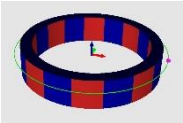

G. Mechanisms of Hysteresis

The following will provide an overview over the basic mechanisms, which govern the shape of hysteresis of ferromagnetic materials.

G1. Domains and Domain-Walls

As briefly described at the end of chapter F. beside the exchange interaction there is an additional coupling of the magnetic moments, which are oriented parallel to each other. This is a coupling to the materials inherent crystal structure. By this there are preferred directions in space to which the parallel oriented moments tend to align. The effect is called magnetic anisotropy, sometimes crystal anisotropy. When such anisotropy is weak or absent the material is called isotropic, when anisotropy is present materials are anisotropic.

Fig. G1 depicts a ferromagnetic particle in demagnetized state. Originated by the many different directions of magnetization in external space, the particle seems to be nonmagnetic. The single volumes with different magnetic orientation are called magnetic domains. Within one single domain all particles are oriented nearly parallel. In the current picture the major orientation is upward or downward, i.e. there is an alignment which might follow here one single crystal axis. Such an orientation where only one direction is preferred is called uniaxial anisotropy. Besides that, alignments to more than one direction may occur, which depend on the materials inherent crystal structure. Classical hard magnetic Ferrites are e.g. characterized by uniaxial anisotropy.

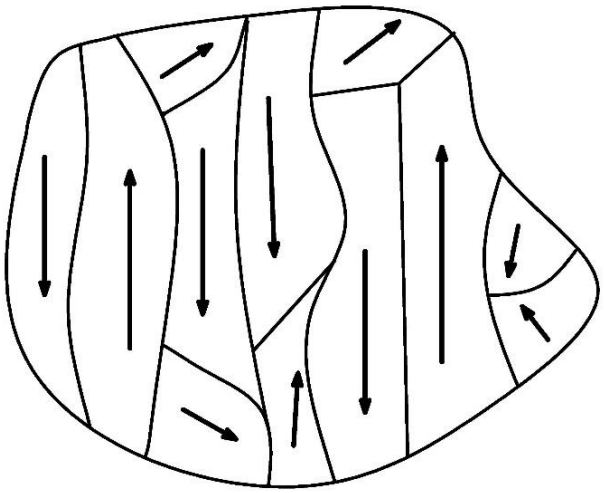

Fig. G1: Ferromagnetic, externally nonmagnetic particle with domain structure and mainly uniaxial anisotropy.

The transition zones between domains are called domain walls or sometimes Bloch walls. Fig. G2 shows an example, how such walls may look like when resolving the single magnetic moments by zooming in.

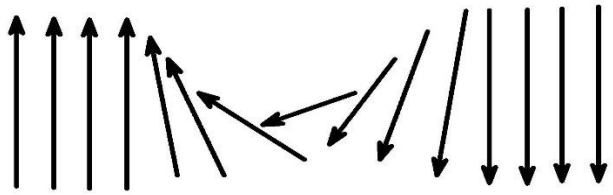

Fig. G2: Example for magnetic moment orientation inside a single domain wall

G2: Micromagnetism

How can structures like above be explained? One answer is, that assemblies of magnetic moments, which are exposed to different interactions, always tend to orient in a way that a minimum of (free) energy is reached. The treatment by an energy approach where energy is minimized is usually called theory of micromagnetism.

The total energy E of a magnetic system can be expressed as a sum of different energy terms.

$$E = E_I + E_A + E_D + E_H + E_S + E_{Ms} \qquad \text{(G1)}$$

Here is:

$$E_I = \int A(\vec{\nabla} \cdot \vec{e}_M)^2 dV \qquad \text{Exchange energy} \qquad \text{(G2)}$$

(A = Exchange stiffness, $\vec{e}_M$ unit vector in direction of magnetization)

$$E_A = -\int K \cdot (\vec{n} \cdot \vec{e}_M)^2 dV \qquad \text{Anisotropy energy} \qquad \text{(G3)}$$

(Uniaxial anisotropy here as an example, $\vec{n}$ = unit vector of preferred direction)

$$E_D = -\frac{\mu_0}{2} \int \vec{H}_d \cdot \vec{M} dV \qquad \text{Demagnetizing energy} \qquad \text{(G4)}$$

($\vec{H}_d$ = internal demagnetizing field, originated by the magnetization itself)

$$E_H = -\mu_0 \int \vec{M} \cdot \vec{H} dV \qquad \text{Energy in external field } \vec{H} \qquad \text{(G5)}$$

The terms E_s and E_{Ms} are caused by the phenomenon of magnetostriction. Magnetostriction means, that magnetization interacts with mechanical stresses. External stresses as well as internal local stresses can both originate changes in magnetization and by this in total energy.

