APPLICATION CONSIDERATIONS OF THE NON-LINEAR FERRITE CHARACTERISTICS

George G. Orenchak

Ferrite International Company
Wadsworth, IL 60083

ABSTRACT

In an effort to increase the understanding of the functional performance of soft ferrite cores, their behavior as functions of dimensions, temperature, magnetizing force, frequency and thermal, mechanical or magnetic stress are examined. Emphasis is placed on the avoidance of pitfalls in designing and testing magnetic components using soft ferrite cores.

INTRODUCTION

Soft ferrites are ceramic electromagnetic (magnetically soft) material, dark grey or black in appearance and physically hard and brittle. They are primarily used as core materials for high frequency inductors and transformers. They are used in high frequency applications because of their inherent high resistivity which results in low eddy current losses.

There are two main soft ferrite material categories: Manganese-Zinc and Nickel-Zinc. Nickel-Zinc ferrites have very high resistivities (in the range of 10^5 ohm-cm or higher) making them ideal for inductors in the frequency range of Megahertz. Nickel-Zinc ferrites typically have very wide hysteresis loops resulting in large hysteresis losses when driven with appreciable magnetizing forces. Because of the large hysteresis losses, they are a poor choice for power applications.

Manganese-Zinc materials have resistivities in the range of 100 ohm-cm, thus they only have low eddy current losses up to several hundred KHz. Manganese-Zinc "power materials" typically have thin, narrow hystersis loops that minimize hysteresis losses at high magnetizing forces. Within the MnZn category there are many materials with properties optimized for specific functional applications. "Telecommunications materials" have controlled temperature coefficients, "input filter materials" have maximum permeabilities and "power materials" are optimized for minimal power dissipation at specific drive conditions and temperatures.

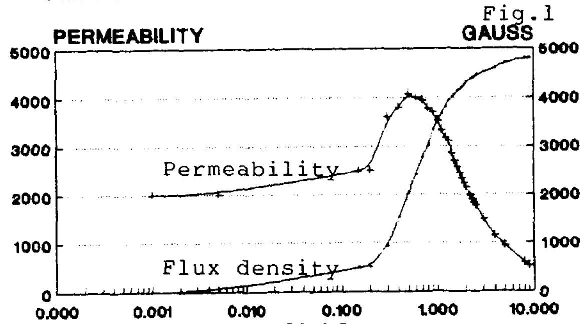
When specifying the proper ferrite core for a given application, the functional performance under specific conditions and temperature ranges should be considered.

BEHAVIOR AS A FUNCTION OF MAGNETIZING FORCE

Permeability is the ability of a material to conduct magnetic flux relative to the ability of air to conduct magnetic flux. It is expressed as flux density (flux per cross sectional area) divided by the magnetizing force ($\mu = B/H$). Permeability is proportional to inductance (the circuit property that opposes any change in current). The behavior of permeability and flux density vs. magnetizing force is shown in Fig. 1.

FLUX DENSITY & PERM vs.MAGNETIZING FORCE

Fig.1



TSF-05

At very low magnetizing forces, (H < .001 Oersted) the permeability is linear (unchanged regardless of the magnitude of magnetizing force under .001 Oersteds). This linear range is considered the initial permeability region. Subjected to higher magnetizing forces, the material permeability rapidly increases. Most "MnZn power materials" have their maximum permeability at a flux density of approximately 2000 gauss. When the material is fully saturated, increases in magnetizing force no longer appreciably increase the flux density and the permeability is equal to 1 (the same permeability of air).

For power transformers, initial permeability is not important. Power materials from various manufacturers may have comparable power permeabilities at high flux densities and function as equivalents in power applications while their initial permeabilites may be quite different.

