TRANSFORMER LAMINATIONS, DESIGN CONSIDERATIONS

Guenter B. Finke, Ph.D.
Magnetic Metals Corporation
Camden, New Jersey 08101

Engineers and designers of transformers and inductors will find the information presented in the following helpful in the selection of magnetic materials and core shapes for specific applications.

Why Magnetic Materials

Magnetic materials are useful for the generation and distribution of electrical power because these materials allow to transmit large power densities at low losses. In addition, voltage and impedance can be easily changed from one level to another, since changes in the flux density of materials induce voltages in copper coils surrounding the magnetic cores (Faraday's law).

The energy density in a magnetic material is

$$E = \tfrac{1}{2} HB \ \left(\frac{A}{cm} \ \frac{V}{cm^2} \right) \text{ or } \left(\frac{VAs}{cm^3} \right) \quad (1)$$

H is the magnetic field, B the magnetic induction ($1\ Vs/cm^2 = 10^8$ Gauss $= 10^4$ Tesla). In a field of 500 A turns/cm and an induction of 2 Tesla, an energy density of $5 \cdot 10^{-2}\ W/cm^3$ can be stored, which is as high as in the best capacitors. By multiplying equation (1) with core volume $V_c = A_c \cdot 1m$, where A_c is the core cross section and $1m$ the mean path length and assuming a sinusoidal change of B at the frequency f, it can be rewritten as follows. The power handling capacity in VA is

$$VA = 4.44\ 1m\ A_c\ f\ B\ H\ 10^{-8} \quad (2)$$

Since $H = ni/1m$, n number of turns, i current in the turns and $ni = S\ Aw\ K$, S current density in the copper wire, Aw core window, 2K copper fill factor (.35% for primary and secondary turns), the power handling capacity of a transformer as derived from the energy storage equation is

$$VA = 4.55\ S\ B\ f\ Ac\ Aw \cdot 10^{-4} \quad (3)$$

in which Ac and Aw are in in^2, B in Tesla, S in A/in^2 and f is the frequency.

The same result is, of course, obtained if we multiply Faraday's law for induction with the current i. $E_i = -n\ Ac\ dB/dt$, where E_i is a voltage induced in n turns by a flux change dB/dt. Solving this equation for sinusoidal flux, we find

$$E_i = 4.44\ nfB\ Ac \cdot 10^{-4} \text{ volts,}$$

in which Ac is in square cm multiplying with i, we find for the power VA

$$VA = 4.44\ n\ f\ B\ Ac\ i \cdot 10^{-4} \quad (4),$$

since $ni = S \cdot Aw \cdot K$, we can substitute in equation 4 and transform into in^2, so that $VA = 4.55\ S\ B \cdot f\ Ac\ Aw \cdot 10^{-4}, (5) = (3)$ in volt amperes.
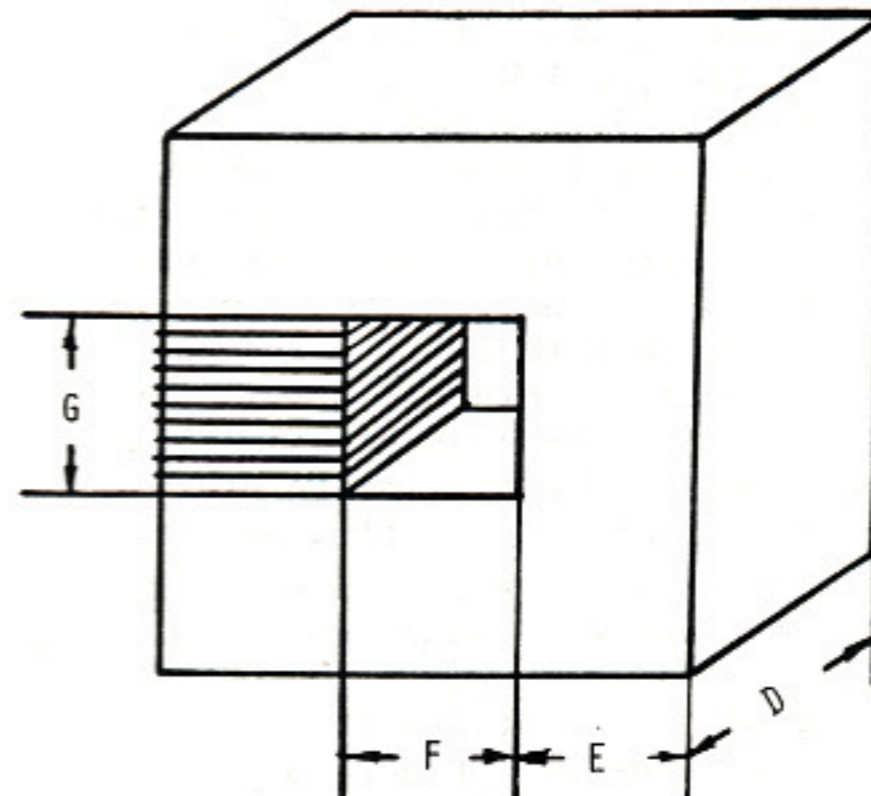

