1.Ferrites

Ferrites are crystalline oxides manufactured by ceramic technology. They belong to a class of materials which exhibit the technically useful property of ferromagnetism.

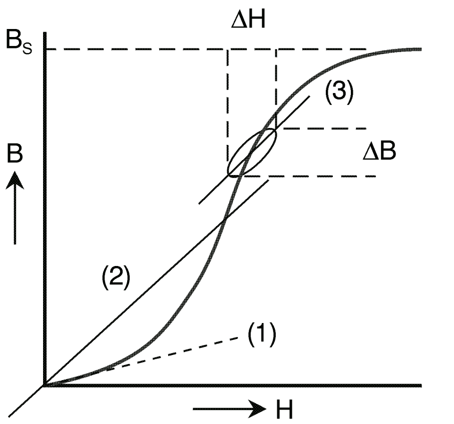
In metals, ferromagnetism is due to the atomic forces aligning adjacent electron 'spins' in parallel, creating very strong magnetic fields within a body.

Ferrites differ from metals in that they are oxides with a 'spinel' crystalline structure. This contains two magnetically opposing layers and can be represented as successive planes of metallic ions separated by oxygen ions. Interactions between metal and oxygen result in a reduction of electron conductivity compared to a metallic material, giving ferrites their high resistivity and low losses at high frequencies. The opposing spins also result in a lower polarisation than for metals and correspondingly lower saturation flux densities.

2.Permeability

The principal properties of ferrites which determine their technical performance are permeability and its variation in response to external field, to frequency and to temperature.

Permeability is defined as the ratio between the magnetic flux density induced in the material and the magnetic force which causes it. A schematic view of this relationship is shown below and has led to several concepts of permeability.



(1) Intrinsic Permeability (ring core)
(2) Amplitude Permeability
(3) Incrimental Permeability

2.1 Intrinsic Permeability

Intrinsic permeability is the ratio between flux density ΔB in a closed ring core, and the applied field strength ΔH at very low a.c. fields.

$$\mu_i = \frac{1}{\mu_o} \cdot \frac{\Delta B}{\Delta H} \quad (\text{Lim. } \Delta H \rightarrow 0)$$ where μo is the magnetic field constant: $$\mu_o = 4\pi \times 10^{-7} \frac{H}{m} \text{ or } \frac{T}{(A/m)}$$

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Measurements are genarally made at a flux density <0.1mT for ring cores and <1mT for components with a sheared flux path. Intrinsic permeability is calculated from:

$$\mu_i = \frac{10^{-6}}{\mu_o} \cdot \frac{L}{n^2} \cdot \sum \frac{l}{A}$$

$\sum \frac{l}{A}$ = Geometric core constant, C_1 (mm $^{-1}$)

n = Number of Turns

L = Inductance (nH)

$$= \frac{1}{0.4\pi} \cdot \frac{L}{n^2} \cdot \sum \frac{l}{A}$$

The intrinsic permeability is also known as the initial permeability (reference to its position on the B vs. H curve), and as the 'toroidal' permeability (reference to its measurement on ring cores).

2.2 Goemetric Core Constants

For a thin walled toroid, a uniform and magnetic flux density may be assumed. For thick toroids and other components, where the cross-sectional area varies along the flux path, it is necessary to calculate 'effective' magnetic dimensions.

Geometric core constants are calculated from component dimensions according to the IEC document 60205, giving constants:

$$C_1 \left(\sum \frac{l}{A}\right) \text{ and } C_2 \left(\sum \frac{l}{A^2}\right)$$

Geometric Core Constant:

$$\sum \frac{l}{A} = C_1 \quad (\text{mm}^{-1})$$

Effective Length

$$L_e = \frac{C_1^2}{C_2} = \frac{\left(\sum \frac{l}{A}\right)^2}{\sum \frac{l}{A^2}} \quad (\text{mm})$$

Effective Area

$$A_e = \frac{C_1}{C_2} = \frac{\sum \frac{l}{A}}{\sum \frac{l}{A^2}} \quad (\text{mm}^2)$$

Effective Volume

$$V_e = \frac{C_1^3}{C_2^2} = l_e . A_e \quad (\text{mm}^3)$$

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2.3 Effective Permeability (μ_e)

In most cases ferrite cores contain an air gap, either purposely introduced for a specific magnetic performance or caused by grinding the mating faces.