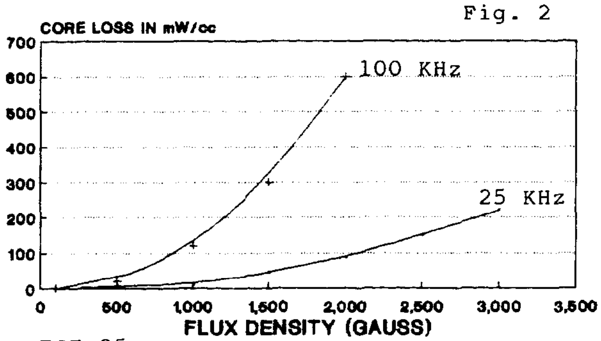
AFFECT OF FLUX DENSITY

Core loss is power dissipated in the core material at relatively high levels of flux density. The lost power is dissipated in the form of heat. Three components contribute to core losses. They are hysteresis losses, eddy current losses and residual losses. Core losses are dependent on the magnitude of the flux density. Fig. 2 shows the behavior of core loss vs. flux density.

As the flux density is increased, the core losses increase exponen-

CORE LOSS vs. FLUX DENSITY

Fig. 2



TSF-05

tially. To reduce the core loss, the flux density could be reduced by choosing a core with a larger cross sectional area. This option affects size, weight and cost. The flux density can also be reduced by operating at a higher frequency or increasing the number of turns on the coil. These options trade improvements to hysteresis losses for higher eddy current losses and higher copper losses. The total power loss may even increase with such trade-offs.

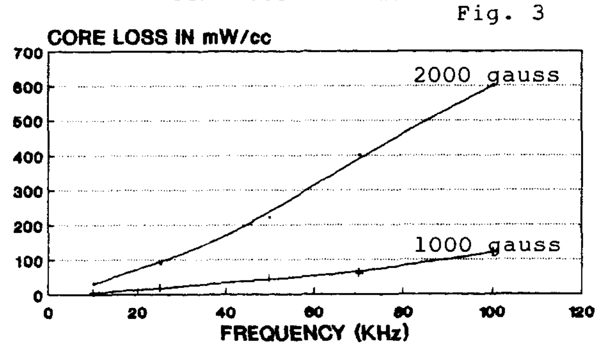
The frequency of operation is usually determined by other components and factors in the design. The core size should be chosen by determining the minimum size core needed for a flux density that would result in the core losses equalling the copper losses of the coil.

BEHAVIOR AS A FUNCTION OF FREQUENCY

Eddy current losses are dependent on frequency. Fig. 3 shows that core losses also increase exponentially with increases in frequency. Soft ferrite manufacturers have reduced core losses of "MnZn power materials" by over 50% in recent years and continue to work on improvements in this area.

CORE LOSS vs. FREQUENCY

Fig. 3



The following formula can be used to approximate core loss of Ferrite International's power materials at gauss levels and frequencies other than those published.

Formula #1

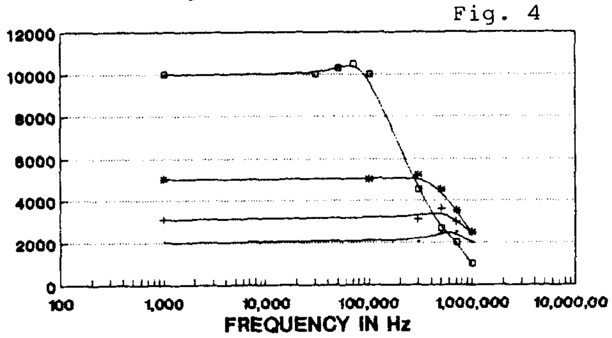
$$PT = (X)\left(\frac{\text{New B}}{\text{Old B}}\right)^{2.3}\left(\frac{\text{New Freq}}{\text{Old Freq}}\right)^{1.25}$$

X = mw/cm^3 from published curve at a particular temperature
New B = Desired gauss level
Old B = Gauss level from published power loss curve
New Freq= Desired frequency
Old Freq= Frequency from published power loss curve
PT = Power loss in mw/cm^3 at desired frequency and gauss level

The frequency response of initial permeability should be considered in the design of low level filters, tuned transformers, matching transformers and pulse transformers. As shown in Fig. 4, typically the higher a materials initial permeability, the lower the usable frequency range.