Fig. 1 Transformer Core

Ac = ED = cross section of core
Aw = Gf = window area

Metallic magnetic materials can be used from low frequencies of a few Hz to high frequencies of few hundred kHz, ferrites and iron powder cores can be used up into the MHz range. With above equations, the designer can select suitable dimensions for the copper coil and the magnetic core cross section at the given frequency which meets the loss requirement. Most manufacturers of core components list in their catalogs the Aw Ac products for available shapes of core structures. Transformers and inductors can be reduced in weight and volume by operating at higher frequency or by selecting materials which can work at a higher flux density.

Magnetic Materials and Their Properties

Iron, cobalt, nickel and their alloys have atomic spacings in various crystalline or amorphous structures which produce an interchange of some spins of their 3-D shell electrons, so that these spins align in domain patterns and cause a strong magnetism called ferromagnetism. The magnetic material properties like saturation flux density, the ease of magnetization, permeability, the core loss, the changes of these properties with temperature are therefore influenced by the atomic structure, the anisotropies of this structure, its impurity levels and the stress patterns in the material. Improvements in the magnetic properties of materials can be made by controlling the purity or adding certain impurities for grain refinement, by adding alloying elements to increase the resistivity, by influencing grain size and grain orientation, by reducing the thickness of materials and influencing domain wall spacing through stress coatings, laser scratching and crystal orientation.

Figure 2 shows the hysteresis loop of a few commercial grade magnetic materials, low carbon steel, grain oriented 3% Si-Fe and 2V cobalt iron, which in 1984 cost in dollar per pound .30, .75 and .35. The area inside the loop is the core loss per cycle at the measured frequency. For motor and low cost transformer laminations, which are not continuously on-line, the low carbon steel is a suitable material. Low carbon steel has, however, a relatively high core loss (wider loop). For continuous on-line transformers grain oriented steel, with its narrower loop and higher flux density, is the optimum choice and for airborne application, where weight reduction is the main consideration, the 2V cobalt iron is the proper material, since it has the highest saturation flux density. Figure 3 gives the magnetization curves for these and some other alloys. Table 1 lists W/1b., VA/1b. and permeability at 1.5 Tesla (15,000 Gauss) for typical commercial steels.
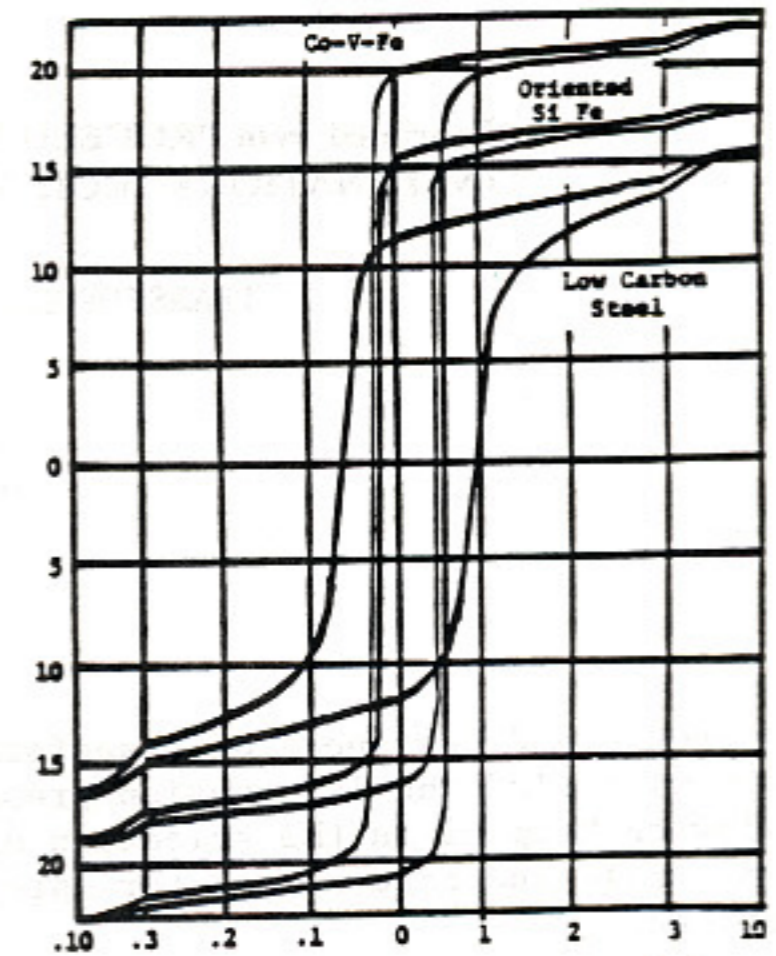
Fig. 2 Hysteresis loops of low carbon. 3% Si grain oriented and 2V cobalt iron steels.

