Study of Magnetic Hysteresis in Ferromagnetic Materials

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The aim of the experiment was to study the variation of induced magnetic field concerning the ex ternal magnetization intensity (H) in ferromagnetic materials, known as magnetic hysteresis. We determined important parameters, including retentivity, saturation point, and coercivity. Additionally, we discussed the phenomenon of degaussing in ferromagnetic materials.

I. OBJECTIVE

To study the magnetic hysteresis loop for a massive iron core.

II. THEORY

Magnetism in matter

The magnetic state of a material can be described by a vector $\vec{M}$ called magnetization, or dipolar magnetic moment per unit volume. In vacuum, the magnetic induction $\vec{B}$ and the applied magnetic field intensity, $\vec{H}$, are connected by the equation:

$$\vec{B} = \mu_o \vec{H} \tag{1}$$

where $\mu_o = 4\pi \times 10-7$ Hm^{-1}, is the absolute magnetic permeability of vacuum. However, in a matter, magnetic induction depends on magnetization $\vec{M}$ in the following way,

$$\vec{B} = \mu_o(\vec{H} + \vec{M}) \tag{2}$$

There is another important parameter called the magnetic susceptibility, χ, which is a measure of the quality of the magnetic material and defined as the magnetization produced per unit applied magnetic field, i.e.,

$$\chi = M/H \tag{3}$$

Magnetism in solids is Broadly classified into 3 categories: diamagnetism, paramagnetism and ferromagnetism.

1. **Diamagnetism** is a very weak effect observed in solids having no permanent magnetic moments. It arises due to changes in the atomic orbital states induced by the applied magnetic field. It exists in all materials but usually suppressed by other stronger effects such as para- or ferromagnetism. For diamagnetic materials, magnetization $\vec{M}$ varies linearly with $\vec{H}$ in opposite direction. Hence $\chi < 0$. Diamagnetism is temperature independent.

2. **Paramagnetism** is also a weak effect, but unlike diamagnetism, the magnetic moment is aligned along the direction of applied magnetic field. Certain atoms and ions (oxygen, air, iron salts, etc.) have a permanent magnetic moment of their own. Without applied magnetic field, these are oriented randomly. Therefore they don't show any magnetization on a macroscopic scale. On applying an external magnetic field, a non-zero macroscopic magnetic moment $\vec{M}$ arises since all the magnetic momenta are aligned along the applied field. The magnetization $\vec{M}$ initially varies linearly with $\vec{H}$ and then saturates at a value Ms, called saturation magnetization. This saturation condition corresponds to the complete alignment of the magnetic dipoles along the applied field direction. However, once the applied field is removed, thermal agitation in the material is enough to disorient the atoms. Paramagnetic materials have a small, positive χ. Paramgnetism is temperature dependent.

3. **Ferromagnetism** is associated with the presence of permanent magnetic dipoles where the magnetic momenta of adjacent atoms are aligned in a particular direction, even in the absence of an external magnetic field. This is known as spontaneous magnetization. A ferromagnetic material contains a number of small regions called domains, which are having spontaneous magnetization values of different magnitude. On application of an external magnetic field $\vec{H}$, these domains align in the direction of $\vec{H}$ and develop a strong macroscopic magnetization $\vec{M}$. The value of χ for a ferromagnetic material is large and positive. Ferromagnetism is temperature dependent as it exists below a certain temperature known as Curie temperature T_C. Some examples of ferromagnetic materials are iron, cobalt and nickel.

Hysteresis

Hysteresis loop (Fig. 1) shows the relation between the magnetization $\vec{M}$ or the magnetic induction $\vec{B}$ as a function of $\vec{H}$. It is a characteristic property of any ferromagnetic material. The dotted line in Fig. 1 shows that as the applied field is increased the magnetization in the domains grows along the so-called easy direction of magnetization and finally attains a **saturation value** at B_S. At this point all the domains point along the direction of applied magnetic field. On decreasing the field, $\vec{B}$ is not reversible and possesses a non-zero value called **remanent induction**, B_r. It can be reduced to zero by applying a reverse magnetic field known as coercive magnetic field or **coercivity**, H_C. A similar variation is observed as the reverse field is varied resulting in a closed loop known as hysteresis loop.

