6.

BH curve tracing

Magnetic characterization of the given materials using Hysteris loop tracer

1. Analysis of the given Ferromagnetic Materials in terms of coercivity, retentivity and saturation magnetization.
2. Identification of magnetic phase.

A note on Magnetic Hysteresis

Magnetic Hysteresis relates to the magnetization properties of a material in which the material becomes magnetized and then de-magnetized. We know that the magnetic flux generated by an electromagnetic coil is the amount of magnetic field or lines of force produced within a given area and that it is more commonly called "Flux Density". The flux density is denoted by the symbol B and its unit is Tesla. We also know that the magnetic strength of an electromagnet depends upon the number of turns of the coil, the current flowing through the coil or the type of core material being used, and if we increase either the current or the number of turns we can increase the magnetic field strength (denoted by symbol H).

The relative permeability symbol μ_r, is defined as the product of μ(absolute permeability) and μ_o, the permeability of free space. The relationship between B and H can be defined by the fact that the relative permeability, μ_r is not a constant but a function of the magnetic field intensity thereby giving magnetic flux density as $B = \mu H$.

So for ferromagnetic materials the ratio of flux density to field strength(B/H) is not constant but varies with flux density. However, for air cored coils or any non-magnetic medium core such as wood or plastic, this ratio can be considered as a constant and this constant is known as μ_o,the permeability of free space. By plotting values of flux density, (B) against field strength, (H) we can produce a set of curves known as magnetization curves or magnetic hysterisis curves or simply BH curves.

Retentivity

Lets assume that we have an electromagnetic coil with a high field strength due to the current flowing through it, and that the ferromagnetic core material has reached its saturation point, maximum flux density. If we now open a switch and remove the magnetizing current flowing through the coil we would expect the magnetic field around the coil to disappear as the magnetic flux is reduced to zero. However, the magnetic flux does not completely disappear as the electromagnetic core material still retains some of its magnetism even when the current has stopped flowing in the coil. This ability to retain some magnetism in the core after magnetization has stopped is called Retentivity or Remanence while the amount of flux density still present in the core is called Residual Magnetism B_r.

The reason for this is that some of the tiny molecular magnets do not return to a completely random pattern and still point in the direction of the original magnetizing field giving them a sort of "memory". Some ferromagnetic materials have a high retentivity(magnetically hard) making them excellent for producing permanent magnets. While other ferromagnetic materials have low retentivity(magnetically soft) making them ideal for use in electromagnets,solenoids or relays. One way to reduce this residual flux density to zero is to reverse the direction of current flow through the coil making the value of H, the magnetic field strength negative and this is called a Coersive Force.

If this reverse current is increased further the flux density will also increase in the reverse direction until the ferromagnetic core reaches saturation again but in the reverse direction from before. Reducing the magnetizing current once again to zero will produce a similar amount of residual magnetism but in the reverse direction. Then by constantly changing the direction of the magnetizing current through the coil from a positive direction to a negative direction,as would be the case in an AC supply, a Magnetic Hysteresis loop of the ferromagnetic core can be produced.

The effect of magnetic hysteresis shows that the magnetization process of a ferromagnetic core and therefore the flux density depends upon the circuit's past history giving the core a form of memory. Then ferromagnetic materials have memory because they remain magnetized after the external magnetic field has been removed. However, soft ferromagnetic materials such as iron or silicon steel have very narrow magnetic hysteresis loops resulting in very small amounts of residual magnetism making them ideal for use in relays and solenoids as they can be easily magnetized and demagnetized.

Hysteresis Loop Tracer

6.1 Introduction

A precise knowledge of various magnetic parameters of ferromagnetic substances and the ability to determine them accurately are important aspects of magnetic studies. These not only have academic significance but are also indispensable for both the manufacturers and users of magnetic materials.

The characteristics which are usually used to define the quality of the substance are coercivity, retentivity, saturation magnetization and hysteresis loss. Furthermore, the understanding of the behaviour of these substances and improvement in their quality demand that the number of magnetic phases present in a system is also known.

The information about the aforementioned properties can be obtained from a magnetization hysteresis loop which can be traced by a number of methods in addition to the slow and laborious ballistic galvanometer method. Among the typical representatives of AC thin films, wires or even rock and mineral samples. Toroidal or ring form samples are more convenient because of the absence of demagnetizing effect due to closed magnetic circuits,but are not practicable to make all test samples in toroidal form with no free ends. Further every time the pickup and magnetizing coils have to be wounded on them and hence are quite inconvenient and time consuming. In the case of open circuit samples, the free end polarities give rise to the demagnetizing field which reduces the local field acting in the specimen and also makes the surrounding field non-uniform. Therefore, it becomes necessary to account for this effect lest the hysteresis loop is sheared. In case of conducting ferromagnetism, several additional problems arises due to eddy currents originating from the periodic changes in applied magnetic field. These currents give rise to a magnetic field in the sample which counteracts the variation of the external field and, in turn, renders the field acting in it non uniform and different from the applied field,both in magnitude and phase. Thus apart from resistive heating of the samples, because of the eddy currents the forward and backward paths traced near saturation will be different, which will lead to a small loop instead of a horizontal line in the magnetic polarization(J) against field(H) plot. The intercept of the magnetic polarization axis, which corresponds to retentivity and saturation magnetic polarization tip will continue to increase with the applied field upto very high values.