We can expect further improvements of the various carbon and silicon steels in regard to core loss and permeability through improved melting techniques, improved processing and heat treatment. In addition, we can expect improvements in the cutting and stamping characteristics of such steels through better coating techniques and control of their mechanical properties like yield/tensile strength and elongation, which greatly influence the cutting and stamping.
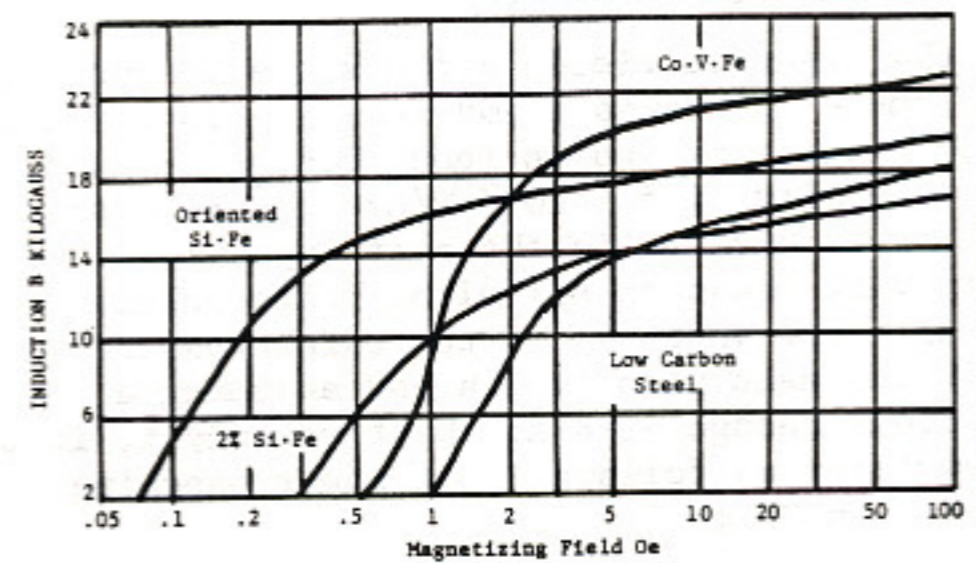
FIGURE 3 – Magnetization curves of cobalt-vanadium-iron, oriented, non-oriented silicon iron and low carbon steel.

Material	Thickness Inches	At 1.5 T, 60 Hz			At 1.0 T, 60 Hz	Comments
		W/#	VA/#	μ	μ	
L.C. Steel	.014, .018, .025	4	6	2,600	5,000	Low cost, moderate core loss
N.O. 5-1% Si Steel	.014, .018, .025	3	6	3,000	6,800	Low cost, improved core loss
N.O. 2-2.5% Si Steel	.014, .018, .025	2	7	2,000	8,000	Low core loss
G.O. 3.2% Si Steel	.014, .0185	.65	.80	30,000	35,000	Best buy for on-line trafo
G.O. 3.2% Si Steel	.008	.2	.60	40,000	42,000	Experimental

Table 1   W/#, VA/# and permeability of low carbon, non oriented and grain oriented Si-Fe steels. Data for underlined thickness.
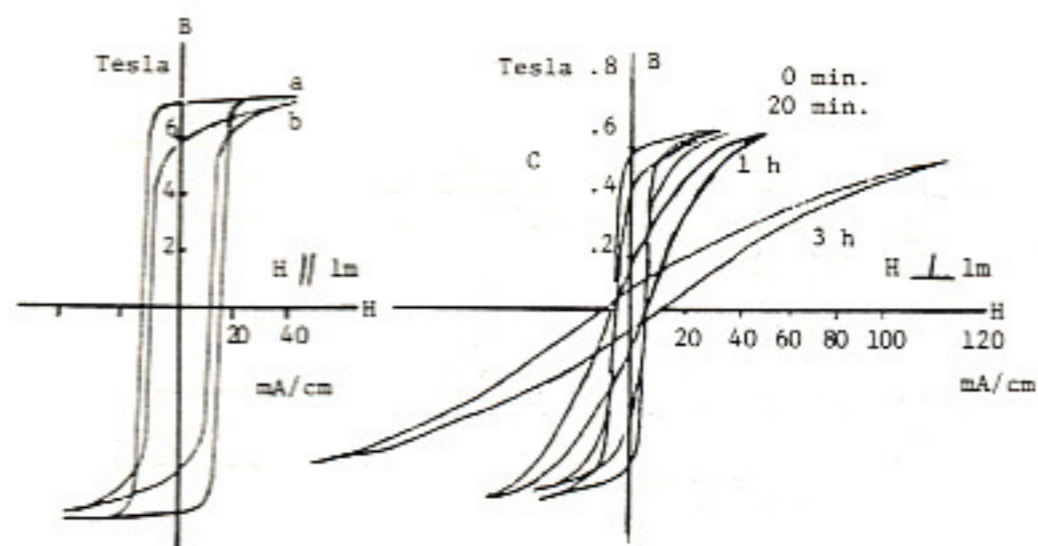
Fig. 4 Hysteresis loops of 80 Ni 5 Mo Re Fe cores annealed to
square the loop a) 3h at 420°C, H∥ to lm
b) Normal material
to flatten the loop c) 20 min.)
1 h) at 310°C, H⊥ lm
3 h)