This results in the permeability of the core being lower than the intrinsic permeability of the material. This reduced permeability is calculated from the inductance of a winding on the core and is the effective permeability, μ_e.

$$\mu_e = \frac{1}{\mu_o} \cdot \frac{L}{n^2} \cdot \sum \frac{l}{A}$$

(See section 'Gapped Cores')

The effective permeability is used in the calculation of losses, temperature coefficient and disaccommodation.

2.4 Inductance Factor (A_L)

It is usual to provide information on the expected inductance when winding a specific core. This information is given by the A_L, inductance factor.

As inductance of a coil is proportional to the square of the number of turns , A_L is the inductance per turn squared.

$$A_L = \frac{L\,(nH)}{n^2}$$

$$= \frac{\mu_e}{\sum \frac{l}{A}} \cdot \mu_o$$

A_L values are generally measured using fully wound coil formers. The number of turns required to produce a specific inductance is:

$$n = \sqrt{\frac{L}{A_L}}$$

2.5 Rod Permeability (μ_{rod})

Many ferrite cores, of which aerial rods and screw cores are typical examples, are used in such a manner that the ferrite material only occupies part of the path of the magnetic lines generated by the current flowing in the winding. The magnetic circuit is then virtually open and very strong demagnetising fields appear at the end faces of the core. Depending on the length-to-diameter ratio for cylindrical cores, the permeability (rod permeability) can be calculated from the intrinsic permeability of the material.

Because of the nature of the magnetic circuit, rod permeability is always much lower than the intrinsic permeability of the material, and the difference between these permeabilities increases as the length-to-diameter ration decreases.

For guidance a graph of μ_{rod} vs. length-to-diameter ratio is given in the component pages for rods.

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2.6 Amplitude Permeability (μ_a)

When a high alternating magnetic field is applied, as in power transformers, the curve of the B vs. H path causes the permeability to change during the cycle.

The definition of permeability which is of greater use to the designer is the amplitude permeability, μ_a, generally at specific flux densities and temperatures.

$$\mu_a = \frac{1}{\mu_o} \cdot \frac{\hat{B}}{\hat{H}}$$

where B is the peak flux density in Tesla (sinusoidal induction) and H is the peak field strength in A/m.

In the case of measurements carried out on the winding of a gapped core the result is an 'effective' amplitude permeability in which the amplitude permeability of an equivalent toroid is reduced by the reluctance of the air gap.

In the material data pages amplitude permeabilities are indicated for toroidal cores. In the component specifications the effective amplitude permeabilities are given.

For components where the cross sectional area of the flux path varies, μ_a is measured setting the peak flux density in the minimum cross section (i.e. the voltage calculation uses A_{min} in place of A_e).

For ferrites used in power applications, information generally includes the bottom limit of the amplitude permeability, at 25°C and 100°C

2.7 Incremental Permeability (μ_D)

Where a d.c current is applied to a winding, producing a biasing field (H_B), the operating point of a small a.c. excitation is moved to a higher point on the B-H curve.

The amplitude permeability of the a.c. excursion is termed the incremental permeability.

$$\mu_\Delta = \frac{1}{\mu_o} \left[\frac{\Delta B}{\Delta H}\right]_{H_B} \quad (\text{Lim.}\, \Delta H \rightarrow 0)$$

For further discussion refer to section 'Gapped Cores D.C. Loading'.

2.8 Saturation Induction (B_{sat})

Saturation flux density (B_S) as that value obtained for a field strength of 800A/m (10 Oersted).

$$B_S = H + 4\pi J_S$$

where J_S is the saturation polarisation of the material.

The saturation induction is an important parameter in the design of power transformers. Although it is an intrinsic property, saturation induction is normally indirectly specified in component data pages for transformer cores as a minimum value of amplitude permeability.

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3.0 Losses (General)

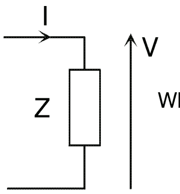
Losses associated with a coil wound on a ferrite core can be represented by the resistive component of its impedance at any frequency and any field strength.

$$Z = R_{wind} + R_h + R_r + R_e + j\omega L$$

R_{wind} is the winding resistance loss
R_h is the hysteresis loss of the core
R_r is the residual loss of the core
R_e is the eddy current loss of the core
$j\omega L$ is the inductive reactance of the core

3.1 Impedance (Z)

The ratio of r.m.s. voltage over r.m.s. current in a circuit with sinusoidal excitation is defined as the impedance and is expressed in Ohms.