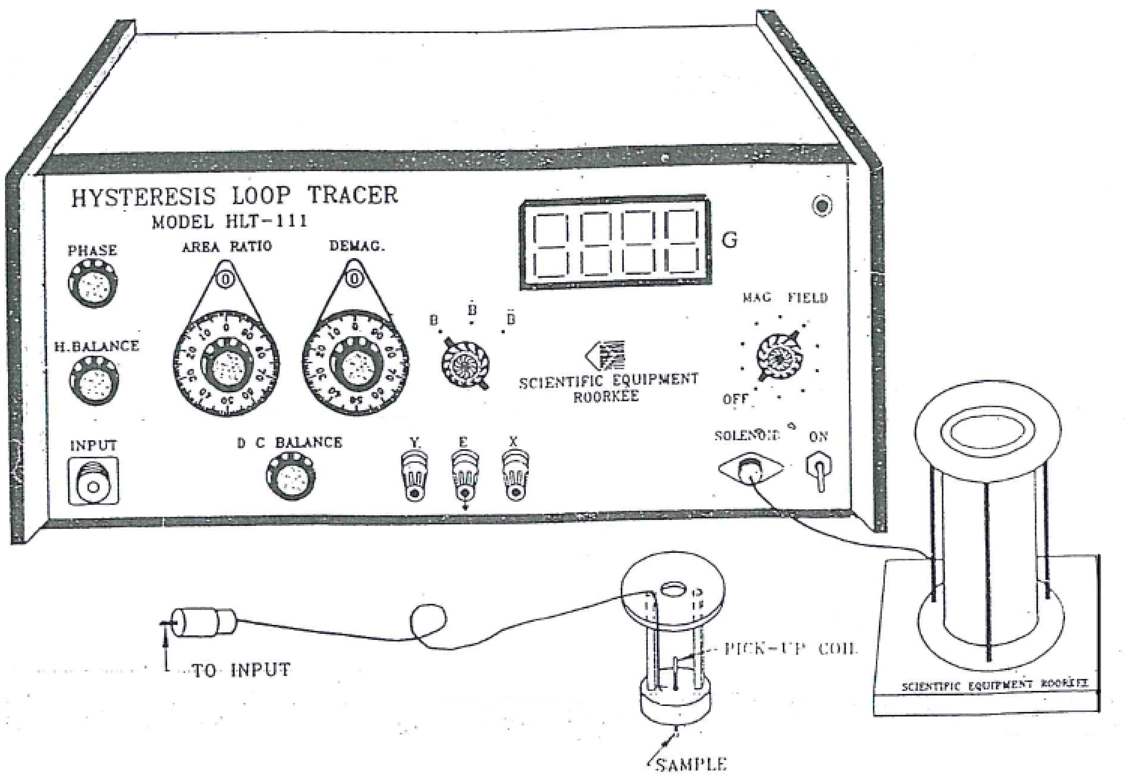

Figure 6.1: Hysteresis Loop tracer

Accordingly,retentivity(J_r) and saturation magnetic polarization(J_s) will be asymptotic values of the J-intercept and tip height respectively against H plots. Furthermore, the width of the loop along the direction of the applied field will depend on its magnitude and will continue to increase because shielding due to eddy currents is proportional to the external field. Therefore, the true value to coercivity (JH_c) corresponding to no eddy currents situation, will be obtained by extrapolating the half loop width against field line to the H=0 axis. Obviously the effect of eddy currents will be more pronounced in thicker samples than in thin ones.

6.1.1 DESIGN PRINCIPLE

When a cylindrical sample is placed coaxially in a periodically varying magnetic field (say by the solenoid) the magnetization in the sample also undergoes a periodic variation. This variation can be picked up by a pick up coil which is placed coaxially with the sample. Normally, the pick up coil is wound near the central part of the sample so that the demagnetization factors involved are ballistic rather than the magnetometric.

For the uniform field H_a produced, the effective field H acting in the cylindrical sample will be

$$H = H_a - NM \tag{6.1}$$

$$H = H_a - \frac{NJ}{\mu_o} \tag{6.2}$$

where N is the normalized demagnetization factor including 4π and J is the magnetic polarization defined by

$$B = \mu_o H + J \tag{6.3}$$

with $B = \mu H$ or $\mu_o(H+M)$ as magnetic induction. The signal corresponding to the applied field, H_a,can be written as

$$e_1 = C_1 H_a \tag{6.4}$$

where C_1 is a constant.

