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FERROMAGNETISM

The question of what kind of magnetic behaviour in a material is the most useful has a sure answer. Ferromagnetic materials are extremely common – for example steel Cobalt and Nickel [1] – and have applications all over the technological world: from transformer cores in power stations to electric motors to RAM hard drives. Ferromagnetism describes the phenomenon whereby a material can be magnetised permanently, with variable strength, and reversibly – by an applied magnetic field.

Atoms are structured so that electrons prefer to sit in pairs in their orbits so that each pair contains electrons with opposite spin, and the orbits are filled from low to high energy. Spin is just a property of particles related to their angular momentum. If the highest energy electron orbiting the nucleus has no electron to pair with then it is unpaired.

Fundamentally, magnetisation in a material is described by magnetic moments: infinitesimally small current loops which act like tiny bar magnets, in that they form the same structure/shape magnetic field (see figure 1). Physically these current loops correspond to the orbits of unpaired electrons around the material's atoms, combined with the electrons' spin. Quantitatively, magnetics moments are described by a vector. Its direction points in the direction of the magnetic field it produces, and its magnitude corresponds to the strength of the magnetic field it produces which depends on the magnitude of the loop's current.

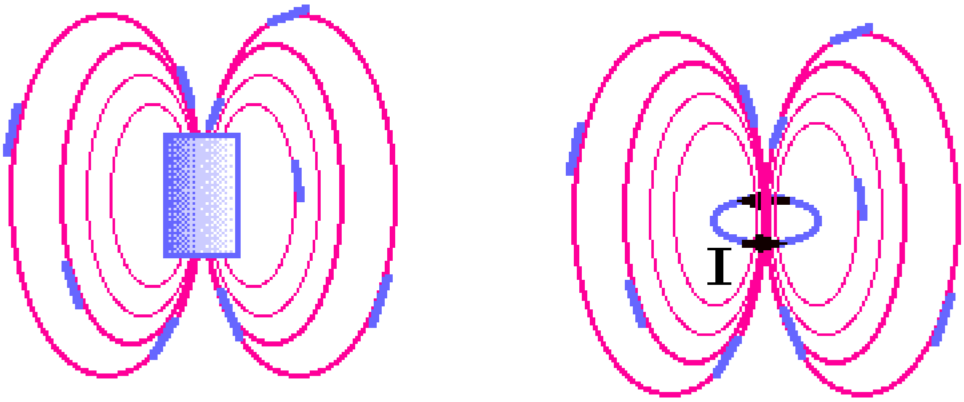

Figure 1: The Magnetic field lines emitted from a Bar Magnet, and a Magnetic Moment, respectively. Carlsmith, D. [Diagram] At:http://www.physics.wisc.edu/undergrads/courses/phys202fall96.html (Accessed on 27.12.10)

Initially the orientations of the material's magnetic moments are influenced only by each other. The total energy of the moments is lowered if they align parallel, because of a quantum mechanical effect between electrons called interaction exchange. Whenever a system has lower energy, it is more stable. This means that if the system is slightly perturbed somehow it tends to return to the lower/lowest energy state. Additionally, the alignment of moments' directions also produces "stray" magnetic fields [2], which have an energy associated with them. This energy can be lowered by cancelling out the stray fields produced if the moments are aligned in antiparallel, parallel or are perpendicular. Therefore, to reduce the stray field and exchange interaction energies the moments align into groups called domains, regions of one net magnetic moment. Most of the material's domain's moments will align parallel or antiparallel because of this also; but some will lie perpendicular to reduce the stray fields at the edges of a sample.

By considering the stray magnetic fields produced by the moments, it can be shown that energy is lower if the domains lie along the axis of a long thin sample, rather than perpendicular to it. Therefore "Shape Anisotropy" effects magnetisation. Additionally, if a material sample is so small that the domain wall energy (see the next paragraph) is larger than the stray field energy, domains cannot form in the sample and it cannot be magnetised in the same manner.

