Nanomagnetism
Part 4 — Learn from loops

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Part IV: LEARN FROM LOOPS — Table of contents

- Extract loop and moments
- Extract magnetic anisotropy
- Extract interactions and distributions
- Understand magnetization processes
- Analyse thermal effects
Part IV: LEARN FROM LOOPS — Hysteresis loops

Manipulation of magnetic materials:
- Application of a magnetic field

Zeeman energy: \( E_Z = -\mu_0 H \cdot M \)

Spontaneous magnetization ≠ Saturation

Spontaneous magnetization

Remanent magnetization

Coercive field

Losses \( W = \mu_0 \oint (H \cdot dM) \)

Magnetic induction \( B = \mu_0 (H + M) \)

Other notation \( J = \mu_0 M \)
Part IV: LEARN FROM LOOPS — Extract moments, extrinsic effects (diamagnetism)

Diamagnetic substrate / holder

\[ M(H) \leftarrow M(H) - \chi H \]

Problems:

- Quantitative compensation a priori difficult
- Approach to saturation difficult to investigate
Part IV: LEARN FROM LOOPS — Extract moments, extrinsic effects (diamagnetism)
Paramagnetic substrate / holder

Example:

- 1nm ferro layer
- 1ppm in 1mm support

\[ M(H) \leftarrow M(H) - \chi(T)H \]

Example: ions impurities in metals, and oxides

Problem: temperature dependent, non-linear
Part IV: LEARN FROM LOOPS — Extract moments, impurities and artifacts

Paramagnetic substrate / holder

Be careful with: cleanliness, tweezers, holders, ink, etc.

Artifacts in various techniques

- X-ray Magnetic Circular Dichroism (XMCD)
- Magneto-Optical Kerr Effect (MOKE)
- Lorentz microscopy
- Etc.

Magnetism of cigarette ashes

Neli Jordanova\textsuperscript{a, *}, Diana Jordanova\textsuperscript{a}, Bernard Henry\textsuperscript{b}, Maxime Le Goff\textsuperscript{b}, Dimo Dimov\textsuperscript{c}, Tsenka Tsacheva\textsuperscript{d}

Available online at www.sciencedirect.com


www.elsevier.com/locate/jmmm
Case of a bulk soft magnetic material

Hypotheses:

1. Use an ellipsoid, cylinder or slab along a main direction so that the demagnetizing field may be homogeneous.

2. Domains can be created to yield a uniform and effective magnetization $M_{\text{eff}}$

Density of energy:

$$E_{\text{tot}} = E_d + E_z$$

$$E_{\text{tot}} = \frac{1}{2} \mu_0 N M_{\text{eff}}^2 - \mu_0 M_{\text{eff}} H_{\text{ext}}$$

Minimization:

$$\frac{\partial E_{\text{tot}}}{\partial M_{\text{eff}}} = \mu_0 N M_{\text{eff}} - \mu_0 H_{\text{ext}}$$

Conclusion for soft magnetic materials

$\Rightarrow$ Susceptibility is constant and equal to $1/N$
Case of an arbitrary material

1. Measure a hysteresis loop $M_1(H_{\text{appl}})$

2. Internal field during loop: $H_d = -N_i \cdot M_1$
   (must be corrected to access intrinsic properties)

3. Plot $M_1(H_{\text{appl}}-N_i M_1)$
   $\Rightarrow M_2(H_{\text{tot}})$

Internal fields must be compensated
Specific aspects to systems with non-ellipsoidal shapes

In a non-ellipsoidal (or cylindrical, slab) system the demagnetizing field is not homogeneous in magnitude nor direction.

1. Initial slope higher than 1/N (demag field smaller than average)
2. Late slope smaller than 1/N (demag field larger than average)

Demagnetizing energy (thus area above loop) is identical:

\[ E_d = \int_0^{M_s} \mu_0 H_{\text{ext}} dM = \frac{1}{2} \mu_0 N M_s^2 \]

In a non-ellipsoidal sample (or cylinder, slab) the loop is overcompensated at low magnetization and undercompensated at high field, even for soft magnetic materials.

This effect adds up to the previous effect of grain shape.