Further the flux linked with the pickup coil of area A_c due to sample of area A_s will be

$$\phi = \mu_o(A_c - A_s)H' + A_s B \tag{6.5}$$

Here H' is the magnetic field, in the free from sample sample area of the pickup coil, will be different from H and the difference will be determined by the magnitude of demagnetizing field. However, when the ration of length of the sample rod to the diameter of the pickup coil is more than 10, the difference between H and H' is too small, so that

$$\dot{\phi} = \mu_o(A_c - A_s)H + A_s B = \mu_o A_c H + A_s(B - \mu_o H) \tag{6.6}$$

$$\phi = \mu_o A_c H + A_s J \tag{6.7}$$

The signal e_2 induced in the pick up coil will be proportional to $\frac{d\phi}{dt}$. After integration the signal(e_3) will, therefore be

$$e_3 = C_3\phi = C_3\mu_o A_c H + C_3 A_s J \tag{6.8}$$

Solving equations(1.1),(1.4) and (1.8) for J and H give

$$C_1 C_3 A_c(\frac{A_s}{A_c} - N)J = C_1 e_3 - \mu_o C_3 A_c e_1 \tag{6.9}$$

and

$$C_1 C_3 A_c(\frac{A_s}{A_c} - N)H = C_3 A_s e_1 - \frac{NC_1 e_3}{\mu_o} \tag{6.10}$$

Based on these equations an electronic circuits may be designed to give values of J and H and hence the Hysteresis loop.

In case the sample contains a number of magnetically different constituents, the loop obtained will be the algebraic sum of individual loops of different phases. The separation of these is not easy in a J-H loop while in a second derivative of J, $\frac{d^2J}{dt^2}$, the identification can be made very clear.

6.1.2 EXPERIMENTAL DESIGN AND ANALYSIS

The aim is to produce electrical signals corresponding to J and H as defined in Eqs.(1.9) and (1.10) so that they can be displayed on CRO(cathode ray oscilloscope). Moreover, it should be able to display $\frac{d\phi}{dt}$ and $\frac{d^2\phi}{dt^2}$ as a function of H or usual time base of the CRO.

A detailed circuit diagram is shown in Fig. 2. The magnetic field has been obtained with a multi-layered solenoid driven by the AC mains at 50Hz and supplied through a variable transformer arrangement. The magnetic field has been calibrated with a Hall probe and is found to be within $\pm 3\%$ of the maximum value over a length of 5cm across the central region. The instantaneous current producing the field is passed through a resistor R_1, in series with the solenoid and measured with an AC ammeter. The resulting signal E_1 is applied across a 500Ω heliopot and an adder amplifier through a 100KΩ resistance.

The signal e_2 corresponding to the rate of change of flux is obtained from a pickup coil wound on a non conducting tube. Necessary arrangements have been made to place the sample coaxially with the pickup winding and in uniform magnetic field. The pickup coil is connected to point B(fig2) through

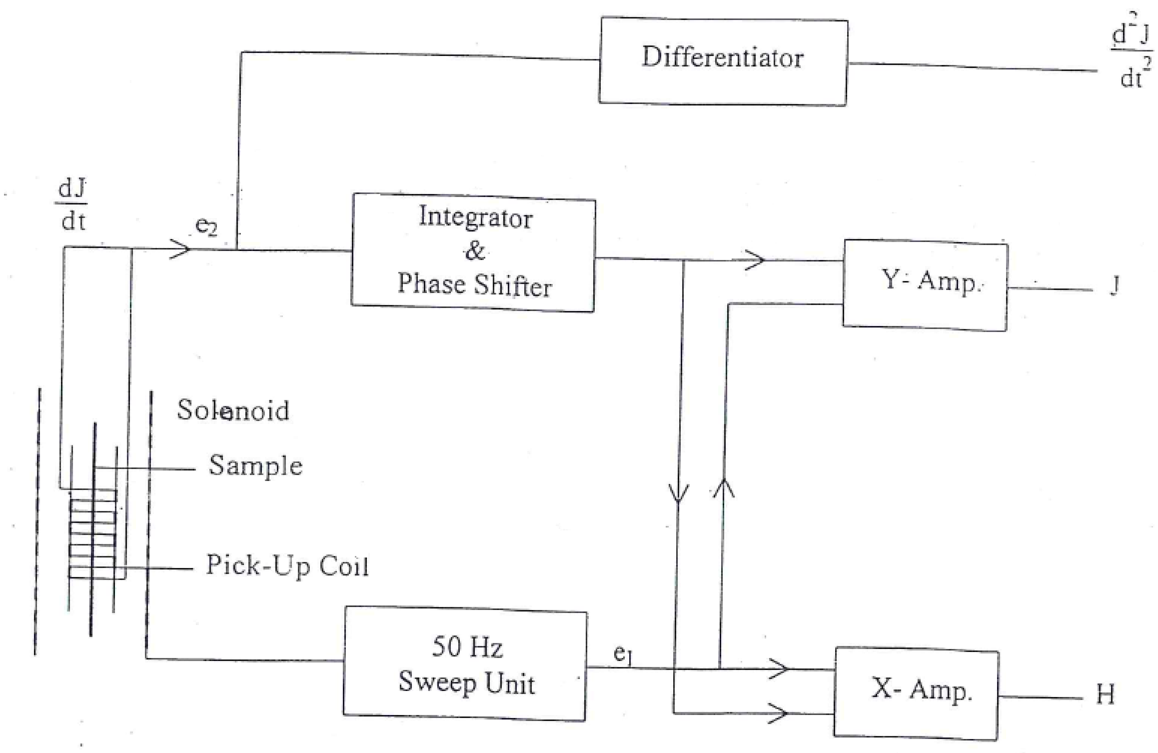

Figure 6.2: Hysteresis Loop tracer

twisted wires, where e_2 constitutes the input for further circuit. To obtain J, $e-2$ is fed to an adjustable gain integrator. Because of capacitive coupling of pickup coil and solenoid, self inductance of pickup coil and integration operation an additional phase will be introduced in the output signal e_3, whose sign can be made negative with respect to e_1 by interchanging the ends of the pickup coil. To render e_3 completely out of phase with e_1,a phase shifter consisting of a 1KΩ potentiometer and 1μF capacitor has been connected at the output of integrator. Amplitude attenuation due to this network is compensated by the gain of the integrator and is not important as addition of signals is performed afterward.