Inductors and electronic transformers
for the telephone industry make use of Ni-Fe
alloys containing 50 and 80% nickel, because
these alloys have high permeability at low
flux densities of .1 to 10 mT. It is well
understood today how to influence the per-
meability and hysteresis loop of such alloys
by changing the crystal anisotropies through
controlled ordering, so that today flat or
very square hysteresis loop materials can be
made. In the 80% Ni-Fe alloys, the variation
of initial permeability with temperature can
be precisely controlled so that inductors and
current transformers of great temperature
stability can be made. Figure 4 shows the
hysteresis loop of 80% Ni-Fe after various
heat treatments in magnetic fields applied
in the direction or perpendicular to the
direction of the operating magnetic field, to
either square or flatten the loop by introduc-
ing uniaxial atomic anisotropies.

Gapped Magnetic Core Structures

High permeability core structures are
often out of necessity or deliberately gapped,
which flattens the loop and makes the permea-
bility lower, but more constant over B and
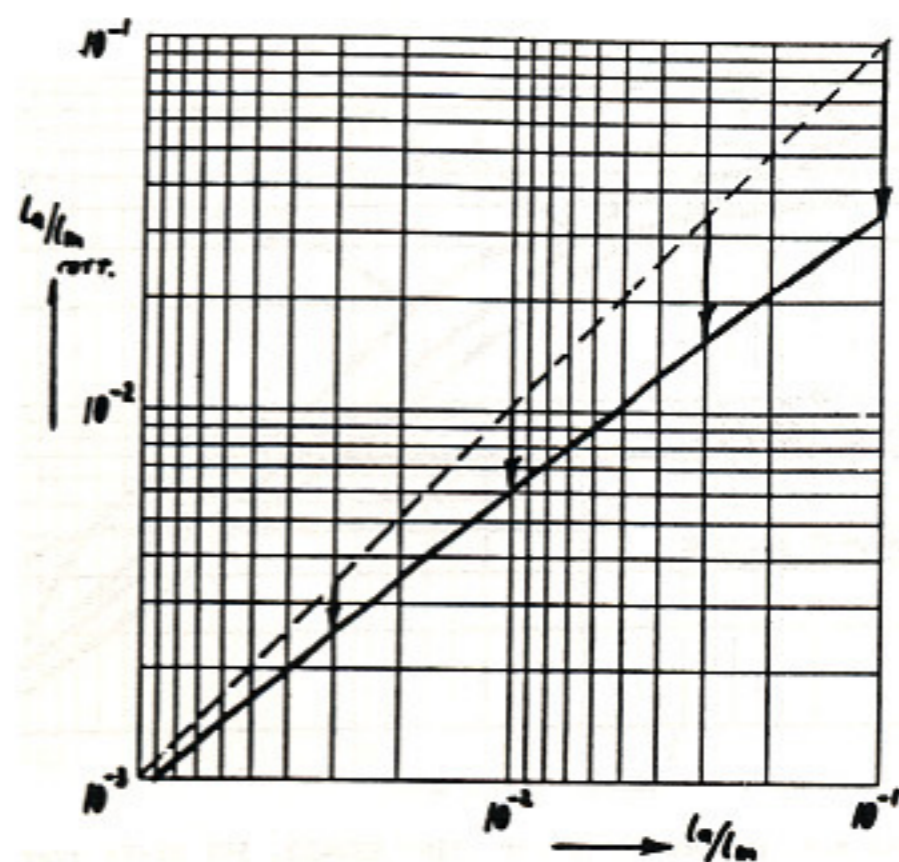over a wide temperature range. Figure 5
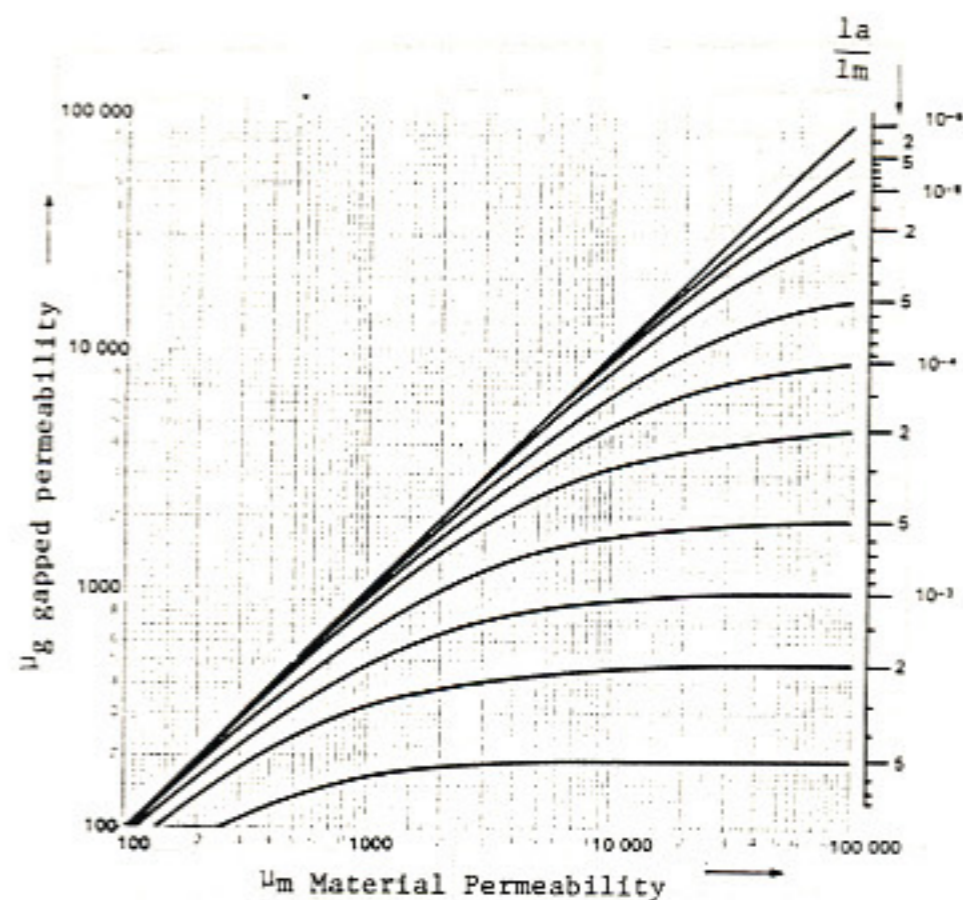