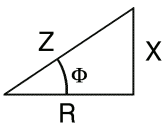


Where $Z = \frac{V}{I} = Z\angle\Phi$

Φ is the angle by which voltage leads the current. Hence,

Resistance, R = ZCos Φ (ohms)
and Reactance, X = ZSin Φ (ohms)

This can be represented in the impedance triangle,



$$Z^2 = R^2 + X^2$$
$$\bar{Z} = R \pm jX$$
$$|Z| = \sqrt{R^2 + X^2}$$

For suppression applications it is advantageous to maximise the resistive component at the interfering frequency.
In the material data pages for F9C and F19 impedance is shown as the modulus value Z only. In some component pages and in the EMC section impedance may be expressed in ohms as;
R + jX, or Z Φ , or as the modulus value.

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3.2 Complex Permeability (μ)

The complex permeability (μ) expands the permeability concept using complex notation to include both an inductive component (real, inductive permeability, μ') and the loss component (imaginary, resistive permeability, μ").

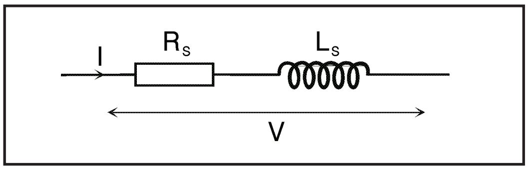
$$\mu = \mu' - j\mu''$$

The impedance (Z) of a loss-free winding would be expressed as:

$$Z = j\,\omega\mu L_0$$

where L_0 is the inductance of a winding on a core with unit permeability.

For a wound ferrite component the impedance can be represented by an inductive reactance in combination with a loss resistance. For series representation:



$$\frac{V}{I} = Z = R_s + j\,\omega L_s$$

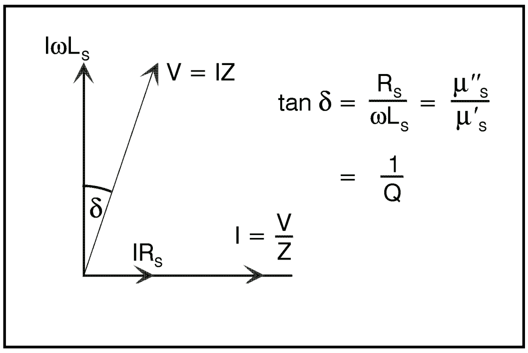
$$= j\omega\mu L_0 = j\,\omega L_0\,(\mu' - j\mu''_s)$$

Hence:

$$R_s = \omega L_0\,\mu''_s$$

$$\omega L_s = \omega L_0\,\mu'_s$$

The inclusion of the resistive loss results in a reduction of the phase angle between voltage and current from 90° by an angle δ, the loss angle.



Q is the magnification factor (see section 3.3) Curves of real and imaginary components of complex permeability (series representation) as a function of frequency are given in the material data pages. As measurements are made at low field strength (<0.1mT) the real component corresponds to the intrinsic initial permeability of the material.

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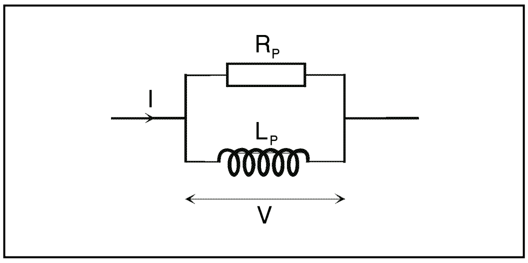
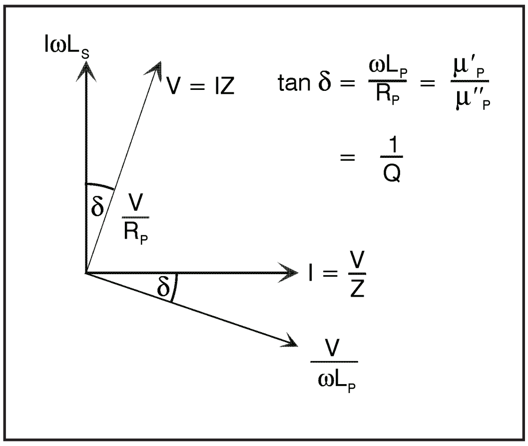
For parallel representation:



$$\frac{1}{Z} = \frac{1}{R_p} + \frac{1}{j\omega L_p} = \frac{1}{j\omega L_o}\left(\frac{1}{\mu'_p} - \frac{1}{j\mu''_p}\right)$$

giving:

$$R_p = \omega L_o \mu''_p,$$
$$\omega L_p = \omega L_o \mu'_p$$



The conversion between series and parallel mode measurement is:

$$R_s = R_p/(1=Q^2) = R_p/(1+1/\tan^2\delta)$$
$$L_s = L_p/(1+1/Q^2) = L_p/(1+\tan^2\delta)$$

and

$$\mu'_p = \mu'_s(1+\tan^2\delta)$$
$$\mu''_p = \mu''_s(1+1/\tan^2\delta)$$

It is common practice to give curves of complex permeability in the series form. However, it should be noted that the series change in real permeability can be misleading, with graphs showing permeability falling off rapidly at high frequencies; this is only a mathematical representation and at this point parallel permeability should be used.