The out of phase signals e_1 and e_3 are added at the input of a unity gain adder amplifier and its output is proportional to J is applied to Y-input of a CRO. Fractions of these signals corresponding to the demagnetization factor and area ration form the input of another adder amplifier with gain 10 whose output after further amplification of 10 is fed to the X-input of CRO and gives H. It may be mentioned that the gains of the amplifier can be adjusted but should always be such that the operational amplifiers are not loaded to saturation.

The selector switch(SW) can change the Y-input of CRO to J,$\frac{d\phi}{dt}$, or $\frac{d^2\phi}{dt^2}$. The $\frac{d\phi}{dt}$ signal is taken directly from the pickup while $\frac{d^2\phi}{dt^2}$ is obtained through an operational amplifier differentiator.

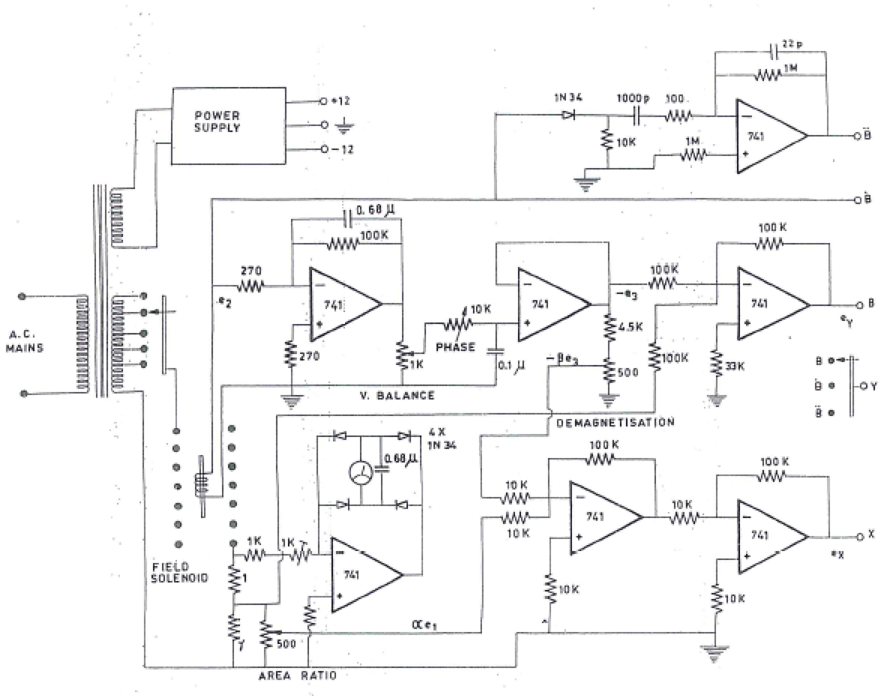

Figure 6.3: Hysteresis Loop tracer

Let us now analyze the circuit.

The magnetic field at the centre of the solenoid for current i flowing through it will be

$$H_a = Ki \tag{6.11}$$

also

$$e_1 = R_1 i \tag{6.12}$$

with symbols defined above. Equation(1.12) reduces to equation(1.4) with $C_1 = R_1/K$. Further, when the sample is placed in a pickup coil of n turns

$$e_2 = n(\frac{d\phi}{dt}) = n\mu_o A_c(\frac{dH}{dt}) + nA_s(\frac{dJ}{dt}) \tag{6.13}$$

by substituting ϕ from equation(1.7), we get

$$-e_3 = -g_1 \int e_2 dt = -g_1 n\mu_o A_c H - g_1 n A_s J \tag{6.14}$$

where g_1 is the gain of the integrator and phase shifter combination. The sum of e_1 and $-e_3$ after amplification becomes

$$e_y = -g_y(e_1 - e_3) = -g_y(C_1H - g_1n\mu_oA_cH + C_1\frac{NJ}{\mu_o} - g_1nA_sJ) \quad (6.15)$$

Using equations(1.1),(1.4) and (1.14), g_y is the gain of this amplifier. If we adjust $C_1 = g_1n\mu_oA_c$then

$$e_y = g_yg_1nA_c(\frac{A_s}{A_c} - N)J \quad (6.16)$$

Fraction α and β of e_1 and $-e_3$ respectively , are added together at the input of the first amplifier for the X-input. If g_x be the total gain of both amplifiers we get

$$e_x = g_x(e_1 - Be_3) = g_xg_1n\mu_oA_c(-B)H + g_xg_1nA_c(N - B\frac{A_s}{A_c})J \quad (6.17)$$