Fig. 5 Effect of air gap upon the gapped core
permeability for various ratios of air
gap la to mean path length lm.

shows the gapped permeability μg over the ma-
terial permeability μm, as calculated by

$$\mu g = \frac{\mu m}{1 + \frac{la}{lm} \mu m} \quad (6)$$

in which la/lm is the ratio of air gap over
mean path length for a given core. For larger
air gaps, the B field at the air gap fringes
over a larger area and the above equations
have to be corrected, as shown in Figure 6.

In nickel iron alloys, for instance,
the initial permeability of 80% Ni-Fe (Super
Perm 80) normally varies from -30 to +60°C by
more than 30%. It can be made temperature
stable by appropriate heat treatment (Super
Therm 80) so that it will not vary by more
than 15%. In laminations such as F-shaped
laminations, the stability can be further
improved by choosing an appropriate air gap
la/lm. This is shown in Figure 7. With this
method, lamination stacks can be made tempera-
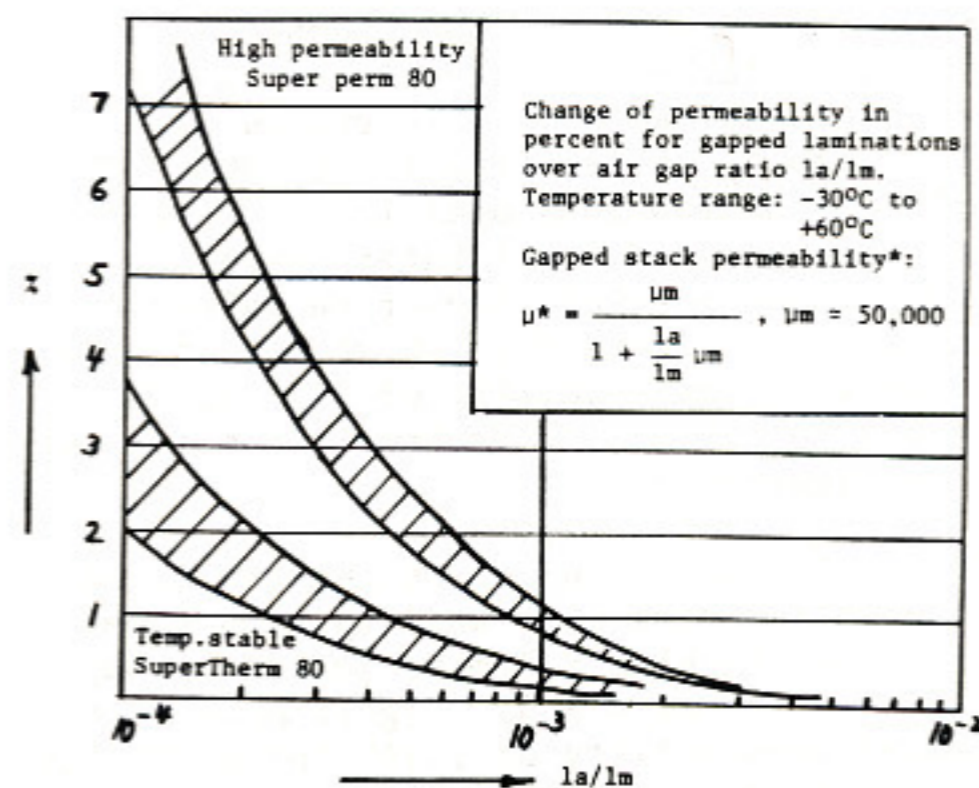ture stable to a variation of less than 1%.