FREQUENCY RESPONSE OF INITIAL PERMEABILITY

Fig. 4



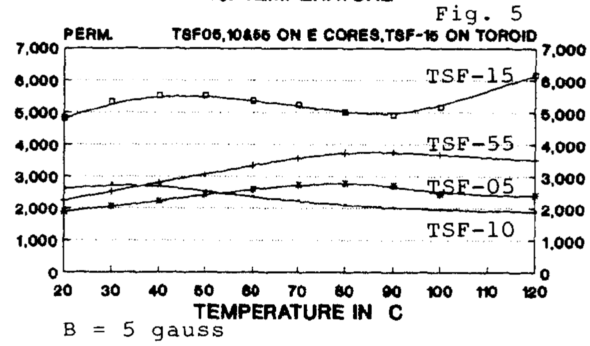
There is no benefit to using an expensive "high perm" material beyond its usable frequency range when a less expensive "lower perm" material functions just as well or better.

TEMPERATURE

Fig. 5 shows the initial permeability vs. temperature of Ferrite International's four MnZn materials. Notice some materials have positive temperature coefficients and some have negative temperature coefficients. In telecommunication applications, it may be essential to choose a material with a minimum temperature coefficient while this parameter for "power applications" is less critical.

INITIAL PERMEABILITY vs. TEMPERATURE

Fig. 5

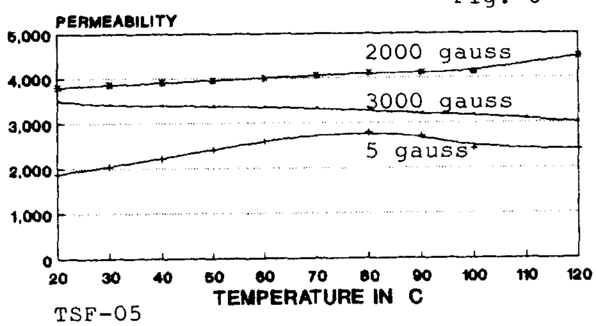


B = 5 gauss

The temperature behavior of the permeability of power materials as shown in Fig. 6 is dependent on flux density. The temperature coefficient is positive at initial perm and 2000 gauss but as the core approaches saturation, the temperature coefficient becomes negative as shown in the curve at 3000 gauss.

PERMEABILITY @ VARIOUS GAUSS LEVELS vs. TEMPERATURE

Fig. 6

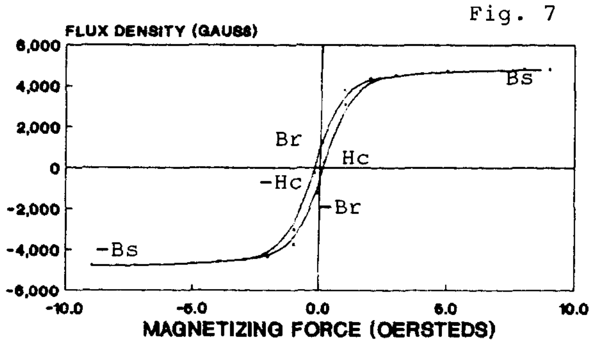


TSF-05

A hysteresis loop is a curve showing the relationship between magnetizing force (H) and the resultant magnetic induction (B) (Fig. 7). Saturation flux density (Bs) is the value of magnetic flux density when the material reaches its limit with respect to the number of flux lines per unit area it can efficiently conduct. After the material is saturated and the magnetizing force is reduced to zero, the magnetic induction does not go to zero but recoils to some value called residual induction (Br). The magnetizing force required to reduce the magnetic induction from Br to zero is referred to as coercive force (Hc).

