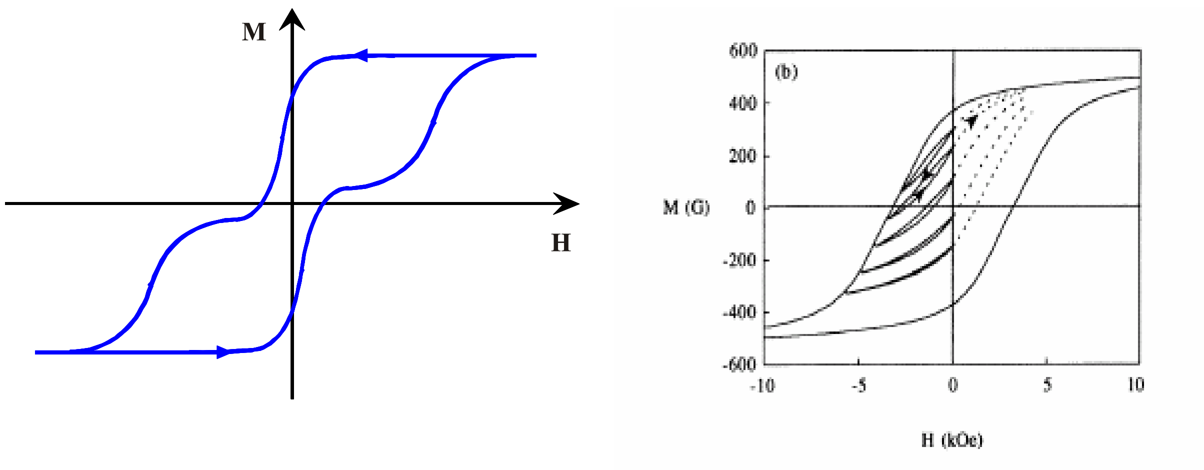


Figure 4. Magnetisation curves in single crystals

In addition to χ_i, χ_m, χ_0, M_s, H_{st} and M_{st}, the first magnetisation curve, curve OABC in figure 3, gives information concerning the magnetisation processes: pinning or nucleation. Magnetisation curves measured in single crystals, figure 4, give information about the anisotropy: easy axis of magnetisation, anisotropy field, magnetic anisotropy, etc. The metamagnetic transitions can also be well evidenced in magnetisation curves [4]. Magnetisation curves are a very useful instrument of research in the domain of spring-type magnetic materials. The form of the magnetisation and demagnetisation curves contains information about the efficiency of the interphase exchange interactions. For this purpose, the reversibility curves can be used in tandem with the hysteresis curves, figure 5.



(a) (b)

Figure 5. **(a)** Major hysteresis loop for non coupled magnetic phases and **(b)** major hysteresis loop with a selection of minor re-magnetization curves (broken lines) and recoil loops for well coupled two-phase $Sm_2Fe_{14}Ga_3C_2$/40vol% -Fe [9].

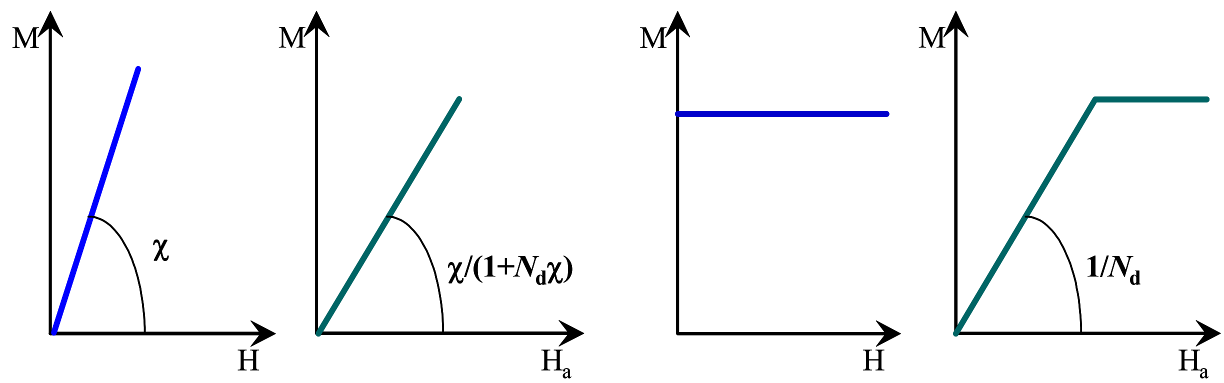
Tacking into account the demagnetisation field, $H_d = - N_d M$ (N_d is the demagnetisation coefficient and M the magnetisation), the internal magnetic field in the measured sample is