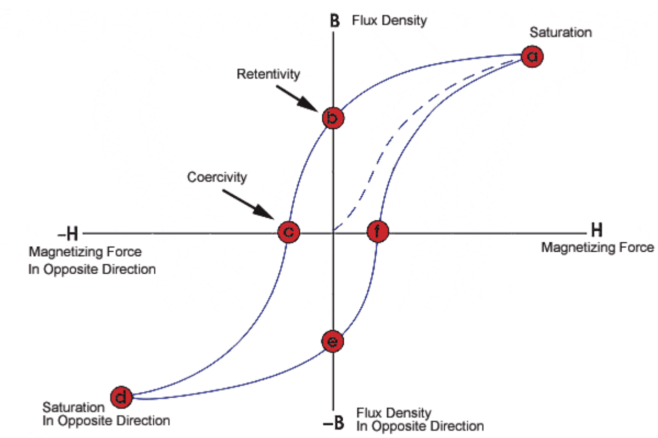

FIG. 1: Hysteresis Loop

Degaussing

Degaussing is the process of decreasing or eliminating a remnant magnetic field present in a ferromagnetic material due to hysteresis. Annealing, hammering or applying a rapidly oscillating magnetic field (Fig. 2) are some of the methods of degaussing which tend to release the domain walls from their pinned state, and the domain boundaries tend to move back to a lower energy configuration.

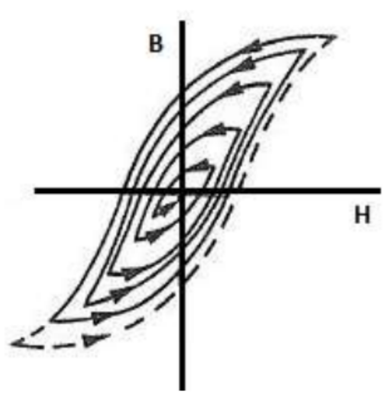

FIG. 2: Degaussing Curve

III. EXPERIMENTAL SETUP

Apparatus

1. Iron core
2. Pair of coils (600 turns each, current limit 2A)
3. DC power supply
4. Digital gauss meter (DGM) with hall probe
5. Reversible switch
6. Connecting wires

IV. OBSERVATIONS

In the experiment, the number of turns of the coil was $n = 600$, average field line length for the sample $L = 232$ mm, and $n/L = 2586.2$ m^{-1}. From the, we are able to calculate applied magnetic field intensity as,

$$H = (n/L)I \tag{4}$$

A observational values for the hysteresis curve and degaussing are given in tables I and II.

I (A)	B (Gauss)	B_r (Gauss)	I (A)	B (Gauss)	B_r (Gauss)
1.953	3620	581	-0.945	-1940	-308
-23	-3510	-403	0.947	2130	493
-1.868	-3360	-410	-0.828	-1702	-282
1.826	3480	580	0.834	1949	479
-1.708	-3140	-390	-0.741	-1512	-263
1.711	3310	571	0.742	1715	448
-1.624	-3050	-389	-0.622	-1245	-219
1.627	3230	569	0.624	1453	413
-1.508	-2870	-384	-0.504	-964	-169
1.509	3050	560	0.505	1177	367
-1.42	-2740	-370	-0.46	-855	-146
1.467	2990	556	0.415	958	321
-1.305	-2570	-359	-0.37	-640	-98
1.308	2750	542	0.326	736	273
-1.22	-2430	-349	-0.221	-279	0
1.224	2620	533	0.221	492	203
-117	-2120	-328	-0.131	-76	72
18	2380	516			

TABLE II: Data from degaussing the iron core

V. DATA ANALYSIS AND CALCULATIONS

Hysteresis Curve

From table I, we can plot the hysteresis curve for the iron core.