Fig. 6 Corrected effective air gap
ratios la/lm for core structure
with larger air gaps.

Fig. 7 Change of initial permeability
for gapped core structure.
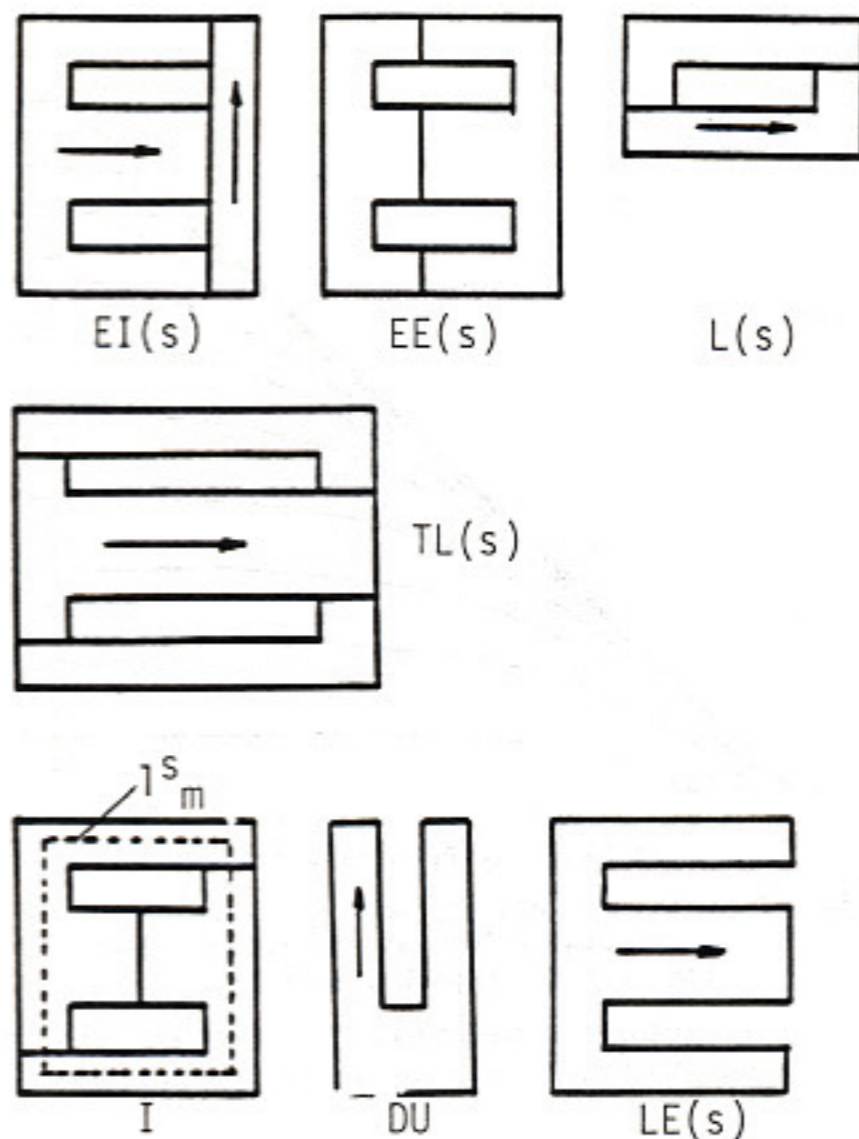
Fig. 8 Typical lamination shapes
(s) scrapless configuration
possible.