Part IV: LEARN FROM LOOPS — Table of contents

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Magnetization loop of a macrospin along a hard axis

\[ e = \sin^2(\theta) - 2h\cos(\theta - \theta_H) \]

Dipolar energy:

\[ H = hH_a \]
\[ H_a = 2K / \mu_0M_s \]
\[ K = N_iK_d \]

Hard axis:

\[ \theta_H = \pi / 2 \]

\[ e = \sin^2(\theta) - 2h\sin(\theta) \]

\[ \frac{\partial e}{\partial \theta} = 2\cos\theta(\sin\theta - h) \]

Equilibrium position

\[ h = \sin\theta = \cos(\theta - \theta_H) = m.u_h \]
Part IV: LEARN FROM LOOPS — Arbitrary anisotropy

**Loops**

\[ E_{mc} = K_1 \sin^2 \theta + K_2 \sin^4 \theta + \ldots \]

- \( K_1 > 0 \)
- \( K_2 = 0 \)
- \( K_2 > 0 \)
- \( K_2 < 0 \)

**Means of analysis**

- **Fit curve** \( H(M) \) (is analytical)
- **Initial susceptibility + saturation or area above curve as**

\[ E_{sat} - E_0 = \mu_0 \oint (H \cdot dM) \]

Uniaxial | Biaxial
Part IV: LEARN FROM LOOPS — Anisotropy, some complications

Distribution

- Use area above curve
- Singular point detection for saturation field


Residual hysteresis

- Compute anhysteretic curve \( M(H) \to \left[ M(H_{up}) + M(H_{down}) \right]/2 \)
Part IV: LEARN FROM LOOPS — High order angular anisotropy

**Issue**

- High remanence in all directions
- Fit over small part of loop → sensitive to imperfections
- Solution: loop under transverse bias field

**Solution**

TBIIST: Transverse Bias Initial Inverse Susceptibility and Torque

Part IV: LEARN FROM LOOPS – Configuration anisotropy

Part IV: LEARN FROM LOOPS — Table of contents

- Extract loop and moments
- Extract magnetic anisotropy
- **Extract interactions and distributions**
- Understand magnetization processes
- Analyse thermal effects
Different loops with distribution

Superposition

Possible effects that may arise

- Distribution of coercive fields
- (Dipolar) interactions
- The loops of the macrospins are slanted
Textbook case

- Uniaxial anisotropy, second order: \( E_{mc} = K \sin^2 \theta \)
- Fully remanent grains

3D distribution

- Remanence: \( m_r^{3D} = 1/2 \)
- Measured anisotropy: \( \langle K^{3D} \rangle = 2K/3 \)

2D distribution

- Remanence: \( m_r^{3D} = 2/\pi \)
- Measured anisotropy: \( \langle K^{3D} \rangle = K/2 \)

Use

- Distribution: estimate \( K \)
- Interactions: impact on increased or decreased remanence
Part IV: LEARN FROM LOOPS — Interactions and distributions: reversible versus irreversible

Distribution of properties

\[ \rho(H_r) = \frac{dm}{dH} \mid_{\text{irreversible}} \]

Hc(T) for a given population of the distribution can be studied at a given stage of the reversal (10\%, 20\% etc.)

Effect of distributions and dipolar interactions are sometimes difficult to disentangle
Part IV: LEARN FROM LOOPS — Interactions and distributions: reversible versus irreversible

**Reconstruct average single hysteresis loop**

- **Ultrathin Fe(110) dots**
- **Arrays of electroplated parallel Ni nanowires**
- **Exchange-spring magnets**

**Susceptibility or distribution?**

- **S. Da-Col et al., Appl. Phys. Lett. 98, 112501 (2011)**

**Scrubiniz multiphased materials**

- Hard
- Soft

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Olivier Fruchart — IEEE Magnetics 7th School — Rio, Aug 2014 — p.IV-22

http://perso.neel.cnrs.fr/olivier.fruchart/slides
Part IV: LEARN FROM LOOPS — Interactions and distributions, minor loops

**Minor loops: negative interactions**

Example: dipolar interactions in arrays of Co/Au(111) pillars

-15 mT

-185 mT

**Minor loops: negligible interactions**

-17 mT

-50 mT

uyên faster than Henkel and Preisach

Other applications: characterization of exchange bias

O. Fruchart et al., unpublished
Fig. 1. Explanation of how to measure the two different remanent magnetisations $M_r$ and $M_d$.

