THE NATURE OF SOFT FERRITES

Ferrites are polycrystalline oxides manufactured by ceramic technology appertaining to a class of materials, which show technically useful properties of feromagnetism. They are very hard, brittle and chemically inert. Ferromagnetic materials-ferrite materials are subdivided by internal energy into a great number of discrete zones, called magnetic domains, in which magnetic moments of adjacent atoms are aligned. Domains consist of small crystals with dimensions of 10 - 20 [µm].

In ferrite materials, magnetization occurs under the influence of an externally applied field. By removing this field, soft ferrite materials return to their non-magnetized state. In this state, the domains are randomly oriented and it is not possible to detect any magnetization by measurement. When an external field is applied, domains tend to align themselves in the direction of the field.

GENERAL DEFINITIONS

1. HYSTERESIS LOOP

If an alternating field is applied to a soft magnetic material, a hysteresis loop is obtained. Ferromagnetic material is placed in a magnetic field and the magnetic flux density B appears as a function of the magnetic field strength H, which is measured by means of a test coil. The relationship shown in the hysteresis loop (Fig.1) has been obtained.

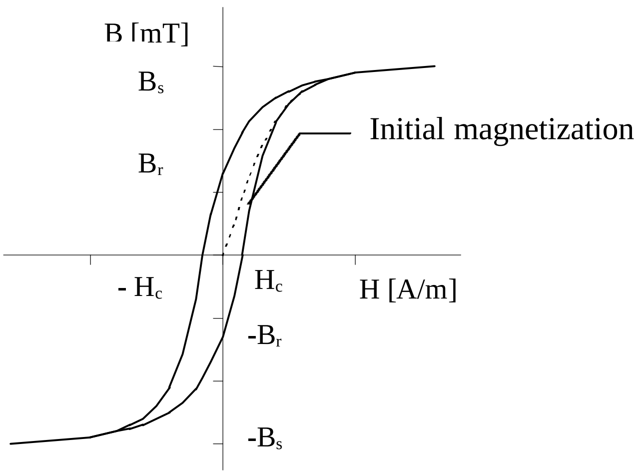


Fig.1

1.1 Initial magnetization curves is described by the relationship

$$B = m_0 m_r \cdot H$$

for the first magnetization following a complete demagnetization.

1.2. B_s **- saturation magnetization** is defined as the maximum flux density in a specific material. In the table "Survey of materials and characteristics" there are specified magnetic densities of materials measured at magnetic field strength of 250 [A/m].

1.3 B_r - remanent flux density
is a magnetic flux density remaining in material before being magnetized to its saturation point, when magnetic field strength decreases to zero.

1.4 H_c - coercitive field strength
is the value of the magnetic field strength which the magnetic flux density of material has previously magnetized to the saturation point decreased to zero.

2. PERMEABILITY
Permeability is generally defined as a ratio between the induced magnetic flux density in the material and the magnetic field strength

$$\mu = \frac{B}{H}$$

2.1 Relative permeability μ_r
is obtained by dividing the absolute permeability by magnetic constant μ_0.

2.2 Initial permeability μ_i
is the limiting value of the amplitude permeability, when the magnetic field strength has approached zero value.

$$\mu_i = \lim_{H \to 0} \mu_a$$

Initial permeability of the magnetically closed ring core (toroid) of square cross section has been established by measuring the inductance of the coil wound formal on the core. Initial permeability may be calculated by the following equation:

$$\mu_i - 1 = \frac{2\pi \cdot (L - L_o)}{\mu_{0} \cdot N^2 \cdot h \cdot \ln \frac{d_0}{d_i}}$$

Initial permeability given in the table "Survey of materials and characteristics" was measured with magnetic flux density $B \leq 0.25$ [mT] and at frequency of 10 [kHz] or 100 [kHz] (μ_i 500) on ring cores T 22x14x7mm.

2.3 Effective permeability μ_e
Effective permeability is dependent on the initial permeability of the soft magnetic material and the dimensions of air-gap and circuit. Effective permeability is the parameter of magnetic circuit formed of different respectively unhomogeneous materials. It is equivalent to the permeability of homogeneous hypothetical magnetic circuit that corresponds in shape, size and in whole reductance to the already mentioned magnetic circuit. Effective permeability for a magnetically closed ferrite core with an air-gap is calculated by the following equation:

$$\mu_e = \frac{L}{\mu_{0} N^2} \cdot \Sigma \frac{l}{A}$$

in which $\Sigma \frac{l}{A}$ is defined as the form factor.