Parameters like e.g. A or K in above formulas represent average values over large number of atoms, i.e. micromagnetism is a continuum approach, what is sometimes also called mesoscopic approximation. By minimizing E with respect to the distribution of M, magnetic structures both with and without external fields can be calculated. In simple cases this can be done analytically. For general problems respective simulations can be performed by use of special software packages. Those do not treat single particles only but also complex assemblies of magnetic materials.

A magnetic material which has been heated above its Curie temperature and cooled down again could show an alignment similar to that in Fig. G1 by minimizing its energy. I.e. the particle would be inherently magnetic, but all the single contributions of domains would balance on average, so that as outward sum a nonmagnetic condition would be observed.

When an external field is applied the energy conditions change. Now the external field energy term eq. G5 has to be added. By a parallel alignment between M and field H a negative contribution appears, which reduces total energy with increasing H. This means a parallel orientation between M and H is preferred and structures like those in Fig. G3 start to develop. Beside a few exceptional locations, where residual domains are existing, e.g. by internal stress agglomerations or the existence of voids, all domains have vanished and a uniform magnetization is governing the material.

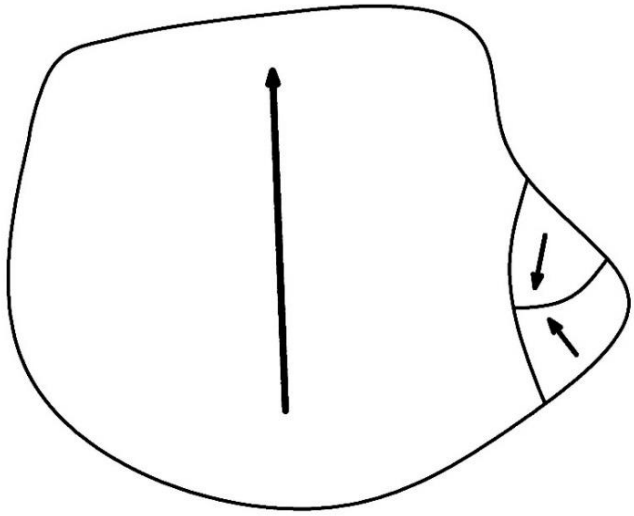

Fig. G3: Magnet particle from Fig. G1 in a strong applied external field.

G3: Hysteresis – Phenomenological Description

The above equations are a basic tool for the description of domain structures as well as related hysteresis effects. But this is by far not sufficient for a detailed description of all modern magnetic materials. Detailed simulations by the method of micromagnetism would also go beyond the frame of this summary. By this reason in the following only a phenomenological explanation of hysteresis processes follows. We constrict this to hard magnetic materials here, but mechanisms in soft magnetic magnets are comparable by their basic effects.

As known also from previous chapters the original state of a magnetic particle like that in Fig G1 will not be recovered, if a strong magnetic field is aligned and then removed again. Instead in a permanent magnetic material a strong remanent polarization can be monitored with a domain structure at least very similar to that of the magnetized state of Fig. G3. At the application of a field in negative direction only a very hesitant reversal of magnetization is observed first. Only at large negative magnetic fields an often fairly abrupt reversal of magnetization direction occurs. The question is which processes govern this behavior. Fig. G4 depicts this schematically.

