

MAGNETIC PROPERTIES OF ELECTRICAL STEELS

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Abstract

A short development of magnetic domain theory and the properties of ferromagnetic materials can be explained by the macroscopic properties and the principle of energy minimisation. In ferromagnetic materials the magnetic domains exist in large volumes which the atomic magnetic moments are aligned parallel due to the strong molecular field. The magnetostatic, magnetocrystalline, magnetoelastic, exchange and domain wall energies determine the domain structure in a ferromagnetic crystal. The domain wall has an optimum thickness due to the exchange and magnetocrystalline anisotropy energies within the wall. A certain number of 180 degree domains occur as a result of an interaction between the magnetoelastic and domain wall energies in an iron crystal.

Key words: electrical steels, magnetic domains, energy minimisation

1. Introduction

Magnetic domain theory is a microscopic approach to account for the observed macroscopic properties of ferromagnetic materials which have higher permeability than other magnetic materials. Building the theory from the atomic magnetic moment of an atom is a good starting point without involving too much quantum mechanics. The origin of the atomic magnetic moments was first suggested by Ampere who proposes that they were due to electrical currents continually circulating within the atom. More precisely, the spin and the orbital moments of electrons in an atom are responsible for the atomic magnetic moment. Further in ferromagnetic materials, permanent atomic magnetic moments exist on the atomic scale basing on the two sorts of electron motions and they are not field induced.

The next question is whether these atomic moments are already in an ordered state before a magnetic field is applied or the order is induced by the field? Scientists at that earlier stage such as Weber and Ewing choose the wrong answer to the question. As a result, they were not able to explain completely to most of the macroscopic properties of ferromagnetic materials such as remanence and relatively high permeability or to the macroscopic structural difference in magnetised and demagnetised states [1].

2. Domain Theory Of Ferromagnetism

2.1. Weiss assumptions

Some years after the Ewing's work which was one of the most advances in the understanding of ferromagnetism was made by Weiss [2]. Weiss built on the earlier work of Ampere, Weber and Ewing and suggested the existence of **magnetic domains** in ferromagnets, in which the atomic magnetic moments were aligned parallel over much larger volumes of the solid. In these domains large number of atomic moments, typically 10^{12} to 10^{15} , is aligned nearly parallel so that the magnetisation within the domain is almost saturated. But the direction of magnetisation of various domains is such that the specimen as a whole has no net magnetic magnetisation.

Weiss further developed the statistical thermodynamic ideas of Boltzmann and Langevin as they applied to magnetic materials. Weiss used the Langevin model of paramagnetism and added an extra term to extent for ferromagnetism, so it is called **Weiss molecular field**, which was in effect an inter atomic interaction which

caused neighbouring atomic magnetic moments to align parallel because this field was so large that the energy could be lower.

Weiss assumed that the molecular field acted in a paramagnetic substance above its Curie temperature, T_c , as well as below. As the temperature dropped to the ferromagnetic phase, this field becomes so significant that it could align the atomic moments almost parallel to give a bulk spontaneous magnetisation, M_s , in the material even in the absence of an applied field.

The spontaneous magnetisation is temperature dependent. At Curie point as shown in Figure 1(a) it is equal to zero (paramagnetic phase) and increases to the saturation magnetisation, M_0 , at 0 degree K [Fig. 1(d)]. At temperatures just below T_c the individual magnetic moments have medium thermal energy which causes them to precess away from the molecular field direction as shown in Fig. 1(b). The precession becomes smaller as the temperatures decreases [Fig. 1(c)]. It is the precession which causes the spontaneous magnetisation, to be smaller than the saturation magnetisation.

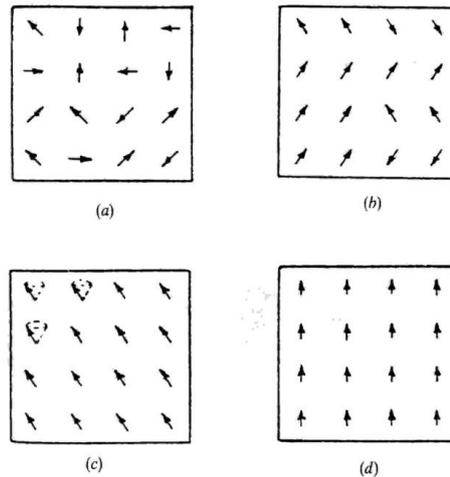


Figure 1. Alignment of individual magnetic moments within a domain at various temperatures;(a) above the Curie point indicating random alignment, (b) below the Curie point, (c) at low temperatures in which the magnetic moments precess about the field direction in low-level excited states and (d) perfect alignment at 0 degree K where there is no thermal energy for precession.