$$\vec{H} = \vec{H}_a + \vec{H}_d \quad (4)$$

and

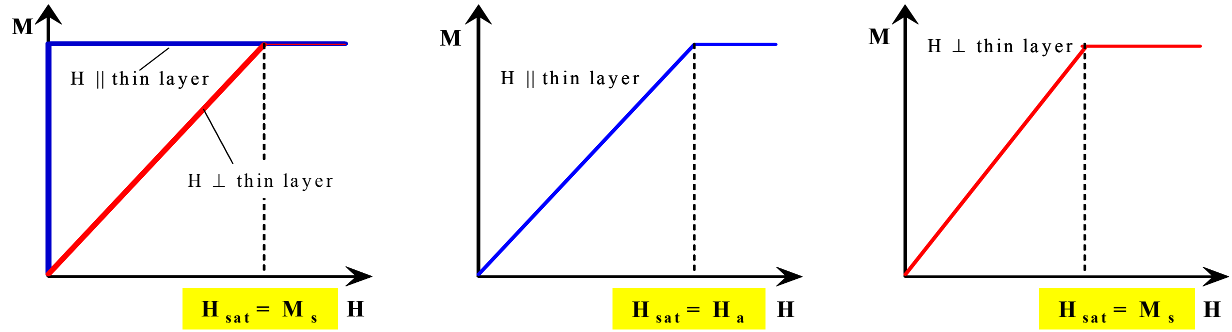
$$M = \chi \cdot H = \frac{\chi}{1 + N_d \chi} H_a \quad (5)$$

consequently, if $N_d \neq 0$, we have a smaller slope if we represent M vs. extern field, Ha, figure 6. This slope $\chi/(1+N_d\chi)$ is named external susceptibility [4]. Based on this fact the computation of



(a) (b)

Figure 6. Magnetisation curves vs. external field H_a and internal field H for: **(a)** samples with a finite susceptibility and **(b)** samples with an infinite susceptibility (ideal ferromagnet) [4].



(a) **(b)** **(c)**

Figure 7. Typical magnetic curves in thin layers: **a)** M_s calculation in samples without magnetocrystalline anisotropy, **b)** and **c)** calculation of H_a and M_s respectively in samples with perpendicular magnetocrystalline anisotropy.

the spontaneous magnetisation and of the anisotropy field in thin magnetic layers is shown in figure 7.

The paramagnetic or diamagnetic susceptibility in samples, with ferromagnetic impurities of concentration c and spontaneous magnetisation M_s, can be computed by the Honda-Oven plot, figure 8. The Arrott plot, figure 9, allows the evaluation of the Curie temperature in ferromagnetic or ferrimagnetic samples. The extended lecture to the school will develope~~d~~ the above examples and will ~~be~~ also take~~n~~ into account other illustrations.

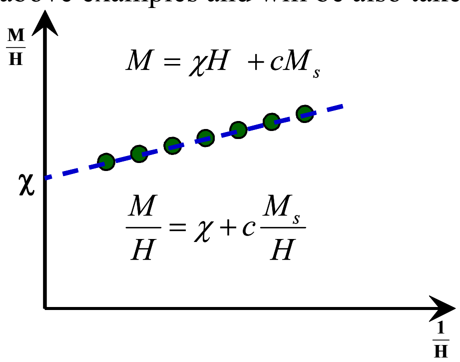


Figure 8. Honda Owen plot.

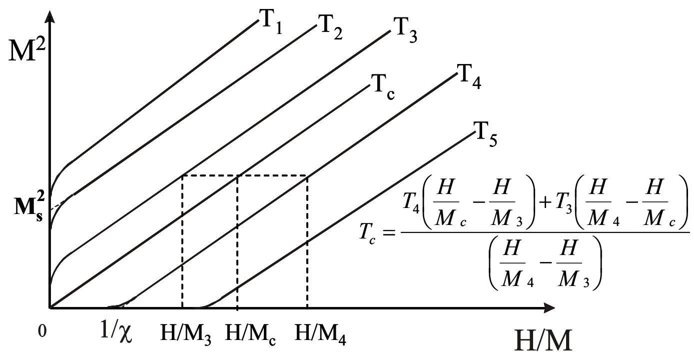


Figure 9. Arrott plot.

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