Digital Computer Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

SUBJECT: GROUP 63 SEMINAR ON MAGNETISM VIII

To: Group 63

From: Arthur Loeb and Norman Menyuk

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Heat Effects:

Temperatures in the region of absolute zero are produced by adiabatically demagnetizing paramagnetic salts which are at a temperature of about 2°K. The temperature is first brought as low as possible by other means, with the substance in a high magnetic field. This field is then abruptly removed, and there is a resultant disalignment of the molecular magnetic dipoles of the paramagnetic salt. This resultant increase in entropy of the system requires energy, but since none is available from outside the system, the temperature drops to a very low value.

The heat capacity at the Curie temperature is also of interest. The molar heat capacity of a system is the amount of heat required to raise a mole of that system one degree centigrade.

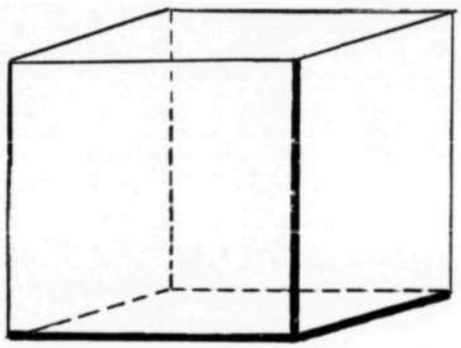
The temperature of a system is a measure of the kinetic motion of its molecules. If heat added does nothing but raise the kinetic motion of the molecules, the heat capacity of the system will be lower than if the heat performs another task as well. On approaching the Curie point of a material the heat added supplies energy needed to disorient the molecular magnetic dipole as well as to raise the temperature. We, therefore, find that the heat capacity of a ferromagnetic material rises sharply near the Curie temperature. Immediately above the Curie temperature the heat capacity drops abruptly.

From the previous lecture we had as two dominant features of ferromagnetic materials:

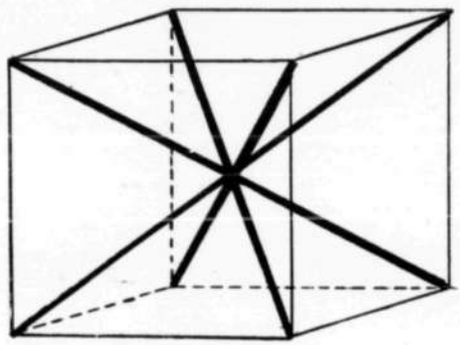
1. Small fields are capable of producing tremendous magnetization.

2. Spin alignments occur within domains, but the domains tend to cancel each other out on a gross level.

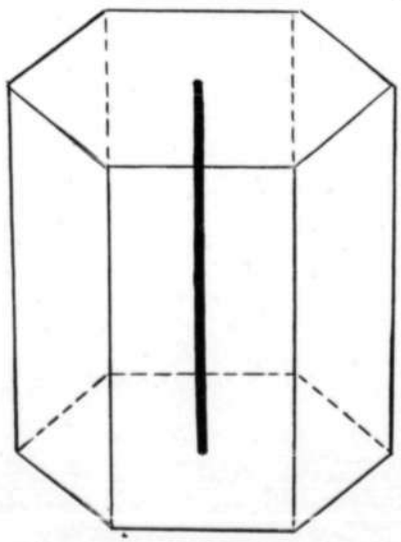
Experiments have shown that most magnetic crystals are anisotropic, having preferred directions of magnetization. These directions of "easy magnetization" are not necessarily the same for different materials, even those having similar crystal structures. Thus iron and nickel, which are both cubic crystals, have different directions of easy magnetization. The preferred directions are shown in Figure 9 for iron, nickel, and cobalt.



(a) Iron



(b) Nickel



(c) Cobalt

Figure 9

These directions of easy magnetization shown in Figure 9 are the 100 direction for iron, the 111 direction for nickel, and the 0001 direction for cobalt. The magnetic anisotropy of these materials is shown graphically in Figure 10.