2.2. Energy considerations

Weiss provided an empirical explanation of why the molecular field did not lead to net spontaneous magnetisation of the material. It was left to Landau and Lifschitz in 1935 to show that the existence of domains is a consequence of energy minimisation. The total energy of a ferromagnetic single crystal may be expressed as;

$$E = E_m + E_k + E_\lambda + E_{ex} + E_w \quad (1)$$

where E_m is the magnetostatic energy, E_k is the magnetocrystalline anisotropy energy, E_λ is the magnetoelastic energy, E_{ex} is the exchange energy and E_w is the domain wall energy.

2.2.1. The magnetostatic energy (E_m)

The magnetostatic energy, E_m , is due to the Coulomb interactions between free magnetic poles. Consider a large single crystal of a uniaxial substance and it is entirely one domain, spontaneously magnetised parallel to the easy axis as shown Figure 2(a). The free poles from the ends are the source of a large magnetic field, H . E_m of this crystal is evaluated over all space where it is appreciable. This considerable energy can be approximately halved, if the crystal splits into two domains magnetised in opposite directions as in Figure 2(b). Because this brings the north and south poles closer to one another, thus decreases the spatial extent of the field H . If the crystal splits into four domains as in Figure 2(c), E_m again decreases, to about 1/4 of its original value and so on. But this division into smaller and smaller domains cannot continue indefinitely, because each domain wall formed in the crystal add an extra energy. Eventually, in equilibrium domain size will be reached. E_m is proportional to the width of the domain. E_m for a multi domain crystal, per unit area of the top surface, has been given by Chikazumi [3];

$$E_m = 1.7M_s^2 d \tag{2}$$

where d is the thickness of the slab-like domains, provided that d is small compared to the length of the crystal or domain, l .

2.2.2. Magnetocrystalline anisotropy energy (E_k)

Magnetic anisotropy is the dependence of the internal energy on the direction of spontaneous magnetisation. This energy is called “**magnetic anisotropy energy**”. Generally, the magnetic anisotropy energy term possesses the crystal symmetry of the material and called the magnetocrystalline anisotropy. The magnetic anisotropy can also be produced by applying mechanical stress to the material. It is also controlled by heat treating the material in a magnetic field or by cold-working it and called **induced magnetic anisotropy**.

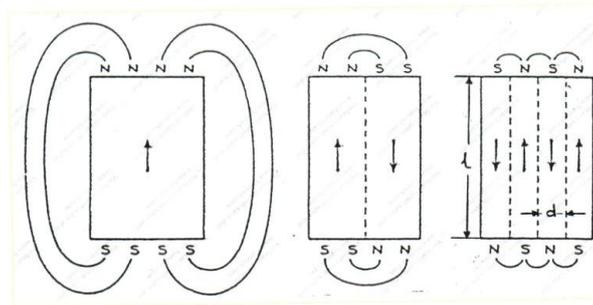


Figure 2. Division into domains to reduce the magnetostatic energy (E_m).

The magnetocrystalline anisotropy energy tends to make the magnetisation of a domain line up along certain crystallographic axes. The axes thus favoured are known as the axes of easy magnetisation. These axes are well-established experimentally and a considerable larger amount of energy may be required to saturate a specimen along arbitrary axes than along one of the easy magnetisation axes. Figure 3 shows the magnetisation curves for the three principle crystallographic directions in an iron single crystal. Generally, the direction of easy magnetisation of a single crystal is in the direction of spontaneous domain magnetisation in the demagnetisation state. It is found experimentally to require the expenditure of a certain amount of energy to magnetise a crystal to saturation in a hard direction is referred to the lower energy required to saturate along a direction of easy magnetisation. The excess energy required in the hard direction is the magnetocrystalline anisotropy energy.

In iron any of the three cube edge directions are the direction of easy magnetisation. E_k of a cubic crystal is given by;

$$E_k = K_1(\alpha_1^2\alpha_2^2 + \alpha_1^2\alpha_3^2 + \alpha_2^2\alpha_3^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) \tag{3}$$

where α_1 , α_2 and α_3 are the direction of cosines of the magnetisation direction with respect to the cubic axis of the crystal. K_1 and K_2 at room temperature are $4.8 \times 10^4 \text{ J/m}^3$ and $\pm 0.5 \times 10^4 \text{ J/m}^3$ for iron.