The initially positive direction of magnetization starts to diminish at some negative fields by the built up of negatively oriented domains. This can happen at the boundaries of magnetic structures like grain boundaries or by interaction with stress centers, voids or inclusions. This mechanism is called domain nucleation. When the field is further increased magnetic moments inside the domain walls tend to turn into the field direction, so that domain walls start to move. By this domains in negative direction are increasing their size at the expense of positive domains. However this movement is restrained by the action of irregularities inside the material. This is called domain pinning. At negative fields such pinning centers can lead to the effect, that only at very large values domain walls break free and an abrupt domain wall movement starts.

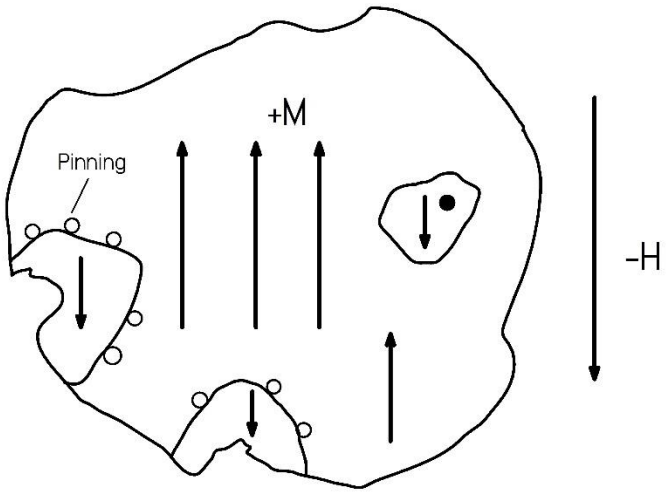

Fig.G4: Mechanisms of magnetization reversal at negative applied fields.

Beside the explained processes also partial rotations of magnetization within single domains can be observed. This is the case e.g. at the first slow decrease of magnetization on the demagnetization curve. Those rotations are mainly reversible, so that the polarization distribution will be recovered after release of the field. This is also valid at the first part of the materials virgin curve or at its approach into saturation. Fig. G5 depicts the major mechanisms which determine hysteresis in the first and second quadrant. Mechanisms in the other quadrants follow analogously.

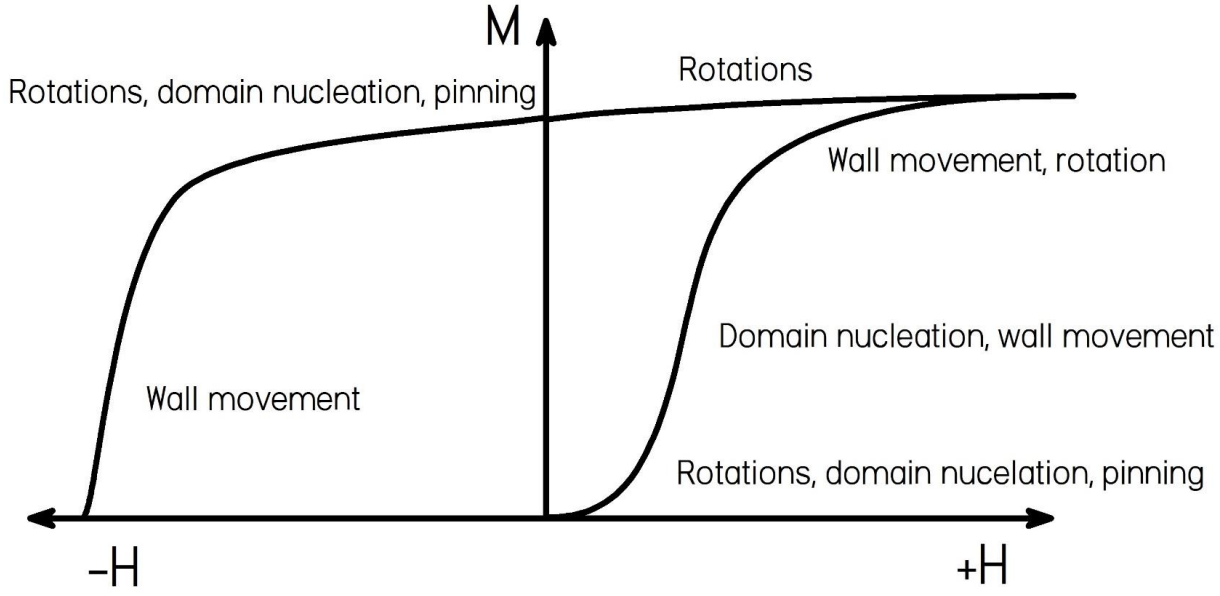

Fig. G5: Mechanisms of hysteresis in its first and second quadrant.