I (A)	H (A/m)	B (Gauss)	I (A)	H (A/m)	B (Gauss)	I (A)	H (A/m)	B (Gauss)	I (A)	H (A/m)	B (Gauss)
0.007	18.1	25	1.065	2754.31	2790	-1.404	-3631.03	-2690	0.116	300.0	-11
0.123	318.1	260	0.983	2542.24	2690	-1.525	-3943.97	-2870	0.146	377.59	70
0.219	566.38	468	0.837	2164.66	2520	-1.637	-4233.62	-3020	0.187	483.62	176
0.345	892.24	745	0.817	2112.93	2440	-1.73	-4474.14	-3150	0.215	556.03	253
0.424	1096.55	935	0.779	2014.66	2380	-1.806	-4670.69	-3240	0.28	724.14	424
0.522	1350	1171	0.694	1794.83	2230	-1.941	-5019.83	-3400	0.37	956.9	670
0.632	1634.48	1429	0.605	1564.66	2070	-1.985	-5133.62	-3450	0.445	1150.86	873
0.723	1869.83	1637	0.516	1334.48	1900	-2.029	-5247.41	-3500	0.505	1306.03	1032
0.807	2087.07	1822	0.4	1034.48	1630	-1.906	-4929.31	-3420	0.622	1608.62	1340
0.908	2348.28	2020	0.295	762.93	1376	-1.805	-4668.1	-3350	0.699	1807.76	1528
1.013	2619.83	2230	0.152	393.1	984	-1.718	-4443.1	-3280	0.835	2159.48	1844
1.18	3051.72	2530	0.074	191.38	782	-1.55	-4008.62	-3150	0.955	2469.83	2100
1.241	3209.48	2630	0.025	64.66	623	-1.481	-3830.17	-3090	1	2586.21	2190
1.303	3369.83	2750	-0.013	-33.62	511	-1.406	-3636.21	-3020	1.09	2818.97	2360
1.4	3620.69	2880	-0.121	-312.93	204	-1.317	-3406.03	-2930	1.12	2896.55	2420
1.527	3949.14	3050	-0.197	-509.48	-13	-1.202	-3108.62	-2800	1.285	3323.28	2710
1.609	4161.21	3160	-0.212	-548.28	-52	-1.109	-2868.1	-2690	1.33	3439.66	2780
1.736	4489.66	3320	-0.274	-708.62	-222	-1.021	-2640.52	-2580	1.372	3548.28	2850
1.83	4732.76	3440	-0.335	-866.38	-390	-0.875	-2262.93	-2370	1.446	3739.66	2960
1.937	5009.48	3560	-0.427	-1104.31	-638	-0.782	-2022.41	-2220	1.49	3853.45	3020
2.006	5187.93	3630	-0.519	-1342.24	-879	-0.663	-1714.66	-2020	1.535	3969.83	3080
1.9	4913.79	3570	-0.642	-1660.34	-1189	-0.574	-1484.48	-1856	1.609	4161.21	3180
1.801	4657.76	3500	-0.718	-1856.9	-1371	-0.5	-1293.1	-1704	1.699	4393.97	3290
1.689	4368.1	3420	-0.81	-2094.83	-1584	-0.396	-1024.14	-1470	1.743	4507.76	3350
1.595	4125	3340	-0.9	-2327.59	-1779	-0.217	-561.21	-1008	1.833	4740.52	3460
1.52	3931.03	3270	-1.022	-2643.1	-2020	-0.114	-294.83	-710	1.906	4929.31	3540
1.282	3315.52	3050	-1.114	-2881.03	-2200	-0.054	-139.66	-540	1.995	5159.48	3640
1.203	3111.21	2960	-1.221	-3157.76	-2390	-0.01	-25.86	-408			
1.155	2987.07	2900	-1.312	-3393.1	-2545	0.011	28.45	-344			