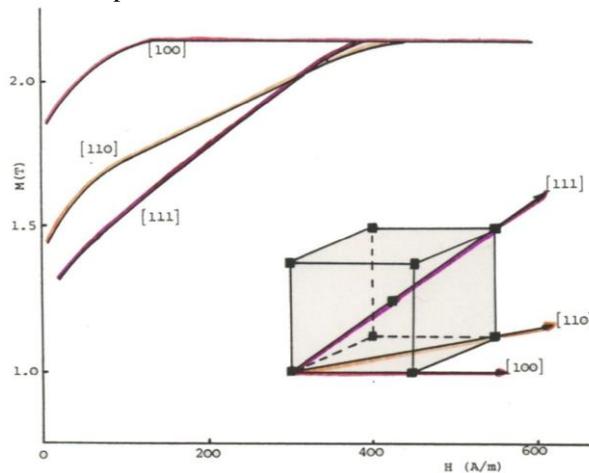


Figure 3. Magnetisation curves along the three principle crystallographic directions in an iron single crystal.

The origin of E_k is believed to be the result of the combined effects of spin-orbit interactions and the partial quenching of the orbital angular momentum. The spin interacts with the orbital motion by means of the spin-orbit coupling and the orbital motion in turn interacts with the crystal structure by means of the electrostatic fields and overlapping wave functions associated with neighbouring atoms in the lattice. The theory was developed by Van Vleck in 1947 [4].

2.2.3. Magnetoelastic energy (E_λ)

The same atomic moment interactions give a rise to ferromagnetism and the magnetic anisotropy produces forces between atoms which tend to strain the lattice anisotropy. The magnetic energy associated with these lattice strain is called the magnetoelastic energy [5]. E_k also causes the magnetoelastic effects within a magnetic material. E_λ decreases linearly with increasing crystal lattice strain and E_λ of a cube crystal can be written as;

$$E_\lambda = -\frac{3}{2}\lambda_{100}\sigma(\alpha_1^2\gamma_1^2 + \alpha_2^2\gamma_2^2 + \alpha_3^2\gamma_3^2) - 3\gamma_{111}\sigma(\alpha_1\alpha_2\gamma_1\gamma_2 + \alpha_2\alpha_3\gamma_2\gamma_3 + \alpha_3\alpha_1\gamma_3\gamma_1) \quad (4)$$

where α_1 , α_2 and α_3 are the direction of cosines of M_s as before and γ_1 , γ_2 and γ_3 are the direction of cosines of stress, σ . This relation is derived by Lee and Kittel [4, 6]. The equilibrium direction of M_s is that which makes E_λ a minimum and λ_{100} , λ_{111} are the saturation magnetostriction. For ease of estimation, several authors assume the magnetostriction is isotropic, so that $\lambda_{100} = \lambda_{111} = \lambda_s$. Equation (4) reduces to a very simple explanation for this isotropic E_λ ;

$$E_\lambda = \frac{3}{2}\lambda_s\sigma\sin^2\theta \quad (5)$$

where $\cos\theta = \alpha_1\gamma_1 + \alpha_2\gamma_2 + \alpha_3\gamma_3$ and θ is the angle between the saturation magnetisation M_s and stress, σ .

2. 2. 4. Exchange energy (E_{ex})

Exchange energy forms an important part of the total energy of many molecules and of the covalent bond in many solid. It is also played a decisive role in ferromagnetism. If two atoms i and j have spin angular momentum $S_i\hbar$ and $S_j\hbar$ respectively, then E_{ex} between them is given by;

$$E = -2JS_iS_j\cos\phi \quad (6)$$

where J is the exchange integral which occurs in the calculation of the exchange effect and ϕ is the angle between the spins. If J is positive, E_{ex} has a minimum when the spins are parallel ($\cos\phi=1$). If J is negative, the lowest energy state results from antiparallel spins. Ferromagnetism is due to the alignment of spin moments on adjacent atoms. A positive value of the exchange integral is therefore a necessary condition for the ferromagnetism to occur. Exchange forces depend mainly on the interatomic distances and not on any geometrical regularity of the atom position. Crystal structure is therefore not a requirement for the ferromagnetism [5].

2. 2. 5. Domain wall energy (E_w)

Domain walls are described by the angle between the M_s vectors in the two domain on either side of the wall. The domain structure of the real single crystal is normally such that 180 and non-180° walls both exist. First imagine change of a 180° wall to be abrupt, occurring from one atom to the next. This abrupt 180° wall would have a large exchange energy associated with it, because the spins adjacent to the wall are antiparallel. This exchange energy can be decreased if the 180° change in spin direction takes place gradually over N atoms, so the angle θ between adjacent spins, equal to π/N , has some value in Figure 4.

