Quantitative FORC Analysis: Mean Field Theory and Local Cluster Corrections

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Magnetizing Arrays - Ridge

\[ H_{\text{tot}} = H + \alpha M(H) \quad \alpha > 0 \]

\[ P(H_K^{\text{min}}) \text{ unmatched (min)} \]

\[ H_{dn}^{\text{min}} = -H_K^{\text{min}} - \alpha M_S \]

\[ H_{up}^{\text{min}} = H_K^{\text{min}} - \alpha M_S \]

Low \( H_C \) end shifted by

\[ \Delta H_B = \alpha M_S \quad \Delta H_C = 0 \]

\[ P(H_K^{\text{max}}) \text{ unmatched (max)} \]

\[ H_{dn}^{\text{max}} = -H_K^{\text{max}} + \alpha M_S \]

\[ H_{up}^{\text{max}} = H_K^{\text{max}} - \alpha M_S \]

High \( H_C \) end shifted by

\[ \Delta H_B = 0 \quad \Delta H_C = \alpha M_S \]
Magnetizing Arrays - Ridge

**Ridge:** unmatched last flip

1. Min $H_K$ end shift $H_B<0$
2. Max $H_K$ end stay $H_B=0$
3. Ridge length decreases
4. Edge ?
5. Negative feature
Magnetizing Arrays - Edge

Edge:

\[ H_{\text{tot}} = H + \alpha M(H) \quad \alpha > 0 \]

\( P(H_{k_{\text{min}}}^\text{up}) \) unmatched (3-4)

**top:**

\[ H = H_{k_{\text{min}}}^\text{min} - \alpha M_S, \quad H_{R} = -H_{k_{\text{min}}}^\text{min} - \alpha M_S \]

**bottom**

\[ H = H_{k_{\text{min}}}^\text{min} + \alpha M_S, \quad H_{R} = -H_{k_{\text{max}}}^\text{max} + \alpha M_S \]

**top:**

\[ H_{C} = H_{k_{\text{min}}}^\text{min}, \quad H_{B} = -\alpha M_S \]

**bottom:**

\[ H_{C} = (H_{k_{\text{min}}}^\text{min} + H_{k_{\text{max}}}^\text{max})/2, \quad H_{B} = \alpha M_S + (H_{k_{\text{min}}}^\text{min} - H_{k_{\text{max}}}^\text{max})/2 \]
**Magnetizing Arrays - Edge**

Edge: unmatched first flip
1. Min $H_K$ end shift $H_B < 0$
2. Max $H_K$ end stay $H_B = 0$
3. Ridge length decreases
4. Edge: no positive edge
5. Edge already generates bent-in negative feature
   (low $H_K$ region)

Fig. 3, Gilbert et al.
Experimentally, the ridge is segmented:
Account for it by including nearest neighbor non-mean field terms

Three primary peaks, three secondary peaks
Beyond Mean Field – Demagnetizing Arrays
Nearest Neighbor Interaction

From left to right columns, simulated family of FORCs, FORC distributions and DC demagnetized remnant states are shown for systems with (a-c) nearest neighbor (n.n.) demagnetizing; (d-f) mean field (m.f.) demagnetizing; (g-i) combined (m.f.+n.n.) demagnetizing; (j-l) n.n. magnetizing; (m-o) combined (m.f.+n.n.) magnetizing interactions.
Beyond Mean Field – Demagnetizing Arrays
Nearest Neighbor Interaction

(D1) positive saturation $\rightarrow$ checkerboard ($\uparrow \uparrow \uparrow \rightarrow \uparrow \downarrow \uparrow : H_{int}=2H_{n.n.}$)

(D2) checkerboard $\rightarrow$ negative saturation ($\downarrow \uparrow \downarrow \rightarrow \downarrow \downarrow \downarrow : H_{int}=-2H_{n.n.}$)

(D3) frust. checkerboard $\rightarrow$ frust. checkerboard ($\downarrow \uparrow \uparrow \rightarrow \downarrow \downarrow \uparrow : H_{int}=0$)

(U1) checkerboard $\rightarrow$ positive saturation ($\uparrow \downarrow \uparrow \rightarrow \uparrow \uparrow \uparrow : H_{int}=2H_{n.n.}$),

(U2) negative saturation $\rightarrow$ checkerboard ($\downarrow \downarrow \downarrow \rightarrow \downarrow \uparrow \downarrow : H_{int}=-2H_{n.n.}$)

(U3) frust. checkerboard $\rightarrow$ frust. checkerboard ($\downarrow \downarrow \uparrow \rightarrow \downarrow \uparrow \uparrow : H_{int}=0$)

peak P1 at $(H_C=H_K, H_B=+2H_{n.n.})$: FORC with the D1 and U1 flips

peak P2 at $(H_C=H_K, H_B=-2H_{n.n.})$: FORC with the D2 and U2 flips

peak P3 at $(H_C=H_K+2H_{n.n.}, H_B=0)$: FORC with the D2 and U1 flips

Peaks strong: flips through energetically favored intermediate state

P1/P2: flips from saturation into checkerboard - demagnetizing interactions

P3: flip from checkerboard into saturation
Experimentally, the ridge is not segmented:
Even when nearest neighbor terms are included:
No energy minimizing intermediate state:
The flipping dipole further destabilizes other dipoles: avalanche
Simulations vs. Experiment: Mean Field plus Nearest Neighbor

Using known material parameters, mean field + nearest neighbor calculation quantitatively reproduced
- experimental FORC
- interaction fields
Mean Field FORC for Hard Soft Composites

Two dipole arrays
Different coercivity distributions
Coupled by:
- they both experience total mean field
- coupled by nearest neighbor interaction $H_{ex}$