The effective permeability is not only the property of material, but also depends on the core shape and size and air-gap length. The following approximate equation applies to an air gap of s << l_e

$$m_e = \frac{1}{\frac{1}{m_i} + \frac{s}{l_e}}$$

2.4 Complex permeability $\underline{m}$

A coil wound on a magnetically closed core, which apart from a certain permeability also provokes some losses and may be simulated by a series connection of an ideal pure inductance L_s and loss resistance R_s. The impedance Z of a coil could be calculated by the following equation:

$$Z = R_s + jw \cdot L_s$$

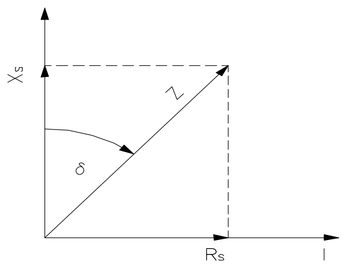
The resistance R_s involves only loss resistance of the core and not of the winding. The impedance Z of a series connection could also be expressed by the complex permeability $\underline{m}$ in which L_o represents the coil inductance without core. Thus we obtain :

$$\underline{m} = \frac{L_s}{L_0} - \frac{jR_s}{wL_0}$$

Complex permeability $\underline{\mu}$ may be expressed as:

$$\underline{m} = m_s' - jm_s'' \,,\; m_s' = \frac{L_s}{L_0} \,,\; m_s'' = \frac{R_s}{wL_0}$$

Inclusion of the resistive loss provokes a reduction of the phase angle between voltage and current from 90° by angle δ denominated the loss angle. From the voltage vector graph of the series combination:



$$\tan d = \frac{R_s}{wL_s} = \frac{m_s''}{m_s'} = \frac{1}{Q}$$

2.5 Amplitude permeability m_a

The relationship between higher field strength and flux densities without the presence of bias field, is given by the amplitude permeability. Amplitude permeability is a relative permeability defined by maximum magnetic flux density *B* and magnetic field strength *H*.

$$m_a = \frac{1}{m_0} x \frac{\hat{B}}{\hat{H}}$$

Magnetic field strength varies periodically and its mean value is at zero point. Material must be properly demagnetized. The magnetic flux density of magnetic domains should be zero. Since the BH loop is far from linear, values depend on the applied field peak strength.

2.6 Apparent permeability m_{app}

We consider an apparent permeability with magnetic open ferrite cores, in which the magnetic lines of force, generated by a current flowing in a winding, pass through the core. The apparent permeability is the ratio between the inductance of a coil with core L and the inductance of the same coil without core L_O :

$$m_{app} = \frac{L}{L_0}$$

2.7 Reversible (incremental) permeability m_{rev}

Where DC current to a winding produces a biasing field (H_{DC}), the operating point of a small A.C. excitation is moved to a higher point on the B - H curve. In such cases measurements of the inductance may differ from those obtained from an A.C. current, when there has been no D.C. pre-magnetization done. The amplitude permeability excursion of the A.C. is defined by the reversible (incremental) permeability.

$$m_{rev} = \frac{1}{m_0 \left(\frac{B}{H} \right)_{H_{DC}}}$$

$$\lim H \to 0$$

3. LOSSES

Losses in the ferrite core are represented by the power which the core takes from alternating electromagnetic field and which it is converted into heat. Eddy current, hysteresis and residual losses represent entire losses of the core.

$$P_{tot} = P_e + P_h + P_r$$

Because of the hysteresis of the magnetization loop B f(H) a specified amount of energy related to the loop area is consumed during each cycle. If the field strength is very low, this energy is very small and may be considered almost negligible, except in cases in which there are usually very low losses. High flux density power losses caused by hysteresis are proportional to the number of cycles (frequency) and flux density.

3.1 Tangens of the loss angle $\tan d$ and quality factor Q

In case of a series substitute connection of the coil with the ferrite core, tangens of the loss angle of the core at low magnetic flux density 0.1 [mT] is expressed as the relation between the loss resistance of the core (without loss resistance of the coil winding) and inductive resistance.

$$\tan d = \frac{R_s}{wL}$$

Acceptability of a ferrite core is defined as a reciprocal value of the loss angle $\tan d$.

$$Q = \frac{1}{\tan d} = \frac{wL}{R_s}$$

3.2 Relative loss factor $\frac{\tan d}{m_i}$

The loss factor of magnetically closed ferrite core with an air gap depends on the size of this air gap. The permeability and loss factor of the core decrease in the same manner as the air gap increases. Therefore :

$$\frac{\tan d}{m_i} = \frac{\tan d_e}{m_e}$$

$\frac{\tan d}{m}$ is the relative loss factor and does not depend on the size of an air gap, when an air gap is not wide.

The magnetic lossescan be split up into three components: hysteresis losses, eddy current losses and residual losses. All this components cause the phase shift.