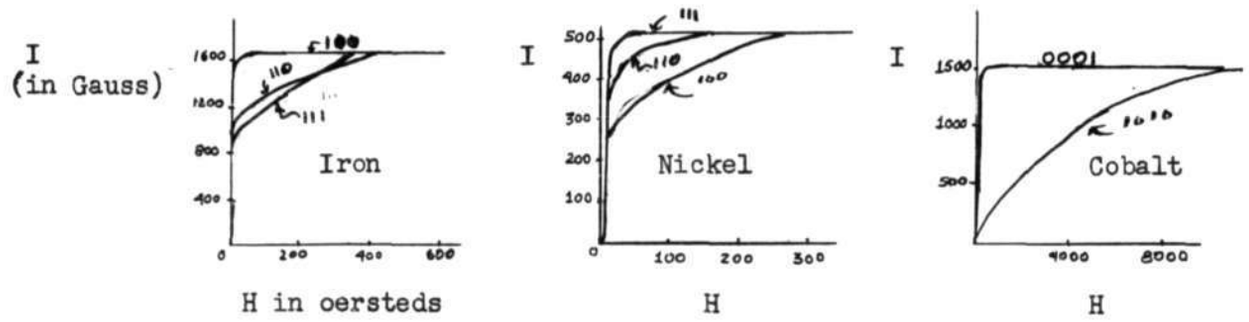


Figure 10

Domain Energies:

There are four major types of energy which enter into domain structure theory. They are: exchange energy, anisotropy energy, magnetoelastic energy, and magnetostatic energy. For the case of a cubic crystal the equations for energy density are:

I Exchange Energy (f_{ex})

$$f_{ex} = JS^2 \sum_{i>j} \varphi_{ij}^2$$

where J = energy integral

S = spin angular momentum

φ_{ij} = angle between directions of neighboring spins

We may note that $f_{ex} = 0$ when $\varphi = 0$. Thus f_{ex} gives excess energy when spins are not aligned parallel. For this reason we will have a large exchange energy density in the domain boundary region.

II Anisotropy Energy (f_k)

It often requires a considerable amount of energy to magnetize a crystal to saturation in a hard direction compared to the lower energy required to saturate along a distance of easy magnetization. The excess energy required in the hard direction is the anisotropy energy. It

can be shown that

$$f_k = K_1 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2)$$

where K_1 = anisotropy constant

$\alpha_1, \alpha_2, \alpha_3$ = direction cosines between field direction and crystal axes.

The magnitude of K_1 is proportional to the area between the magnetization curves for hardest and easiest direction.

III Magneto-elastic energy (f_{me})

The magneto-elastic energy arises from the interaction between the magnetization and deformation of the lattice. Since the ease of magnetization depends upon the distance between lattice elements, deforming the crystal may increase or decrease the magnetization. Conversely, applying a field to the crystal may cause lattice deformation.

We find

$$f_{me} = \frac{3}{2} \lambda T \sin^2 \theta$$

where λ = isotropic magnetostriction

T = tension

θ = angle between tension and magnetization

IV Magnetic Field Energy (f_{mag})

$$f_{mag} = -\frac{1}{2} \vec{I} \cdot \vec{H}$$

The familiar factor of one-half arises because this is a case of self-energy. The field against which the work is being done is not external but is due to the magnetization itself. We must, therefore, sum over a field range of 0 to H. It is similar to the factor of one-half arising in the energy stored in a condenser ($\frac{1}{2} CV^2$) or the energy of a coil ($\frac{1}{2} LI^2$).

The domain structure of a ferromagnetic material will be such as to minimize the energy resulting from the four factors listed above. The size and shape of the domains in a particular case will depend upon the ferromagnetic material, the orientation of the boundary surfaces of the crystals, the dimensions of the material, the state of stress, and the magnetic field intensity. Unless all these factors are known, it is impossible to predict the domain structure. The arrangements shown in Figure 11 are examples of stable configurations.