HYSTERESIS CURVE

Fig. 7

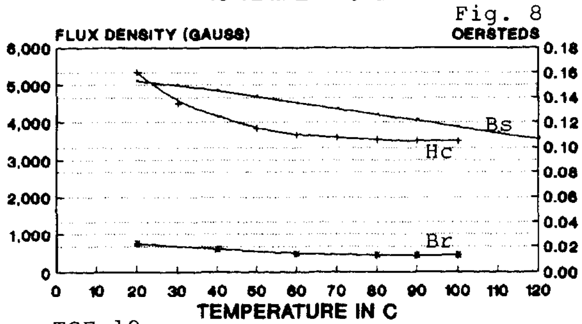


TSF-05

Saturation flux density(Bs), residual magnetism (Br) and coercive force (Hc) vs. temperature are shown in Fig. 8. It is important to design

HYSTERISIS PROPERTIES vs TEMPERATURE

Fig. 8



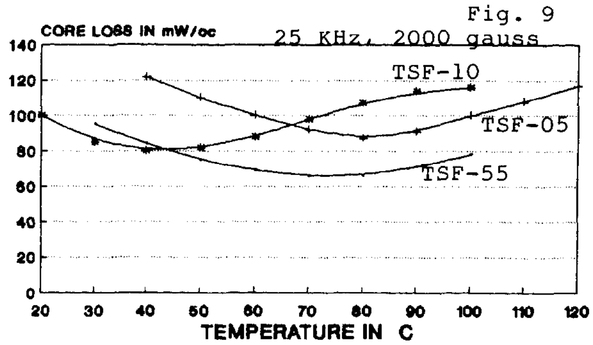
TSF-10

power transformers and output inductors to operate at flux densities below saturation at the highest temperature the cores will be exposed to.

Manufacturers can optimize power materials to have minimum core losses at a particular temperature. Fig. 9 shows core loss vs. temperature of Ferrite International's three power materials. Compositional changes will change the temperature where the minimum core loss occurs.

CORE LOSS vs. TEMPERATURE

Fig. 9



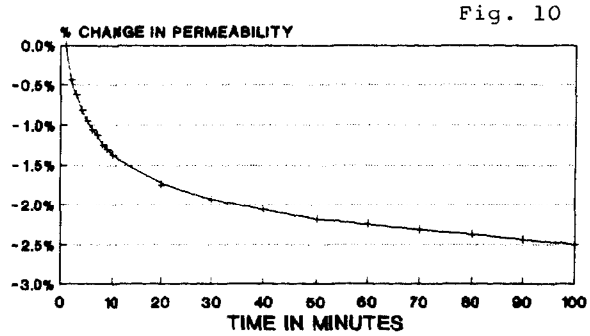
Ferrites are ceramics and mechanically cannot withstand large thermal shocks. To be safe, it is advised to keep temperature gradients across a core under 50° C. Thermal cracking is rarely a problem in field applications but is not uncommon in the production function of oven curing transformers.

STRESS

Disaccomodation is the variation of permeability with time. When ferrites are subjected to a mechanical, magnetic or thermal disturbance, the initial permeability is raised to an unstable value from which it returns as a function of time as shown in Fig. 10. This process is indefinitely repeatable. Under normal operating temperatures, soft ferrites do not age (do not permanently change with time).

DISACCOMMODATION INDUCTANCE vs. TIME

Fig. 10



Mechanical stress due to excessive tension when winding toroids, excessive clamping pressure when assembling mated cores or pressure induced from coatings or glues can cause the initial permeability to decrease. The permeability remains decreased until the stress is removed.

PHYSICAL CORE DIMENSIONS

The physical core dimensions have a large effect on the magnetic components performance. The mechanical dimensions determine the cores effective magnetic path length, cross sectional area and volume.

Inductance is dependent upon both the effective path length and cross sectional area.

Formula #2

$$L = \frac{.004\pi N^2 \ Ae \times 10^{-6} \ \mu e}{Le} \text{ in Henries}$$

Magnetizing force is dependent on the effective path length.

Formula #3

$$Hac = \frac{.4\pi N \sqrt{2} \ Irms}{Le} \text{ in Oersteds}$$

Magnetic flux density (magnetic induction) is dependent on the effective cross sectional area.