3.3 Hysteresis material constant h_B

The hysteresis material constant h_B characterizes the hysteresis losses in ferrite material. It does not depend on the air gap. It represents a nonlinearity of BH curves.

$$h_B = \frac{\Delta R_h}{wL \cdot m_e \cdot \Delta B}$$

Hysteresis constant h specified in the table "Survey of materials and characteristics" was measured on [kHz and at magnetic flux densities of 1.5 [ ] and 3 mT]

3.4 Power losses $_V$

energized - magnetized by higher hysteresis loop. In such cases the specific power loss

apply :

$$U \cdot I \cdot \qquad \frac{P}{V} = \frac{P_V}{V_e}$$

The power loss may be empirically expressed by:

$$P_V = k \cdot f^{\,a} \cdot B^{\,b}$$

The constant "a" has values between 1.2 - 1.7 and constant "b" between 2.1 - 2.7 .

On given pages of material these constants are more commonly expressed in total power loss at specific flux densities, frequencies and temperatures by assuming sinusoidal induction.

4. STABILITY

4.1 Relative temperature coefficient of the permeability a_F

The permeability of ferrite is a function of temperature. It generally increase with temperature to maximum value and then drops sharply to a value of 1. Temperature coefficient of a magnetically closed ferrite core with an air-gap decreases at the same rate as does the initial permeability. That is why a_F is specified as a constant of material independent of the air-gap.

$$a_F = \frac{m_{i2} - m_{i1}}{m_{i1} m_{i2} \cdot \left(J_2 - J_1\right)}$$

Temperature coefficient of a coil inductance, having ferrite core with an air-gap, may be calculated by multiplying the relative temperature coefficient of the ferrite material, by which the core is made of, with effective permeability of the core:

$$\frac{\Delta L}{L} = a_F \cdot m_e \cdot \Delta J$$

4.2 Disaccommodation factor D_F

Disaccommodation should be understood as a time variation of the initial permeability occurring after each demagnetization under constant operating conditions. It has been proved by experiments that initial permeability decreases in a linear way by plotting time on a logarithmic scale. Therefore the time variation criterion of initial permeability is defined as disaccommodation factor D_F which denotes the material constant depending on the air gap.

$$D_F = \frac{m_{i1} - m_{i2}}{m_{i1}^2 \cdot \log\left(\frac{t_2}{t_1}\right)}$$

The disaccommodation factor makes possible to make estimates of permeability variations for a long period (years), even though measured in a short interval. Disaccommodation factors specified in the catalogue were measured on toroids at 40 [°C] in intervals of 10 and 100 minutes after demagnetization. Cores were demagnetized with an alternating current, the amplitude of which decreased exponentially from max. value to zero at frequency of 150 [Hz].

4.3 Curie temperature T_c

Curie temperature is the temperature above which the disruption of magnetic ordering in the crystal lattice by increasing thermal motion causes the material to lose its ferromagnetic characteristic, and the permeability falls near zero. Curie temperature on given pages of material is defined at temperatures where the initial permeability has fallen by 10 % from its room temperature value.

4.4 Specific resistivity *r*

Specific resistivity given on pages specifying material data were measured on disks with Indium-Gallium electrodes at low current density (< 50 [A / m^2]). In the following table dependence of frequency on specific resistivity with 15G material is shown :

f (kHz)	10	100	500	1000
ρ (Ωm)	3.0	2.8	2.5	2.0

Influence of the frequency on specific resistivity with materials E, F and C is small.

5. MAGNETIC CORE SHAPE CHARACTERISTICS

5.1 Geometric core constants

Goemetric core constants are calculated from component dimensions according to the international standard IEC 205.

Form factor :

$$\sum \frac{l}{A} = \frac{l_e}{A_e}$$

Effective length l_e :

$$l_e = \frac{C_1^2}{C_2}$$

by taking into consideration

$$C_1 = \sum \frac{l}{A}\ , \quad C_2 = \sum \frac{l}{A^2}$$

Effective area A_e :

$$A_e = \frac{C_1}{C_2}$$

Effective volume V_e :

$$V_e = \frac{C_1^3}{C_2^2} = l_e \cdot A_e$$

5.2 Inductance of coil with ferrite core L

For a particulare core shape, magnetic data are influenced to a significant extent by its geometry. Inductance of coil on ferrite core is defined:

$$L = \frac{\mu_0 \mu_e \cdot N^2 \cdot A_e}{l_e}$$

in which *N* represents the number of turns. The magnetic constant is determined as μ_0.

$$\mu_0 = 4\pi \cdot 10^{-7}\ \text{[Vs / Am]}$$

5.3 Inductance factor A_L

Inductance factor A_L expresses the inductance of a coil wound with one turn on the ferrite core.

$$A_L = \frac{L}{N^2}$$

A_L factor is usually given in [nH] as a constant of the core and is used to calculate the number of turns required for a given inductance.