The size of the walls separating these domains (where the orientation of the magnetic moment must change, see figure 2,) is governed by a compromise of two competing factors. Firstly, the interaction exchange energy attracting moments to align in parallel favours larger domain walls so that there is less of a change in orientation between any two successive moments. The orientation wants to rotate slowly as you move through the domain wall. In contrast, an effect known as "Magnetocrystalline energy" strives for smaller domain walls. The structures of ferromagnetic materials are usually anisotropic (differing in different directions), containing certain "crystallographic" directions (specific axes within the crystal structure) where the magnetisation is easier and harder. The Magnetocrystalline energy is lowered if the moments are always in the direction of the "easy axis" of magnetisation or as close to it as possible. Therefore abrupt moment direction flips in narrow domain walls is preferred. [3]

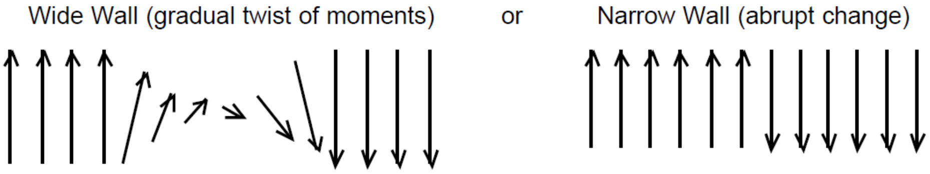

Figure 2: The Directions of magnetic moments in wide and narrow Domain walls, respectively. Barber, Z. 2012 [Diagram] *Course B: Materials for Devices.* P.41 *Part 1A Materials Science Lecture Handout* Cambridge University.

When an external magnetic field is applied to the material, its domains change such that the one that is in the direction closest to the applied magnetic field grows and others shrink. Consider this in terms of energy: before the field is applied there is an equal probability and energy of the moment facing in any direction, after the field is applied the direction closest to the field direction (along an easy axis in the material's structure) is more stable as it does the smallest amount against the applied field – so this is the direction of growth. The work done is proportional to the force exerted which depends on the Sine of the angle between the moment and applied field directions which decreases as they become closer parallel.

As the applied field strength increases, the domains evolve more until the favourable ones grow enough to replace the others. Eventually only one domain remains, which is initially aligned in the direction of the easy axis of the material's structure. As the strength increases further, the orientation of the remaining domain rotates to be parallel to the applied field. At this point Saturation magnetisation is reached; the material cannot become any more magnetised. [1]

If the external field is switched off at this point, the magnetisation will drop slightly to the 'Remnant magnetisation'. At this point, the domains once again face in the easy axis orientation because it is more stable. But if another oppositely directed field is applied, the magnetisation will begin to drop to zero. It will then re-emerge in the opposite direction whilst the domains return to the normal pre-field structure and then other now favourable domains grow instead, until the same result of saturation magnetisation occurs. The positive and negative Saturation and Remnant magnetisations are of the same magnitude. The field required to reduce the magnetisation back to zero is known as the Coercive field.

Because the evolution of domains in switching the magnetisation is not the same in both directions, it doesn't take the same path on a graph of field strength from magnetisation versus applied field strength. This is equivalent to saying there is a resulting energy loss as the magnetisation is switched because of the energy required to change all the moments/domains according to the types of energy already discussed. Hence the graph represents a Hysteresis loop which is characteristic to that material; as shown in figure 3. The area contained within the loop corresponds to the energy lost in the cycle of switching the magnetisation and then switching is back to the start per volume of material.