Formula #4

$$B = \frac{Erms \times 10^8}{4.44 \ F \ N \ Ae} \text{ in gauss}$$ (for a sine wave condition)

Apparent power, the energy handling capability of a core is related to the product of its effective cross sectional area and the cores window area (area available for windings).

Formula #5

$$Ap = WaAc = \frac{Pt \times 10^4}{Ku \ Kf \ B \ fJ}$$

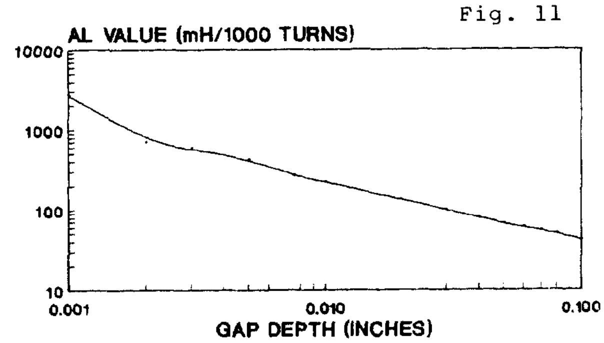
L = Inductance in Henries
H = Magnetic field strength (magnetizing force) in Oersteds
μe = Effective permeability
N = Number of turns
F = Frequency in Hz
Pt = Apparent power in watts
Ku = Window utilization factor
Kf = Wave form coefficient
B = Magnetic flux density (magnetic induction) in gauss
J = Current density A/cm^2
Ae = Effective cross sectional area
Le = Effective magnetic path length

GAPPED CORES

Gaps in the flux path of magnetic structures stabilize the inductance, make them more difficult to saturate and increase their energy storage capacity. A typical tolerance of +/- 20% on the inductance factor (A_L value in nH/N^2) of a core set can be reduced to +/- 5% or less by introducing a gap in the flux path. The gap also makes the inductance of the core set less sensitive to variations in temperature and magnetizing force.

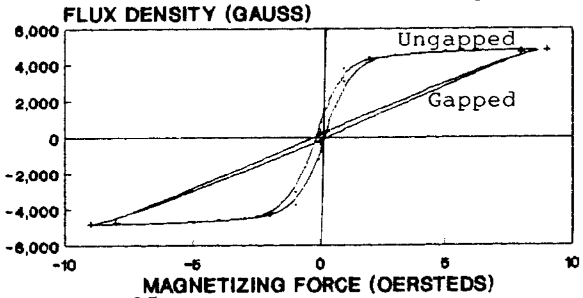
Fig. 11 shows the relationship between inductance factor and gap depth. Applications where gaps smaller than what is feasible to machine (< .005 inches) can be accomplished by placing a non-magnetic material such as Mylar in between the mating surfaces.

INDUCTANCE FACTOR (AL) vs. GAP DEPTH
Fig. 11



The hysteresis loop of a gapped core vs. an ungapped core is shown in Fig. 12. Notice that the gapped structure requires much more magnetizing force to saturate it. The larger the gap is the more the hysteresis loop shears resulting in lower effective permeability, but requiring a higher magnetizing force to saturate the core.

HYSTERESIS CURVE
OF GAPPED vs. UNGAPPED CORES
Fig. 12



TSF-05

SUMMARY

A soft ferrite's magnetic properties can change drastically when exposed to different conditions. Users should be aware of the effects temperature, pressure, mechanical or electrical shock, magnetizing force and frequency have on soft ferrite cores.

Whatever the application may be, ferrite manufacturers are willing, able and eager to help users select the correct ferrite material and core geometry.

REFERENCES

E. C. Snelling, Soft Ferrite Properties and Applications, Butterworth & Co., LTD., 1988

C. U. Parker, "Testing Soft Ferrites" Coil Winding Proceedings 1989, pp. 200-207.

C. Wm. T. McLyman, Magnetic Core Selection for Transformers and Inductors Marcel Dekker, Inc., 1982

Soft Ferrite Guidelines, Magnetic Materials Producers Association, 1989.