The steep branches of hystereses are usually determined by wall movements. Partially switching processes of magnetization direction within single domains can happen in addition, i.e. polarization rotates abruptly. Flat areas of hystereses are determined more by partial rotations. Magnetic materials can be governed by domain nucleation processes or by domain pinning. Which one of both is governing can be observed especially at the shape of the virgin curve, see Fig. G6.

In pinning determined materials the virgin curve is first governed by partial rotations of magnetization. At some field level then a break free of domain walls takes place and a majority of domains pointing into the external field direction

starts to originate. At the nucleation process domain walls can move freely from the beginning and positively oriented domains are easily originated.

On the demagnetizing curve in the second quadrant in pinning determined materials a large amount of domain walls are restrained by their movement first, until they finally break free and M changes more abruptly. When the material is nucleation governed here also an initial reluctance in change of magnetization can appear. In this case the reason for an initially flat demagnetization curve can be found in the fact, that first some energy for creation of domains has to be raised.

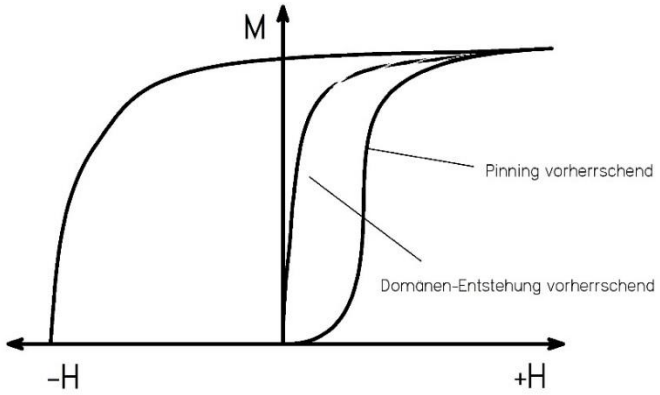

Fig. G6: Differences in virgin curve shape by domain nucleation compared to domain wall pinning.

G4: Single Domain Particles

The above mechanisms are valid for the majority of modern magnetic materials like sintered NdFeB, SmCo and the majority of hard magnetic Ferrites. Other sorts of magnets can be described as so called single domain particles. This means magnetic particles consist of one single domain, which can switch its direction at a specific amount of applied external field. This switching of field directions can happen in different ways. In detail these are coherent rotations, curling or buckling, see partially in Fig. G7. Very popular to describe a single domain particle behavior is the model of Stoner and Wohlfahrt, which also uses the theory of micromagnetism with parts of the above described energy terms. For a single particle here one gets an exactly rectangular hysteresis. When the material is assumed to consist of many such particles with some distribution of inherent parameters, particle sizes and orientations, realistic models for magnetic hystereses can be derived. The classical Stoner-Wohlfahrt model however is constricted to coherent rotations only.

Single domain particles are for example hard magnetic nanoparticles or specific sorts of fine grained Ferrites.

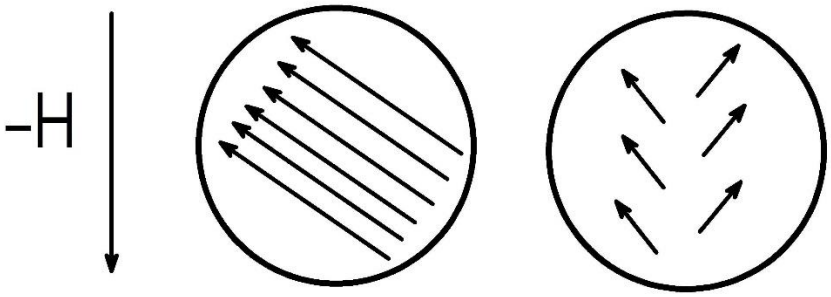

Fig.G7: Magnetization reversal in single domain particles by coherent rotation (left) or by buckling (right).