After substituting $C_1 = g_1n\mu_oA_c$, J will be eliminated from the right hand side of equation(1.17). By adjusting α and β such that

$$\alpha = \frac{A_s}{A_c} \quad (6.18)$$

and

$$\beta = N \quad (6.19)$$

we get

$$e_x = g_xg_1n\mu_oA_c(\frac{A_s}{A_c} - N)H \quad (6.20)$$

Equation(1.16) and (1.20) can be written as

$$H = G_o\frac{e_x}{(\frac{A_s}{A_c} - N)} \quad (6.21)$$

and

$$J = \frac{G_o\mu_og_xe_y}{g_y(\frac{A_s}{A_c} - N)} \quad (6.22)$$

where

$$\frac{1}{G_o} = g_xg_1n\mu_oA_c \quad (6.23)$$

Equations(1.21) and (1.22) define the magnetic quantities H and J in terms of electrical signals e_x and e_y respectively.

6.1.3 Method

CALIBRATION

When an empty pick up coil is placed in the solenoid field, the signal e_2 will only be due to the flux linking with coil area. In this case J=0,$\alpha = 1$,N=0, so that $H = H_a$ and Eqs.(1.16) and (1.20) yield

$$e_y = 0 \tag{6.24}$$

and

$$e_x = G_o^{-1} H_a \tag{6.25}$$

i.e. on CRO it will be only a horizontal straight line representing the magnetic field H_a. This situation will, obviously, be obtained only when the condition for (1.16) is satisfied. Thus without a sample in the pickup coil a good horizontal straight line is a proof pf complete cancellation of signals at the input of the Y-amplifier. This can be achieved by adjusting the gain of the integrator and also the phase with the help of network meant for this purpose. From known values of H_a and the corresponding magnitude of e_x, we can determine G_o and hence calibrate the instrument. The dimensions of a given sample define the values of demagnetization factor and the area ratio pertaining to the pickup coil.The demagnetization factor can be obtained from the Appendix. These values are adjusted with the value of 10turn heliopots provided for this purpose. The value of the area ratio can be adjusted upto three decimal places whereas that of N upto four(zero to 0.1max). The sample is now placed in the pickup coil. The plots of J,$\frac{dJ}{dt}$ and $\frac{d^2J}{dt^2}$ against H can be studied by putting the selector switch at appropriate positions. The graph of these quantities can also be obtained from time base by using the internal time base of CRO.

Since eddy currents are present in conducting ferromagnetic materials, the resulting J-H loop has a small loop in the saturation portion due to differences in phases for the forward paths. Moreover, these plots do not show horizontal lines at saturation and hence their shapes can't be employed as a criterion to adjust the value of demagnetization factor.

The values of loop width, intercept on the J-axis and saturation position are determined in terms of volts for different applied fields. Plots of these against magnetic field are then used to extract the value of coercivity, retentivity and saturation magnetic polarization. The first corresponds to the intercept of the width against currents straight line on the Y-axis and it is essentially the measure of the width under no shielding effects. On the other hand, the remaining two parameters are derived from asymptotic extensions of the corresponding plots because these refer to the situation when shielding effects are insignificant. caution is necessary in making the straight line fit for loop widths as function of current data as the points for small values of magnetic current have some what lower magnitudes. This is due to the fact that incomplete saturation produces lower coercivity values in the material. The geometrically obtained values of potential are,in turn, used to find the corresponding magnetic parameters through equations(1.21) and (1.22).If the area ratio for a particular sample is so small that the loop does not exhibit observable width, the signal e_x can be enhanced by multiplying α and β by a suitable factor and adjusting the two heliopots accordingly. The ultimate value of the intercept can be normalized by the same factor to give the correct value of coercivity.

6.1.4 Observations

For this equipment diameter of pickup coil=3.21mm
g_x=100
g_y=1

Sample: Commercial Nickel
Length of sample=39mm
Diameter of sample=1.17mm

Therefore,
Area ratio ($\frac{A_s}{A_c}$) =0.133
Demagnetization factor(N)=0.0029(Appendix)

Calibration
Settings:Without sample. Oscilloscope at D.C. Bal. adjusted for horizontal straight line in the centre. Demagnetization at zero and Area ratio 0.40 at magnetic field 200 Gauss(rms)
e_x=64mm, or
e_x =7.0V(if read by applying on Y input of CRO)

For Area ratio 1
e_x=160mm or e_x=17.5V

Table 6.1: Coercivity

S.No.	**Mag. Field (rms) (Gauss)**	**2xLoop width (mm)**
1.	30	7.0
2.	62	9.0
3.	94	11.0
4.	138	12.5
5.	179	14.0
6.	226	15.5
7.	266	16.75
8.	302	18.0
9.	336	18.75

From equation(1.25)
G_o(rms)=$\frac{200}{160}$=1.25gauss/mm
G_o(peak to peak)=1.25x2.82=3.53gauss/mm,

also
G_o(rms)=$\frac{200}{17.5}$=11.43gauss/volt
G_o(peak to peak)=11.43x2.82=32.23gauss/volt

By adjusting N and $\frac{A_s}{A_c}$ as given above the J-H loop width is too small. Thus both are adjusted to three times i.e. 0.0087 and 0.399 respectively.