Although series representation befits suppression and wide band applications, it is physically more correct to consider the parallel form and conversion to this is preferable in transformer applications where a more useful expression of in-phase and out-of-phase current can be gained.

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3.3 Q (Magnification Factor)

The quality of an inductor in a resonant circuit is commonly described by the Q factor, the ratio of reactance and resistance at a given frequency,

$$Q = \frac{\omega L}{R}$$

As the Q of capacitors is high, the Q of a resonant circuit, which is the ratio between the centre frequency and the spacing between ±3dB points on the resonance curve, is determined by the Q of the inductor.

$$Q = \frac{1}{\tan\delta} = \frac{1}{\mu_i \,.\, \text{Loss Factor}}$$

In open-circuit cores, the true Q value is dependant on the properties of the ferrite material and shape and size of the core. It can only be found by measuring the Q value of the winding, both with and without the core and calculating the a.c. resistance of the winding. Therefore,

$$R_{total} = R_{ferrite} + R_{wind}$$
$$= \frac{\omega L}{Q_{total}}$$

where L is the inductance of the coil with the core.

$$R_{wind} = \frac{\omega L}{\mu_{coil} \,.\, Q_{wind}}$$

as the inductance of the winding without the core is reduced by a factor of coil (the ratio of inductance of coil with core to inductance of coil without core). The direct comparison of the values of Q is only possible when all conditions of measurement are held constant.

3.4 Losses at low magnetising field strength

For individual grades of ferrite information on losses at low field strengths is given by the loss factors normalised to unit intrinsic permeability. It is understood that the loss coefficients are always proportional to the effective permeability of such cores.

3.4.1 Loss Factor (residual and eddy current)

Residual and eddy current losses are measured together at a flux density of <0.1mT for ring cores, and <1mT for components with a sheared flux path.

$$L.F. = \frac{R_{(r+e)}}{\omega L} \cdot \frac{1}{\mu_i}$$
$$= \frac{\tan\delta_{(r+e)}}{\mu_i} = \frac{1}{\mu_i \,.\, Q_{(r+e)}}$$

For a gapped core with an effective permeability μe, the residual & eddy current loss coefficient is:

i.e. it is reduced by a factor of μ_e/μ_i Similarly the $Q_{(r+e)}$ is increased by a factor of μ_i/μ_e

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3.4.2 Hysteresis Loss (Low magnetising field strengths)

Hysteresis loss must be normalised not only with respect to unit intrinsic permeability, but also with respect to unit flux density.

Hysteresis material constant (η_B)(IEC Publication 125, 128).

$$\eta_B = \frac{\tan \delta_h}{\mu i \,.\, \hat{B}} \quad (\mathrm{mT \times 10^{-6}})$$

where tan $\delta_h = R_h/\omega L$ and B is the peak flux density. This definition is quoted in the material data pages where measurement of R_s and L_s are made on an impedance analyser at two peak fluxdensities of 1.5 and 3.0mT.

Where a sheared or gapped core is involved, the hysteresis loss is reduced by a factor μ_e/μ, and tan $\delta_h = \eta_B . \mu_e . B$.

3.5 Losses at high magnetising field strengths. Power Loss Density (P_V)

The previous hysteresis loss factors can only be applied when the flux density in the core is relatively low (up to say, 20mT).

When the flux density is high, as in power applications, the losses are specified as the power loss density (P_V) (i.e. total power losses per unit volume of the core) at a given frequency and flux density.

The power loss density may be empirically expressed as a function of frequency and flux density by the relation:

$$P_v = k.f^a.B^b \quad \mathrm{mW/cm^3}$$

where constant ‘a’ has values between 1.3 & 1.6.
constant ‘b’ has values between 2.2 & 2.6.
‘k’ is a constant dependant upon temperature.

Power losses are expressed in the material data for power ferrites in mW/cm^3. In component data it is more commonly expressed in total power loss (Watts) at specific flux densities, frequencies and temperatures, assuming sinusoidal induction.