On the other hand, the spins within the wall are pointing in non-easy directions, so that the crystal anisotropy energy within the wall is higher than it is in the adjoining domains. While γ_{ex} tries to make the wall as wide as possible, γ_k tries to make the wall thin in order to reduce the number of spins pointing in non-easy directions. As a result of this competition the wall has a finite width and a certain structure [Fig. 5].

Also, the wall has certain energy per unit area of its surface, because the spins in it are not quite parallel to one another and not parallel to an easy axis. The first theoretical examination of the structure of a domain

wall was made by Bloch and domain walls are accordingly often called Bloch walls. The extra exchange energy existing within the wall is given by;

$$\gamma_{ex} = JS^2\theta^2 \tag{7}$$

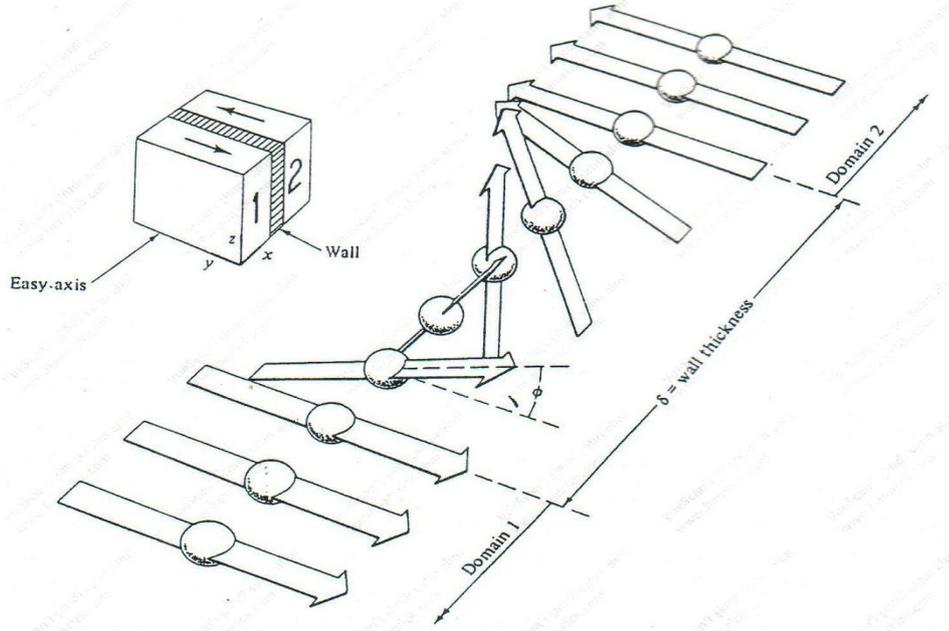


Figure 4. Internal structure of a 180 degree wall.

obtained by equation (6). To find γ_{ex} per unit area of domain wall, an assumption about the crystal structure must be made. It is a simple cubic structure with an atom at each corner of a cell of edge, a , and the plane of the wall is parallel to cube face (100). The wall is atoms thick and per unit area of wall, there will be $1/a^2$ rows of N atoms. Therefore, the extra exchange energy per unit area of wall is;

$$\gamma_{ex} = \frac{JS^2\pi^2}{Na^2} \tag{8}$$

The anisotropy energy is of the order of the anisotropy constant K times the volume of the wall. Therefore, the anisotropy energy in the per unit area of wall is;

$$\gamma_k = KNa \tag{9}$$

The total energy per unit area, for a wall of thickness $\delta=Na$, is;

$$\gamma = \frac{JS^2\pi^2}{\delta a} \tag{10}$$

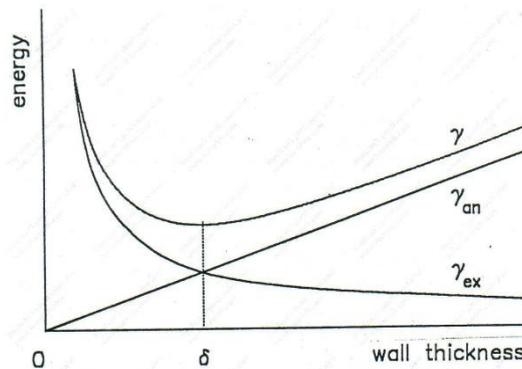


Figure 5. Dependence of total wall energy γ (dashed curve) on wall thickness δ .