The measurements for Coercivity, Saturation Magnetization and Retentivity are given in table 1.1 ,1.2 and 1.3.

Table 6.2: Saturation Magnetization

S.No.	**Mag. Field (rms) (Gauss)**	**Tip to Tip height(mV)**
1.	29	205
2.	61	370
3.	96	400
4.	137	420
5.	176	430
6.	223	440
7.	264	445
8.	298	450
9.	331	450

Table 6.3: Retentivity

S.No.	**Mag. Field (rms) (Gauss)**	**2xIntercept (mV)**
1.	29	170
2.	61	260
3.	95	265
4.	136	270
5.	175	270
6.	219	275
7.	263	275
8.	302	275
9.	335	275

From the graphs Fig(5) and Fig(6), we have
Loop width=2.9mm(after dividing by the multiplying factor 3)
2xIntercept=280mV
Tip to tip height=457.5mV

(a)Coercivity Since $e_x = \frac{1}{2}\times$ loop width $=\frac{1}{2} \times 2.9 = 1.45$mm

$H = \frac{G_o e_x}{(\frac{A_s}{A_c} - N)} = \frac{3.53\times1.45}{0.133-0.0029} = 39.30$ from equation(1.21)

(b)Saturation magnetization

$\mu_s = \frac{J_s}{4\pi}$ from equation(1.3)

$(e_y)_s = \frac{1}{2}\times$tip to tip height =457.5/2=228.75mV

$\mu_s = \frac{J_s}{4\pi} = \frac{G_o \mu_o g_x (e_y)_s}{g_y(\frac{A_s}{A_c} - N)\times 4\pi}$ from equation(1.22)

$\mu_s = \frac{32.23\times1\times100\times0.229}{1\times(0.133-0.0029)\times12.56} = 452$ gauss

(c)Retentivity

$\mu_r = \frac{J_r}{4\pi}$ from equation(1.3)

$(e_y)_r = \frac{1}{2} \times (2\times$ Intercept$)=\frac{1}{2} \times 280 = 140$mV

$$\frac{J_r}{4\pi} = \frac{G_o \mu_o g_x (e_y)_r}{g_y(\frac{A_s}{A_c} - N)\times 4\pi} = \frac{32.23\times1\times100\times0.140}{1\times(0.133-0.0029)\times12.56} = 276 \text{ gauss}$$

QUESTIONS
1. Explain the difference in J-H loop of hard and soft iron samples?
2. Why the loop width graph was extrapolated to zero magnetic field?
3. Why the asymptotes were drawn for finding J_s and J_r ?

APPENDIX

Demagnetizing Factors for Ellipsoids of Revolution For Prolate Spheriods, c is the polar axis

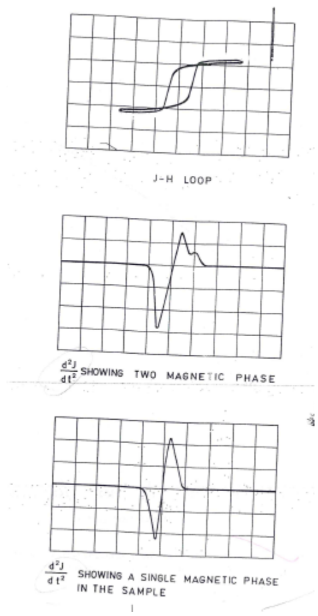

Figure 6.4: Different curves J-H and $\frac{d^J}{dt^2}$ for two and single magnetic phase

C/a	$N_c/4$	**C/a**	$N_c/4$	**C/a**	$N_c/4$
1.0	0.333333	4.0	0.075407	20	0.006749
1.1	308285	4.1	72990	21	6230
1.2	286128	4.2	70693	22	5771
1.3	266420	4.3	68509	23	5363
1.4	248803	4.4	66431	24	4998
1.5	0.232981	4.5	0.064450	25	0.004671
1.6	218713	4.6	62562	30	3444
1.7	205794	4.7	60760	35	2655
1.8	194056	4.8	59039	40	2116
1.9	183353	4.9	57394	45	1730
2.0	0.173564	5.0	0.050821	50	0.001443
2.1	164585	5.5	48890	60	1053
2.2	156326	6.0	43230	70	0.805
2.3	148710	6.5	38541	80	0.637
2.4	141669	7.0	34609	90	0.518
2.5	0.135146	7.5	0.031275	100	0.000430
2.6	129090	8.0	28421	110	363
2.7	123455	8.5	25958	120	311
2.8	118203	9.0	23816	130	270
2.9	113298	9.5	21939	140	236
3.0	0.108709	10	0.020286	150	0.000209
3.1	104410	11	17515	200	125
3.2	100376	12	15297	250	083
3.3	096584	13	13490	300	060
3.4	093015	14	11997	350	045
3.5	0.089651	15	0.010749	400	0.000036
3.6	86477	16	09692	500	24
3.7	83478	17	08790	600	17
3.8	80641	18	08013	700	13
3.9	77954	19	07339	800	10