3.6 Frequency Range

The range of frequencies in which a grade of ferrite material may be used depends upon the conditions of the application and on the configuration of the core.

The upper limit of the range is based on the rapid rise of loss factor at and above a certain frequency. This point is easily measured for any given core. If the core is to be used in a transformer, the circumstances are different. It is not only the loss in the core and winding that is significant but the relationship between the shunt reactance of the transformer winding and the impedance of the source or load circuit is also of fundamental importance. Leakage inductance also determines the losses in the transformer at the high-frequency end of its working range.

It must be clearly stated that manufacturers test their products at frequencies specified in their tabulated publications and the behaviour of ferrite material outside these frequencies cannot be guaranteed.

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4. Stability

4.1 Temperature Factor and Temperature Coefficient

Temperature coefficient is the proportional inductance rise per °C.

$$T.C. = \frac{\Delta L}{L \Delta T} = \frac{\Delta \mu}{\mu \Delta T}$$

Where ΔT is the temperature rise (°C) causing the change ΔL in inductance (or Δμ permeability).

Temperature Factor is normalised to the unit permeability and is expressed in ppm/°C and given for a specified temperature range (25°C to 55°C).

$$T.F. = \frac{\Delta \mu}{\mu_i \Delta T} / \mu_i$$

$$= \frac{\Delta \mu}{\mu_i^2 . \Delta T}$$

When a core has a closed magnetic path with a gap the μ_e is used.

Temperature Coefficient = T.F. x μ_e

i.e. T.C. reduced by μ_e/μ_i.

In open-circuit core configurations the temperature coefficient can only be ascertained by direct measurement in each specific case.

4.2 Curie Temperature (θ_C)

The **Curie temperature** is the temperature above which the disruption of magnetic ordering by increasing thermal motion causes the material to lose its ferromagnetic character, and the permeability falls to near unity. This is a reversible effect and lowering the temperature below the Curie Point restores the permeability.

The **Curie temperature** of each material is defined in the data pages at the temperature where the intrinsic permeability has fallen to 10% of its room temperature value.

4.3 Disaccommodation Factor

After a ferrite core has been subjected to a shock (thermal, mechanical or magnetic) its permeability abruptly increases and immediately begins drifting downwards. This continues for a very long period. The decrease in permeability is linear when plotted on a logarithmic scale,

This form of instability is termed **disaccommodation**.

$$DF = \frac{\mu_2 - \mu_1}{\mu_1 . \log_{10} t_2/t_1}$$

where μ_1 is the permeability at the time t_1, and μ_2 is the permeability at the time t_2. The relative inductance drop in the period 1 to 10 hours after the shock is the same as the in the period 1 to 10 years, so that the long-term instability of the inductance can be predicted.

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In the case of a core with a closed magnetic path, but containing a gap the μ_e is used.

i.e. Disaccommodation = D.F. x μ_e

i.e. the coefficient is reduced by a factor μ_e/μ_i

The relationship in the case of open circuit cores is not so simple and it is generally not possible to predict the actual value of their disaccommodation coefficients.

Specified disaccommodation measurements in the data pages are carried out at 50°C.

5.0 Resistivity

Ferrites are semi-conducting materials and their resistivity varies with the grade of ferrite.

For nickel-zinc ferrites, the resistivity is of the order of 105 to 107 ohm-cm. For manganese-zinc ferrites, it is appreciably lower, say 101 to 103 ohm-cm, but remaining very much higher than the resistivity of metals and metallic alloys.

6.0 Dielectric Constant

Manganese-zinc ferrites have high values of dielectric constant which in some cases may approach 10^6 at a frequency of 1kHz. The value of the dielectric constant drops with the frequency, not very rapidly at first but then more and more steeply until at very high frequencies it approaches a value of 10.

Because of the high dielectric constant of some cores (particularly when they are made from Manganese Zinc) it is important to insulate the winding from the core with a layer of tape. In this way, losses due to increased self capacitance will be reduced.

7.0 Physical Parameters

Exact values of the physical parameters of ferrite components cannot be given as those obtained will depend both upon the type of material used and the conditions under which it is manufactured. However, the table below indicates the order of magnitude of these values:

Tensile Strength:	20 N/mm^2
Compressive Strength:	100 N/mm^2
Hardness:	10000 N/mm^2 (Vickers HV_{15})
Linear Expansion Coefficient:	10×10^{-6}/°C (Room Temperature)
Youngs Modulus:	1.5×10^5 N/mm^2
Thermal Conductivity:	4×10^{-3} J/mm sec °C
Density:	4 to 5 g/cm^3

8.0 Perminvar Ferrites

Magnetically Permivar ferrites are those which have undergone further heat treatment after sintering to increase the alignment of their magnetic domains. Such materials are characterised by their high values of Q and low losses at high frequencies and are ideal for tuned applications. It should be noted that permivar ferrites may be irreversibly degraded if subjected to a strong magnetic field, excessive heat or mechanical shock.