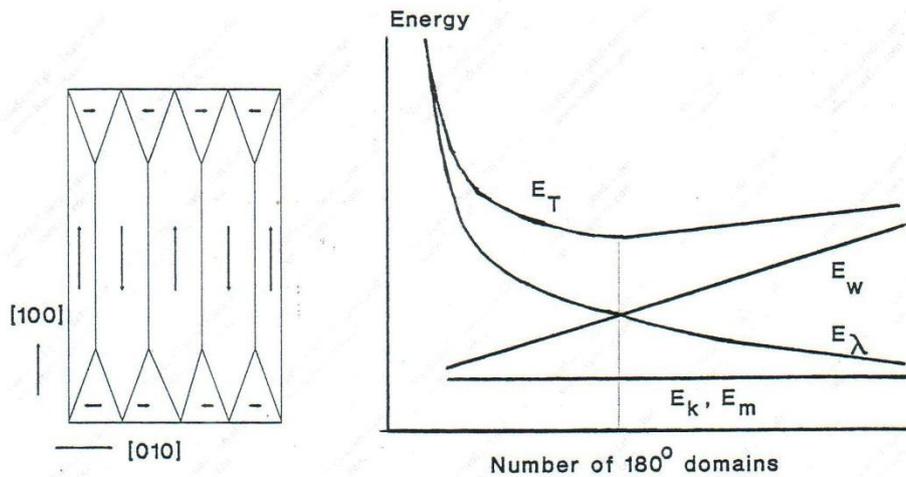


Figure 6. Shape of the crystal and minimum total energy in an iron crystal.

This energy has a minimum for a particular value of δ as shown in Figure 5 by the dashed curve. This minimum is given by;

$$\delta = \sqrt{\frac{JS^2\pi^2}{Ka}} \quad (11)$$

3. Energy Minimisation

In order to have minimum total energy each energy term must be stable energy level. E_m is the Coulomb interaction between the magnetic free poles so it can be reduced if the crystal splits into domains. E_k is the dependence of the internal energy on the direction of spontaneous magnetisation. It tends to make the magnetisation of a domain line-up along certain crystallographic axes; E_k is at minimum level if the angle between the easy direction and the magnetic moments of atoms (spins) is equal to zero. E_λ is associated with the same atomic magnetic moment interactions in the lattice. E_λ has a minimum when the saturation magnetisation, M_s , and stress, σ , at the right angles. E_λ has a significant value due to the crystal which has a positive magnetostriction, λ . A lot of stress occurs inside the crystal since the material is hard. E_λ is inversely proportional to the number of 180 degree domains. When the number of 180 degree domain is increased to reduce E_λ , the total of E_w is also increased since each domain wall adds an extra energy.

Finally the total energy in an iron crystal has a minimum value when a certain shape and number of domain occur in the crystal as shown in Figure 6. But actual material has a polycrystalline structure (Fig. 7), so the interactions between the crystals are also affected the total energy and hence the domain structure.

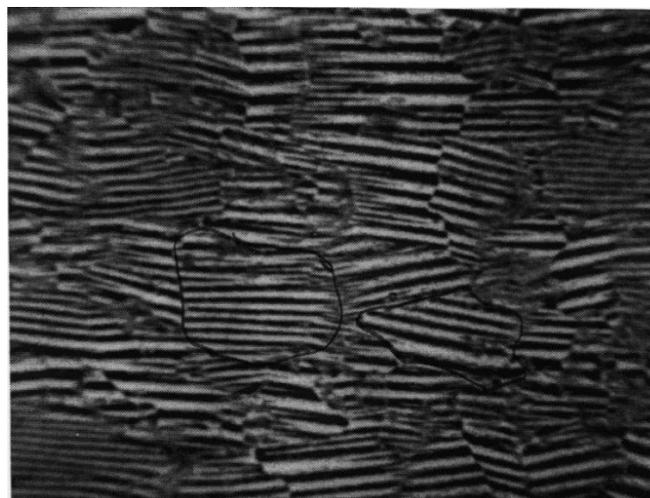


Figure 7. The domain structure of polycrystalline grain oriented 3% Si-Fe.

4. Conclusion

The domain structure in a crystal is arranged such that the sum of several free energy terms is minimum total energy level. In order to have a minimum total energy each energy term has to be stable energy level. So, the formation of domains within a crystal can be easily understood as a result of energy minimisation.

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