$$EE \atop EI \Big\} \quad \mu_s = \frac{\mu_m \; l_m}{l_m + 2a \left(\coth \dfrac{\lambda_1}{a} + \tanh \dfrac{\lambda_2}{a} \right)}$$

$$DU \Big\} \quad \mu_s = \frac{\mu \; l_m}{l_m - w + a \; \dfrac{2 - \tanh \dfrac{\lambda_1}{a} \tanh \dfrac{w}{a} - \tanh^2 \dfrac{w}{a}}{\tanh \dfrac{\lambda_1}{a} + \tanh \dfrac{w}{a} - 2 \tanh \dfrac{\lambda_1}{a} \tanh^2 \dfrac{w}{a}}}$$

Fig. 9 Stack permeability μ_s for 1 X 1 overlapped EI, EE, DU, DE laminations

t = thickness
la = air gap between lamination layer
a = $\sqrt{la \; t \; \mu_m}$ effective shearing length
λ_1 = overlap length
λ_2 = shunt length
μ_m = permeability

Core Structures

Some transformers, like current transformers, can be built with toroidal core structures and toroidal copper windings, to minimize fringing field losses. This is, however, expensive. Most power and electronic transformers use bobbin or stick wound copper coils into which laminations are inserted, often by automatic stacking machines. Figure 8 shows typical shapes of scrapless EI, EE, L and TL laminations which, in most cases, have geometric dimensions providing long flux paths in grain direction. Other non scrapless shapes, like F and EE laminations, are useful because they allow to adjust the air gap in the center of the coil by maintaining a self shielding flux path lm* around the coil, thus preventing cross talk in the electronic coils. Sometimes EE laminations with an air gap stamped in the center leg, often bonded into stacks, are used to minimize cross talk. E-core stacks are available with A_L values from 160 to 800. DU, DE and Long E laminations minimize effective air gaps when stacked 1 X 1 interleaved, so that the highest possible induction values can be obtained. In Figure 9 is shown how to calculate the stack permeability of EE, EI, DU laminations (per Pfeifer, Brenner) from its geometric configurations.

The hysteresis loop can be sheared to improve the incremental permeability with superposed d.c. by stacking E laminations in groups of 2 X 2 or 3 X 3 or 4 X 4. Figure 10 shows the incremental permeability of .014" thick, 2425EE laminations made of 50% Ni-Fe, stacked 1 X 1, 2 X 2, 3 X 3 or 4 X 4 interleaved over and butt

stacked with various gaps, the d.c. premagnetization. Such stacking methods allow to maximize the inductance for a.c. signals with superposed d.c. at a very low cost. To calculate the permeability for lamination stacks, stacked 2 X 2 or 3 X 3, the thickness t and the air gap la in Figure 8 have to be doubled.
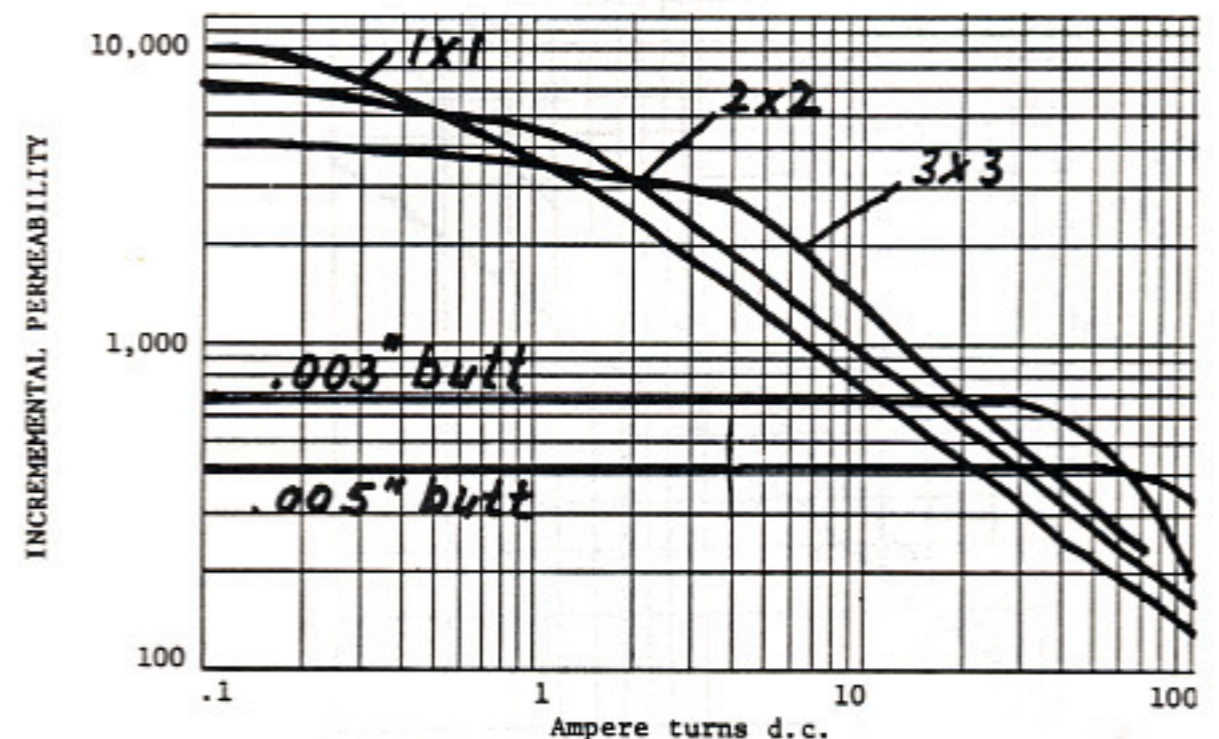