9. Manufacturing Considerations

9.1 General Manufacturing Process

Commercially available ferrite materials fall into two main classes - Manganese Zinc ferrite and Nickel Zinc ferrite. Both are manufactured in the same way but display different electrical characteristics and this allows their use in a wide variety of applications.

Ferrite is a ceramic material made from three principle metal oxides -Iron, Manganese (or Nickel) and Zinc. These are intimately mixed in exact proportions, granulated and pre-fired (a process known as “calcining”) at a temperature of 1000°C to partially form the final material. The pre-fired granules are then ground into a fine powder in a ball mill and a binding material is added. After drying, the powder is ready to be pressed, extruded or injection moulded into the required component shape. The “green” components thus formed are sintered at between 1200oC and 13500C where they densify and shrink to formed a fully formed cubic crystalline material with its cells arranged in a spinel lattice.

9.2 Physical Shrinkage

The exact amount by which a ferrite component shrinks during manufacture will depend on the material and the process itself, but is typically about 11%- 18%.

Controlling the final size of a component is difficult since the shrinkage can vary both within a batch and between batches. As a result, the specified tolerances on the dimensions of such components is usually wide and if closer dimensions are required, the component must be ground or lapped. This adds cost to a component so it is often desirable to make allowances in the design to accommodate the wider tolerances.

The following information on general dimensional tolerances is given as guidance to those specifying new components:

a) Pressed Parts:

Between pressed faces:
The greater of ± 2% or ± 0.25mm (Mn-Zn)
The greater of ± 3% or ± 0.30mm (Ni-Zn)

Between pressed-ground faces ± 0.2mm
Between ground-ground faces ± 0.05mm

(b) Extruded Parts:

As detailed in the data sheets for rods and tubes

(c) Injection Moulded Parts:

The greater of ± 3% or ± 0.30mm

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10.0 Effects of Mechanical Stressing

When a ferrite component is physically stressed it undergoes changes in its electrical characteristics. Compression beyond an ill defined limit causes a decrease in effective permeability at low flux densities and an increase in the losses - an effect which is also seen in metal alloy cores if there are stamped or spirally wound.

Unfortunately, ferrite components can be stressed by three commonly used practices:

1. During the grinding of their surfaces

2. Whilst they are being clamped together as a complete core

3. When they are being encapsulated in a synthetic resin as an insulating coating

During the **grinding** of polycrystalline ferrites, stresses are applied to the surface and underlying layers which lead to the permanent deformation of the structure. However, it is possible to grind until a perfect, stressfree finish is obtained but economical factors generally prohibit this in all but the manufacture of specialist, high permeability components.

Clamping a pair of cores is another process which can induce enough stress to impair the performance of the core assembly. If the clamping is relatively light and the applied force is directed along the axis of the mating cores, the effect can be beneficial with the permeability increased and the losses reduced. However, if the clamping force is great, subjecting the mating surfaces to high stress levels, the electromagnetic characteristics will be degraded and structural damage (cracking) may occur in the polycrystalline structure of the ferrite.

The third and most common cause of stress in finished ferrite components (particularly toroids) is when they are **encapsulated** in either an epoxy or nylon coating. The ferrite is heated, either when the coating is applied or afterwards and when both cool, the difference in the thermal coefficients of expansion of the ferrite and the coating, produces stresses in the ferrite which may reduce its permeability by as much as 20%. This effect is reduced if components are coated in wet epoxy or enclosed in plastic caps but these processes are expensive and are generally reserved for higher permeability toroids.

Alternatively, the shrinkage of compounds used for potting may be reduced by adding an inorganic material such as silica or glass fibre to the coating material.

The shape of the hysteresis loop is changed by any compression to the core; if the magnetostriction (a small change in the dimension parallel to the direction of the applied field) is negative, as with Ni- Zn ferrites, the loop becomes more square. If the magnetostriction is positive, the loop becomes less square.

Finally, if a core is gapped, all effects of stressing are greatly diminished (unless the stress effects the actual length of the gap itself!).

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