Measure of dipolar interactions

$$\Delta M_H(x) = M_d(x) - [1 - 2M_r(x)]$$

- The analysis of interactions on qualitative
- Long experiments (ac demagnetization)
Part IV: LEARN FROM LOOPS — Interactions and distributions: Preisach model and FORC

**Preisach model**


- Distribution function
  \[ \mu(\alpha, \beta) \text{ with } \alpha > \beta \]
- No true link between real particles and \( \mu \)

**Solving**

\[ \mu(\alpha', \beta') = \frac{1}{2} \frac{\partial^2 f_{\alpha', \beta'}}{\partial \alpha' \partial \beta'} \]

- Long experiments (1D set of hysteresis curves)
- Better suited to bulk materials with strong interactions
Recent 'rediscovery' or 're-interpretation' : the FORc diagrams:

First-Order Reversal Curves

→ Outline distribution of switching field and bias field


Ex : arrays of parallel permalloy nanowires wire increasing diameter

M. S. Salem et al., J. Mater. Chem. 22, 8549 (2012)
Part IV: LEARN FROM LOOPS — Table of contents

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Use first-magnetization curves to determine the type of coercivity

Part IV: LEARN FROM LOOPS – Initial magnetization curve

- Nucleation-limited
  - Ex: Sm$_2$Co$_{17}$

- Propagation-limited
  - Ex: SmCo$_5$
Part IV: LEARN FROM LOOPS — Angular dependence of coercivity

Max($H_c$) for easy axis $\rightarrow$ nucleation

Ultrathin uniaxial Fe(110) dots

$1/cos\theta$ law $\rightarrow$ propagation

E. J. Kondorsky, J. Exp. Theor. Fiz. 10, 420 (1940)

Hypothesis:

$\Rightarrow$ Based on nucleation volume

$\Rightarrow$ $H_c \ll H_a$

Energy barrier $E_0$

overcome by gain in Zeeman energy plus thermal energy

$$E_0 = -\mu_0 M_s v_a H \cos(\theta_H) + 25k_B T$$


D. Givord et al., JMMM 72, 247 (1988)
Part IV: LEARN FROM LOOPS — Table of contents

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Part IV: LEARN FROM LOOPS — Temperature and time dependence

Activation volume

Also called: nucleation volume

Can be used for:

- Estimating $H_c(T)$
- Estimating long-time relaxation
- Determination of dimensionality

Note: of the order of domain wall width $\delta$

More detailed models:

### Thermal activation

\[ \tau = \tau_0 \exp \left( \frac{\Delta \varepsilon}{k_B T} \right) \]

\[ \Delta \varepsilon = k_B T \ln (\tau/\tau_0) \]

\[ \tau_0 \approx 10^{-10} \text{ s} \]

Lab measurement: \( \tau \approx 1 \text{ s} \) \( \Rightarrow \Delta \varepsilon \approx 25k_B T \)

\[ H_c = \frac{2K}{\mu_0 M_S} \left( 1 - \sqrt{\frac{25k_B T}{KV}} \right) \]

### Notice, for magnetic recording:

\[ \tau \approx 10^9 \text{ s} \]

\[ KV_b \approx 40 - 60k_B T \]
Part IV: LEARN FROM LOOPS — Superparamagnetism, extract volume

**Formalism**

<table>
<thead>
<tr>
<th>Energy</th>
<th>Partition function</th>
<th>Average moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E = KV \cdot f(\theta, \phi) - \mu_0 H )</td>
<td>( Z = \sum \exp(-\beta E) )</td>
<td>( \langle \mu \rangle = \frac{1}{\beta \mu_0 Z} \frac{\partial Z}{\partial H} )</td>
</tr>
</tbody>
</table>

**Isotropic case**

\[
Z = \int_{-\infty}^{\infty} \exp(-\beta E) d\mu
\]

Note: equivalent to integration over solid angle

\[
\langle \mu \rangle = M [\text{cotanh}(x) - 1/x]
\]

**Infinite anisotropy**

\[
Z = \exp(\beta \mu_0 MH) + \exp(-\beta \mu_0 MH)
\]

\[
\langle \mu \rangle = M \text{tanh}(x)
\]

Brillouin \( \frac{1}{2} \) function

**Note:**

Use the moment \( M \) of the particule, not spin \( \frac{1}{2} \).

\( x = \beta \mu_0 MH \)