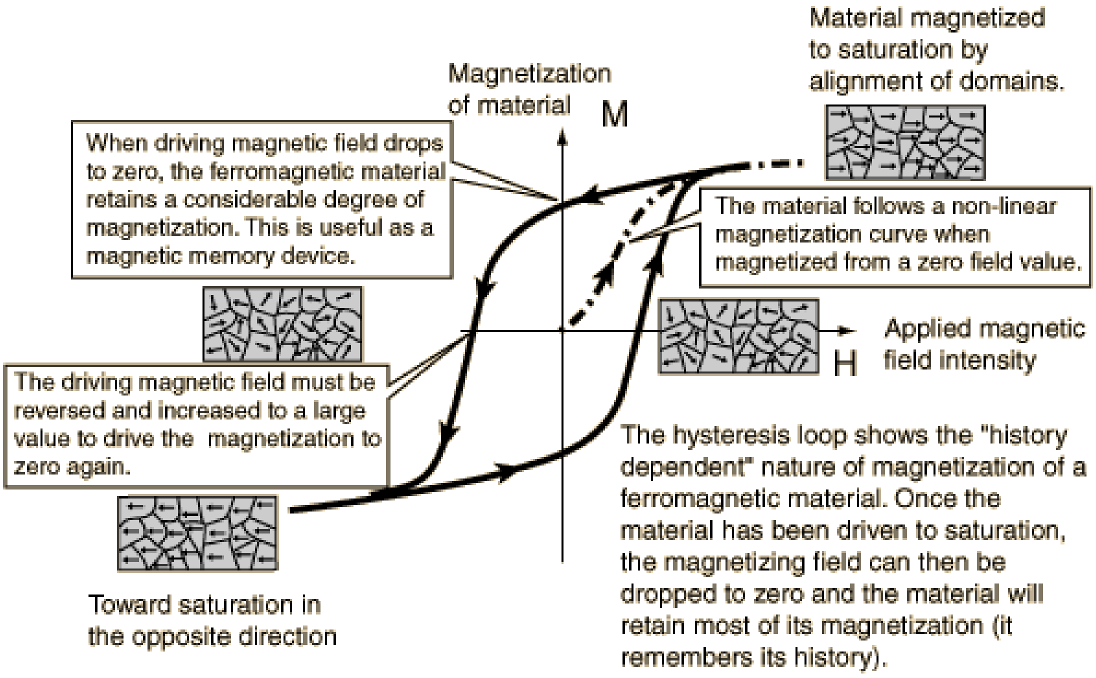

Figure 3: Hysteresis Loop for Ferromagnetic Materials. Nave, C. (2012) [Diagram] At: http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html (Accessed 27.12.2013)

The parameter which quantitatively describes the ease of magnetising a ferromagnetic material is its permeability μ. This is a parameter which changes throughout the hysteretic cycle, as it becomes easier to magnetise a material which already has partially aligned/evolved domains. The value of this is found from the gradient of the hysteresis loop, corresponding to the change in field produced by magnetisation per change in applied field strength. Algebraically, permeability is equal to the product of the permeability of free space (the vacuum) μ_0 and $(1+\chi)$ [4]. χ is the magnetic susceptibility of the material which equals the ratio of magnetisation to applied field strength. For ferromagnetic materials, the susceptibility is positive and can be very large.

When a material is magnetised, it can produce a strain which changes its dimensions slightly. Each domain will produce a slightly different dimension change from a potentially different strain, resulting in some Elastic Strain energy at the walls. This phenomenon is called Magnetostriction [2] and is described by the Magnetostriction coefficient Λ which tells you the fractional change in length of a material from zero to saturation magnetisation which may be positive or negative.

Because ferromagnetism is structurally dependant, it is also temperature dependant since the structure of materials changes with temperature. At a certain temperature, a phase change (change in structure) will occur, which means the material can no longer form two equal probability direction moments – and so is not Ferromagnetic but

Paramagnetic. Paramagnetism is a much weaker response to an applied magnetic field; additionally the magnetisation it induces is not switchable and does not remain once the applied field is removed. The transition temperature is known as the Curie temperature [5].

The characteristic Hysteresis loop's appearance determines the material's applications [6]. Three characteristics are important: the magnitude of Saturation magnetisation; the size of the hysteresis loop's area; and the flatness of the loop. The larger the Saturation magnetisation, the higher the field strength which can be passed through the material is. For a larger area, the energy loss per cycle grows. Therefore it is harder to switch the material's magnetisation and so the material becomes a hard/permanent magnet. These are used in electrical Motors and Generators. For smaller areas, the energy loss is lower and materials become soft magnets which are used in electrical Transformers which need to switch fields quickly. Transformer magnets need to also have a high Saturation magnetisation since they use high voltages and in so need strong magnetic fields also. Materials with a strongly defined positive and negative magnetisation are used in RAM hard drives as the two magnetisations correspond to on and off – or 1 and 0 – which is the basis of computer storage.

In conclusion, ferromagnetism is a diversely applicable principle with a relatively simple explanation. It is described fully using the formation and grouping of magnetic moments and how they change with an applied magnetic field.

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