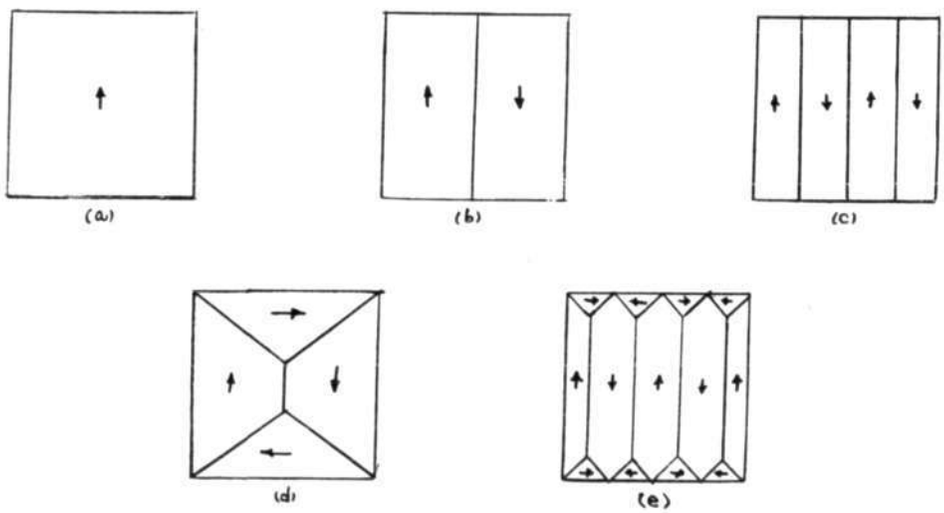
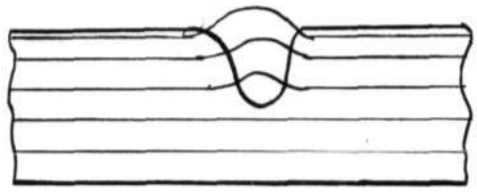


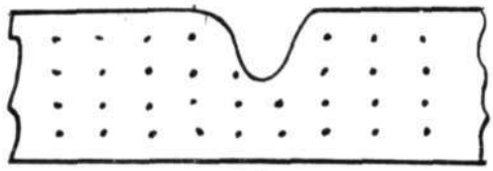
Figure 11

Figure 11(a) represents the case of a strong magnetic energy and no wall energy. The wall energy is a function of the exchange, anisotropy and magnetoelastic energies. As we go to Figures 11(b) and 11(c) we decrease the magnetic energy considerably, but increase the wall energy by introducing one and three domain walls respectively. The last two figures represent domains in which there are no surface poles, but the number of walls has increased to five in 11(d) and to twenty in 11(e).

Powder patterns, as mentioned previously, show the position of the domain boundaries. They do not show the direction of magnetization, and the scratch technique has been devised to do this. If a scratch is made on the surface there will be a colloidal deposit in the scratch for magnetization normal to the scratch, and no deposition for magnetization parallel to the scratch. This can be better understood with the help of Figure 12. The colloid particles are attracted by the leakage flux, and there is none for the magnetization parallel to the scratch.



(a)
Magnetization Normal to Scratch



(b)
Magnetization Parallel to Scratch
Figure 12

In order to better understand the various effects which take place at the microscopic level, a series of analogies may be made with the situation at a tennis match operating under admittedly artificial conditions. Then, with all due apologies to the United States Lawn Tennis Association, we will label the tennis match conditions, TMC, and will follow this by its magnetic analogue, MA.

1. TMC - All the spectators have their gaze fixed on one person. (e.g. Gussie Moran)

   MA - A single domain with all spins lined up.

2. TMC - The person being watched walks across field, and since everyone has nothing better to do until the match begins, all eyes follow her. It should be noted that only the heads move; the benches remain stubbornly motionless.

   MA - Domain rotation. Crystal lattice remains unchanged.

3. TMC - As everyone is watching Miss Moran on the field, Mrs. Roosevelt arrives on the side. Those nearest turn in her direction and let their neighbor know of her arrival. In this way word of her arrival spreads slowly through the crowd, and more people turn to see her.

   MA - Domain wall motion.

4. TMC - However, some of the spectators are Republicans. They don't see any reason for all this fuss about Mrs. Roosevelt and so they don't pass along the word of her arrival.

   MA - Resistance to domain rotation.

5. TMC - The Democrats make so much noise that a large number of people to the right of the Republicans become aware of Mrs. Roosevelt's presence and they quickly turn to see her.

   MA - A high magnetic field causing a Barkhausen jump.

6. TMC - It would appear that Gussie Moran has been forgotten, but no. The match has begun, and Miss Moran and Mrs. Kiner are batting the ball back and forth. The spectators' heads are turning from left to right to left to right, etc.

   MA - Alternating current input. Pattern reversible.

7. TMC - After the match is over and all the spectators have left, the benches are straightened out to permit people to more easily view the tennis court.

   MA - The cold rolling of metal, which aligns the crystals.

Signed Norman Menyuk
Norman Menyuk

Signed Arthur D. Loch
Arthur Loch

Approved DRB
D. R. Brown

jmm

Group 62 (15)