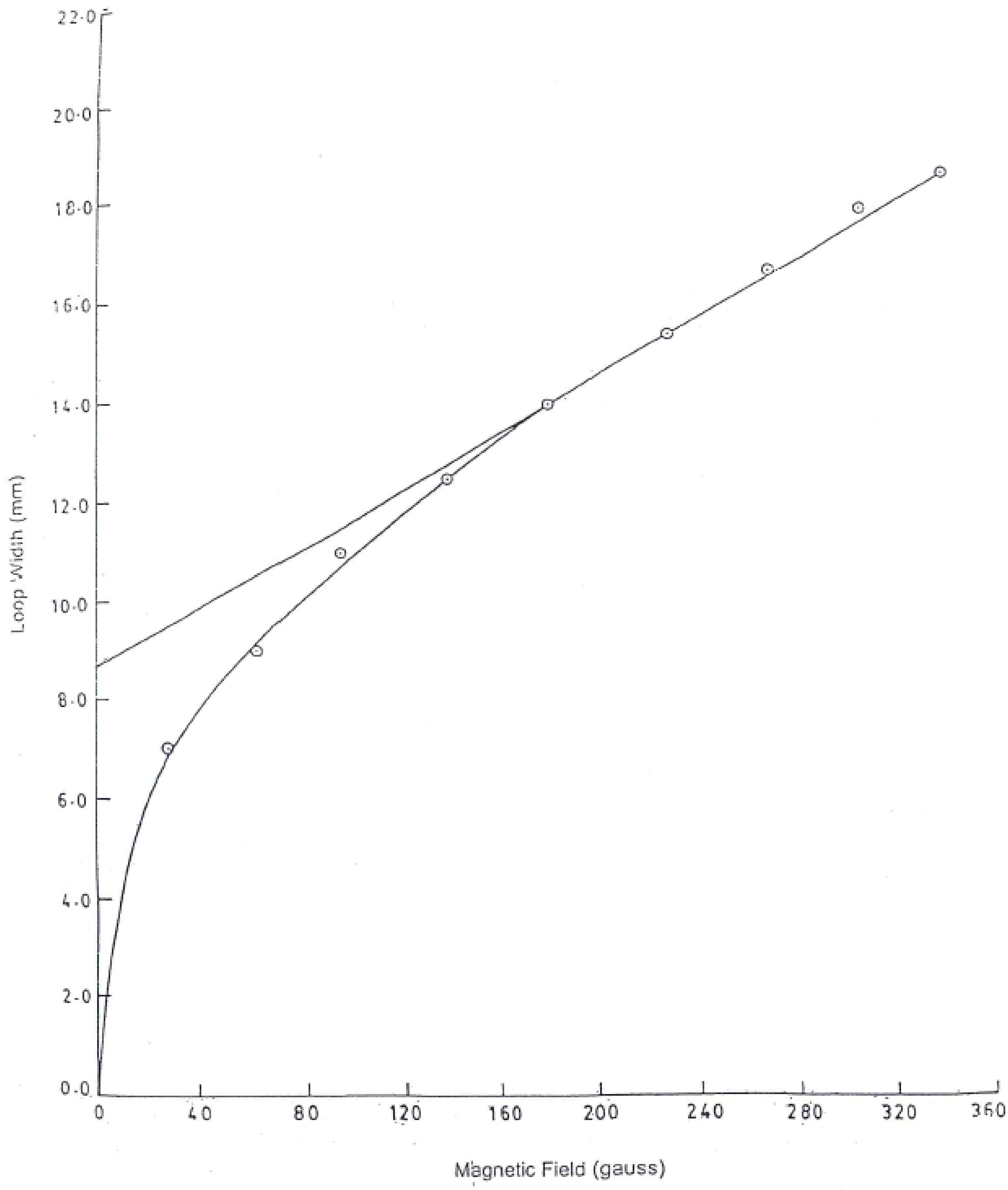

Figure 6.5: Dependence of loop width on magnetic field. The intercept of straight line fit gives coercivity from equation.

