Why is the initial magnetization of a FM zero?
Because of the formation of domains - small regions in which all the magnetic dipoles are aligned parallel to each other. In the demagnetized state, the total magnetization averages to zero.

Why do domains form?
To minimize the total magnetic energy

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Single domain
- minimum exchange energy
- large magnetostatic energy
(Magnetization creates an external field which wants to demagnetize the block! 
\* it's called the demagnetizing field)

Divide block into domains
\* lower magnetostatic energy but increased exchange energy

No poles & surface:
- no magnetostatic energy
- but increased exchange, anisotropy + magnetostriction energies
MAGNETOCRYSTALLINE ANISOTROPY ENERGY

The magnetization in FM crystals tends to align along certain preferred crystallographic directions. The preferred directions are called the 'easy' axes since it's easiest to magnetize a demagnetized sample to saturation if the field is applied along a preferred direction.

The origin of hard and easy axes in the spin-orbit coupling:

- Different spin orientations lead to different orbital overlap and different energies.
- Large applied field required to reach saturation.
Different materials have different easy axes. For example, in BCC iron, the easy axis is in the cube edge: $\langle 100 \rangle$, $\langle 010 \rangle$, $\langle 001 \rangle$, $\langle 100 \rangle$, $\langle 010 \rangle$, $\langle 001 \rangle$.

The magnetization can align itself with equal ease along any of the cube edge directions.

The energy difference between samples magnetized along easy and hard directions is called the magnetocrystalline anisotropy energy.

To optimize magnetocrystalline anisotropy energy, domains form with their magnetization pointing along easy directions. This arrangement occurs in BCC iron.
MAGNETOSTRICTION
- the change in length of a ferromagnetic material when it is magnetized.

**POSITIVE MAGNETOSTRICTION** $\Rightarrow$ elongation along direction of magnetization (e.g., Fe)

**NEGATIVE MAGNETOSTRICTION** $\Rightarrow$ contraction along direction of magnetization (e.g., Ni).

In Fe, magnetostriiction causes the triangular domains of closure to try to elongate horizontally, and the long domains to try to elongate vertically.

The result is an elastic strain energy added to the total energy.
The elastic strain energy is proportional to the volume of the domains of closure, and can be lowered by reducing their size:

The origin of magnetostriiction is the spin-orbit coupling:
Domains form to minimize the magnetic energy

Exchange energy is minimized if all dipoles are parallel but this gives a large magnetostatic energy.

Magnetocrystalline energy determines preferred magnetization directions. Both (b) and (c) have lower magnetostatic energy than (a), but (c) has magnetostrictive energy.

This is the best compromise:

(a)  
(b)  
(c)  
(d)
Bloch Walls
- boundaries between adjacent domains
- ~4 millionths of an inch thick
- direction of magnetization changes by 90° or 180°.

Twist Boundary:

Exchange energy favors wide walls
Anisotropy energy favors narrow walls
The most energetically favorable domain walls don't produce magnetic poles within the material and don't introduce demagnetizing fields.

90° Tilt Boundary:

The spins rotate through the wall in such a way that they make a constant angle of 45° both with the wall normal and the surface.

The magnetization perpendicular to the boundary does not change across the wall, therefore no magnetic poles or demagnetizing fields arise.
Neél Walls occur in thin films, where it is energetically more favorable to form free poles on the wall surface rather than the film surface.

The spins rotate around an axis normal to the surface of the film.

**PLAN VIEW:**

![Diagram showing the orientation of spins in a thin film with Neél Walls]
Magnetization and Hysteresis

Initial demagnetized state, \( M = 0 \)

- Single domain magnetization rotates from the easy axis to the field direction.
- Irreversible (domain walls pass impurities) → hysteresis
- Reversible: No hysteresis
- Apply \( H \): Domain closest to field direction enlarges by domain wall motion.
Ferromagnetic Domains
When domain walls intersect an imperfection in a crystal, they eliminate the magnetostatic energy and lower the energy.

Magnetostatic Energy associated with an imperfection

Elimination of the magnetostatic energy by a domain wall.

Domain walls tend to stay pinned at imperfections, and energy is required to move them past the imperfection.
Motion of a Boundary past an Imperfection:

- High magnetostatic energy
- Magnetostatic energy eliminated
- Field forces boundary to move, but domains of closure cling to the imperfection forming spike-like domains
- The spike domains snap off and the boundary can move freely again
The variation in energy as a Bloch wall moves through an imperfect crystal might look like this:

Energy which must be provided by the external magnetic field to move the wall past the imperfection.

Local energy minimum where wall intersects imperfection.

Domain wall intersects another imperfection.
The sharp changes in flux which occur when the spikes snap from the domain boundary can be heard (Barkhausen noise) using an amplifier, or observed in a high resolution B-H plot:

**Conclusion:** Hysteresis properties (and hence applications) depend on sample purity and quality; they can be modified by processing!
Fig. 42 Relative permeabilities and coercive forces (in Oe) of various ferromagnetic materials.

- Transformers (Amorphous Metal Alloys)
- Processing is very important!
Ferromagnetic materials made of many small regions (domains), each has a large magnetization.

Fig. 6 — Schematic view of domains in an unmagnetized section of an iron bar. Each triangular area represents a magnetic domain composed of parallel oriented dipoles. The interactions between the dipoles in a domain are very strong.

An applied field rearranges the domains and makes them parallel.

Fig. 11 — Variation of intrinsic magnetization $B_i$ with magnetizing field $H$ on a magnetic material. Such data can be obtained with the use of the equipment shown in Fig. 10.
Structure of Domain Wall:

Fig. 27 — The change in orientation of magnetic dipoles across a 180° domain boundary. In the domain wall, magnetic poles at the surface will attract magnetic colloid.

- Exchange energy prefers a wide wall.
- Magnetocrystalline anisotropy prefers a narrow wall.

- When domain walls move they encounter crystal imperfections (e.g. defects, dopants, vacancies) ⇒ BIG EFFECT on coercive force and hysteresis.
Defect 'pins' the domain boundary \( \rightarrow \text{BARKHAUSEN EFFECT} \)

\[ B \]

\[ H \]

\[ (c) \]

PINNING reduces magnetostatic energy

Wall moving this direction

\[ (a) \] \hspace{5cm} \[ (b) \] \hspace{5cm} \[ (c) \]

\[ \text{HIGH magnetostatic energy} \]

\[ \text{REDUCED magnetostatic energy} \]

Fig. 9.27 Passage of a domain wall through an inclusion.

\( (: : \text{Anisotropic defect arrangement} \rightarrow \text{anisotropic response!}) \)