TABLE I: Data for the Hysteresis Curve

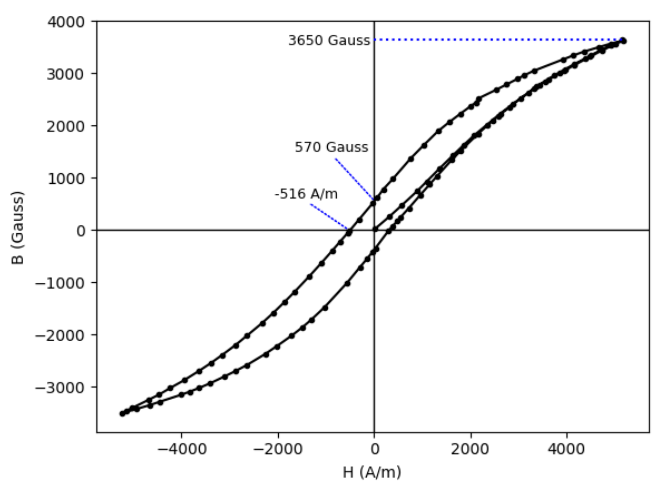

FIG. 3: Induced Magnetic field intensity (B) vs Applied Magnetic field intensity (H) curve

From Fig. 3, we can find the the following parameters:

- Saturation magnetization, by finding the saturation value of B, which is $B_S \approx 3650$ Gauss.
- Remanence or Retentivity, by finding $B|_{H=0} = B_r = 570$ Gauss.
- Coercivity, by finding $H|_{B=0} = H_C = 516$ A/m (in magnitude).

Degaussing the Iron Core

From table II, B vs |B$_r$| plot was generated as follows.

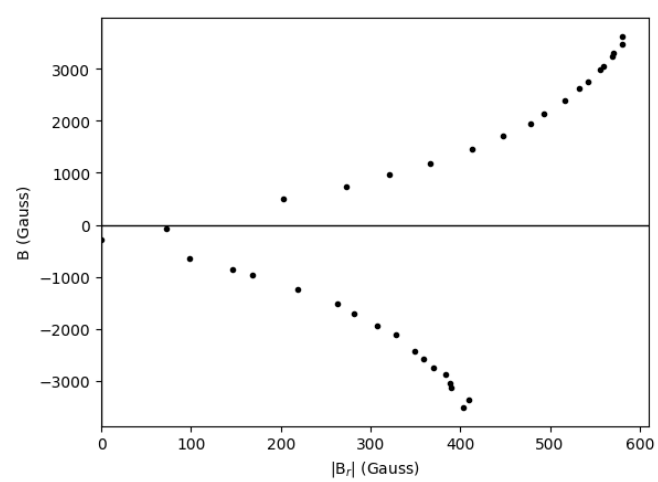

FIG. 4: Induced Magnetic field intensity (B) vs Magnitude of Remnant magnetic field at $I = 0$ ($|B_r|$)

Here, we can see that the remnant magnetic field decreases and eventually reaches 0 as we continue degaussing the iron core.

VI. ERROR ANALYSIS

From Eq. (4), uncertainity in H can be calculated as,

$$\frac{\Delta H}{H} = \frac{\Delta I}{I}$$
$$\text{or, } \Delta H = \frac{H \Delta I}{I} = \frac{H \Delta I}{H \times (L/n)} \tag{5}$$

Where $\Delta I = 0.001$, is the least count of the multimeter. Using equation (5) we can find the uncertainity in coercivity as,

$$\Delta H = \frac{516 \times 0.001}{0.199}$$
$$= 3 \text{ A/m}$$

Additionally, the least count of the Gauss meter is 1 Gauss.

VII. RESULTS AND DISCUSSION

From the hysteresis curve of the ferromagnetic block, we have found out the following parameters.

- Saturation magnetization, $B_S = (3650 \pm 1)$ Gauss
- Remanence, $B_r = (570 \pm 1)$ Gauss
- Coercivity, $H_C = (516 \pm 3)$ A/m

Only ferromagnetic materials exhibit hysteresis curves. The area under the curve represents the energy lost in one complete cycle during magnetization and demagnetization. Materials with greater retentivity are used as permanent magnets.

We also we able to successgly degauss the iron core, i.e. remove any remnant magnetic field by applying a rapidly oscillating magnetic field.

VIII. PRECAUTIONS

- Avoid flow of large current in the coils for prolonged time.
- Avoid taking readings out of order.

[1] SPS, *Lab Manual: Study of magnetic hysteresis in ferromagnetic materials*, NISER (2023).

[2] C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons., 1996).