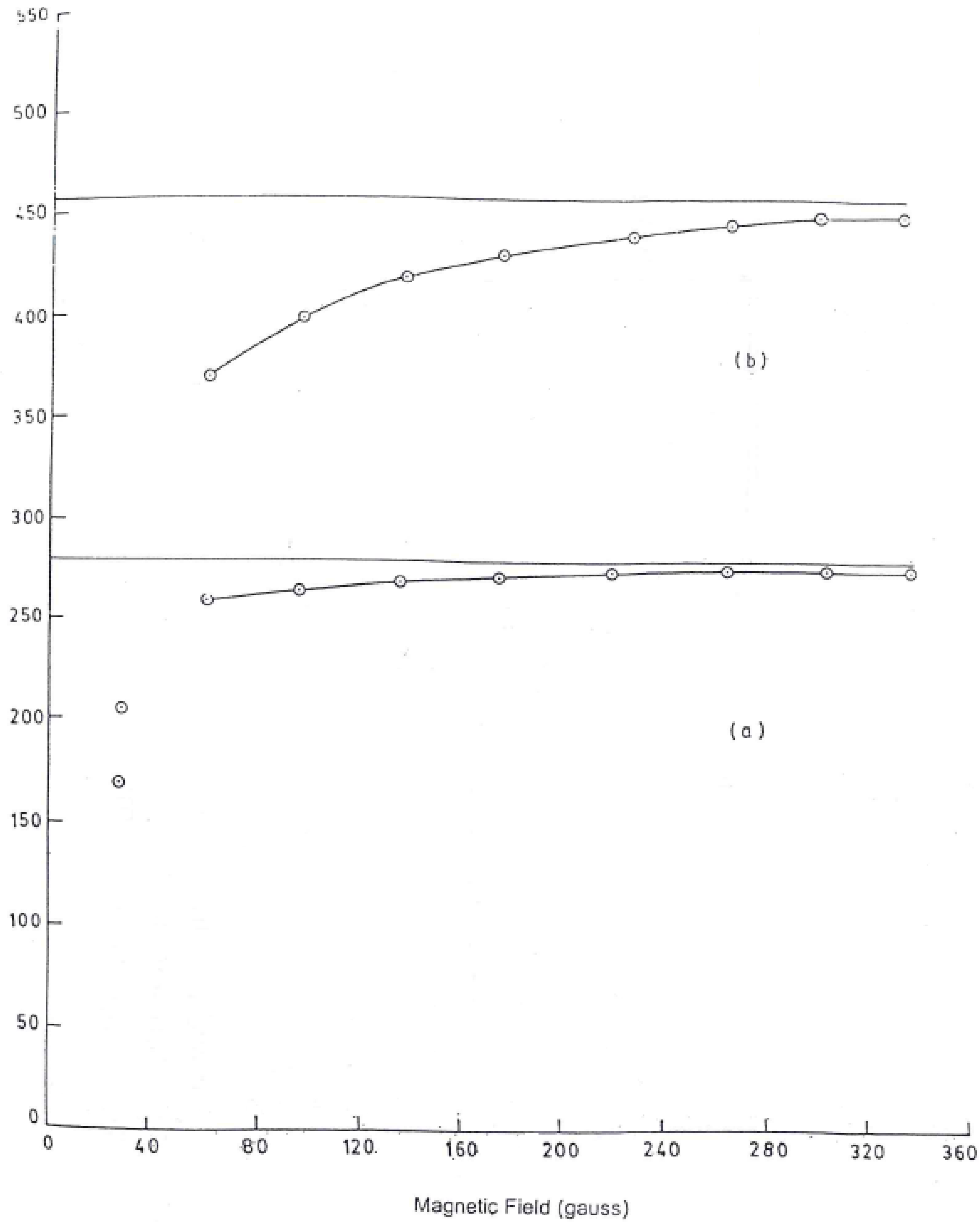

Figure 6.6: Dependence of (a) Twice the Intercept on the Y-axis, and (b) Tip to tip separation of J-H Plot for commercial Nickel on Magnetic Field.

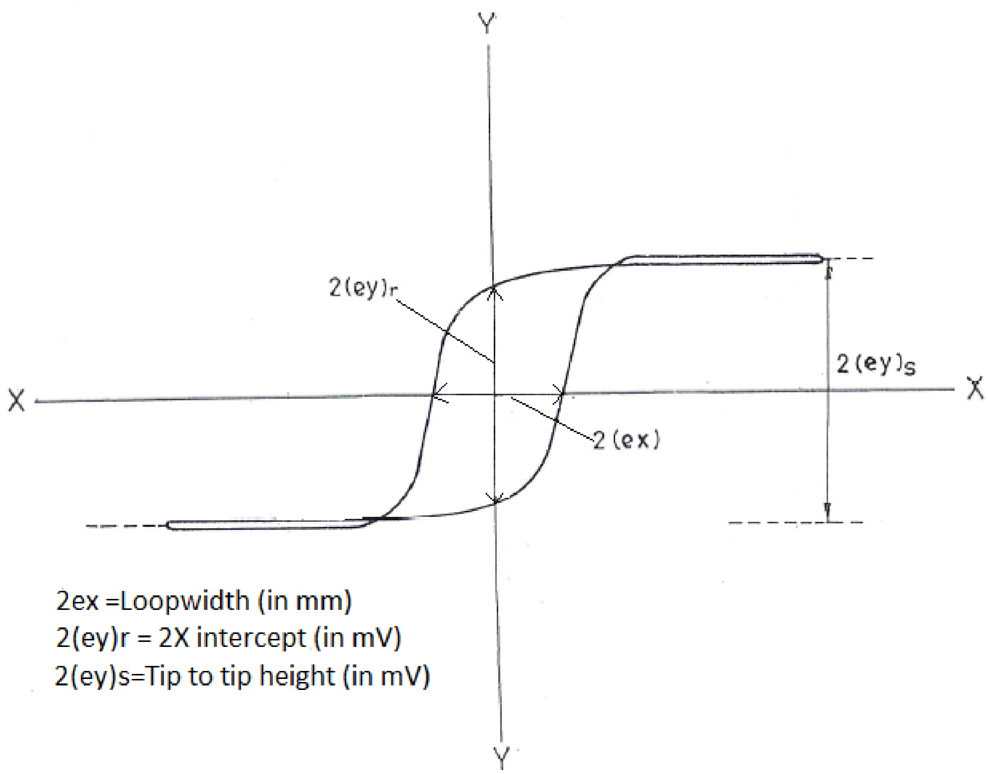

Figure 6.7: The hysteresis Loop