Fig. 10 Incremental a.c. permeability for .014" EE2425, 50% Ni-Fe over superposed d.c. field, stacked 1 X 1, 2 X 2, 3 X 3 and butt gapped.
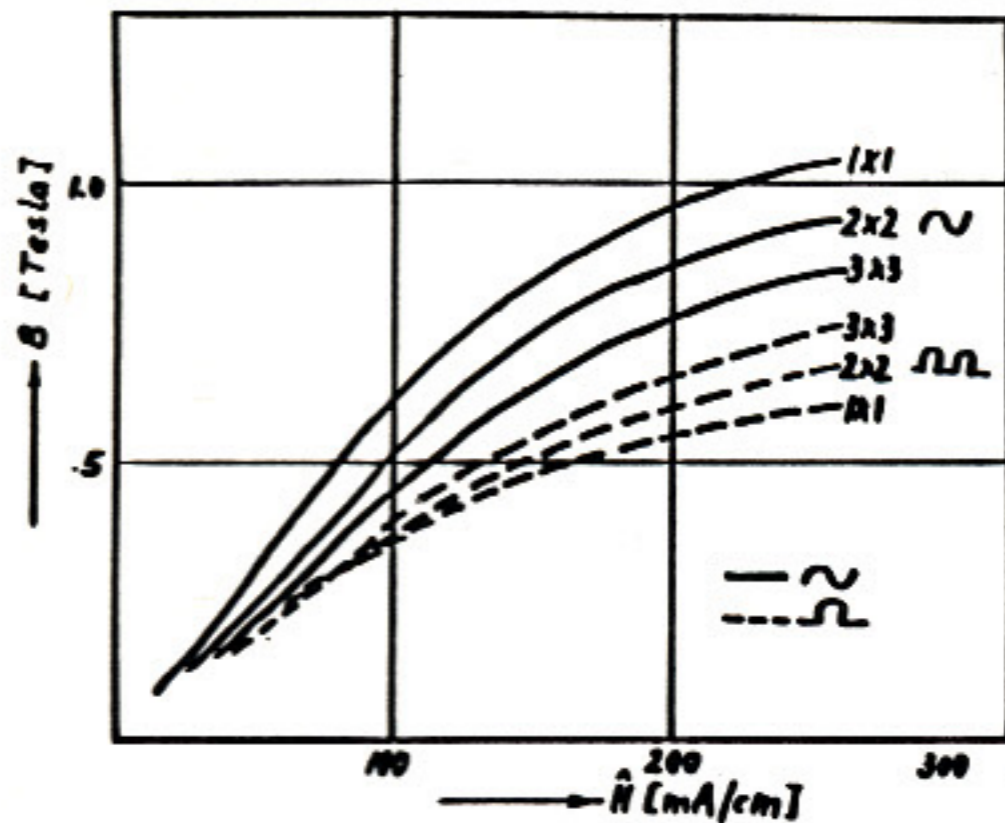
Fig. 11 Magnetization curves of 124DU, .014",
50% NiFe stacked 1 X 1, 2 X 2, 3 X 3.
Magnetization $\sim$ sinusoidal
Magnetization Ω halfwave ($B_r \rightarrow B_m$)

Figure 11 shows the magnetization curves of 124DU laminations made of 4914, stacked in packs of 1 X 1 to 3 X 3 laminations and magnetized with full sinewave and halfwaves. These examples show how powerful a tool controlled stacking of laminations is in the control of the hysteresis loop and the permeability. Above considerations will hopefully inspire designers to use all these tools available to maximize the efficiency of power and electronic transformers. Proper selection of material, lamination shape and stacking method. Consultation with the Engineering Departments of suppliers, to optimize designs, is always recommended and has normally great paybacks.

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