A user guide to soft magnetic materials

Overview: What are the primary criteria for choosing a material?

Firstly, we have to consider what a core "sees":

- Magnetic field created by the sum of all currents (let's call it the "net current") through all windings, i.e.

  $$H = I_{net}(t) / l_{Fe}$$

  $$I_{net} = \sum_{1}^{x} I \cdot N_x$$

  (l_{Fe} = main length of magnetic path in the core; I = current considering the direction; x = number of windings; N_x = number of turns of x^{th} winding (i.e. 1st, 2nd).

  Especially the peak net current, under which proper functioning of the component is ensured (no saturation), is important for design; for one winding it's simply the current amplitude multiplied with the number of turns.
- Frequency of net current. Usually the net current doesn't follow a sinus but consists of a bias (DC) current and several harmonics of a fundamental frequency.
- Operational temperature and its changes
- Mechanical load

Secondly, what is the basic function of the core, what electrical parameters are relevant, and what are the underlying material parameters:

a) Cores, when wound, are used as inductive components, so the basic function is to provide defined impedance in the application frequency range. Impedance, i.e. ratio between voltage and current, is described by inductance (for chokes, transformers) or output voltage for given current (for sensors, including current transformers or GFCI = Ground Fault Current Interrupters), but is always based on the material parameter **permeability μ** (a complex number), depending on frequency and field strength.

For the A_L-value (inductance with N = 1) we have for example

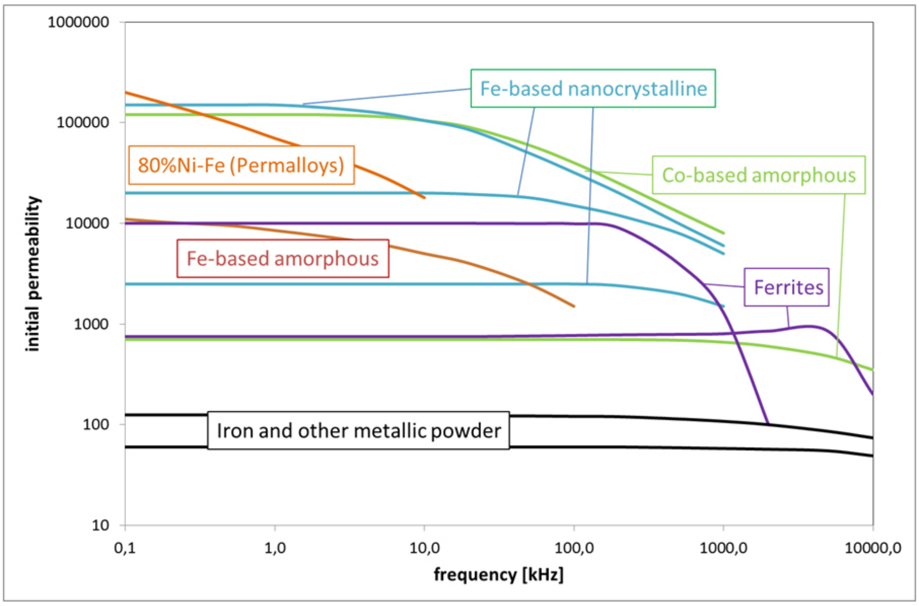
$$A_L = \mu(f, H) \cdot \mu_0 \frac{A_{Fe}}{l_{Fe}}$$

with A_{Fe} being the core's cross section. Note that l_{Fe} is often calculated wrongly: it's not the arithmetic mean value of all magnetic path lengths – the latter must be weighted with the magnetic field strength. The error of wrongly calculated inductance can easily exceed 10% for compact cores.

The frequency behavior of μ, and therefore L, is determined by a cut-off frequency

$$f_{cut} = \frac{4 \cdot \rho_{el}}{\pi \cdot \mu_0 \cdot \mu_i \cdot x^2}$$

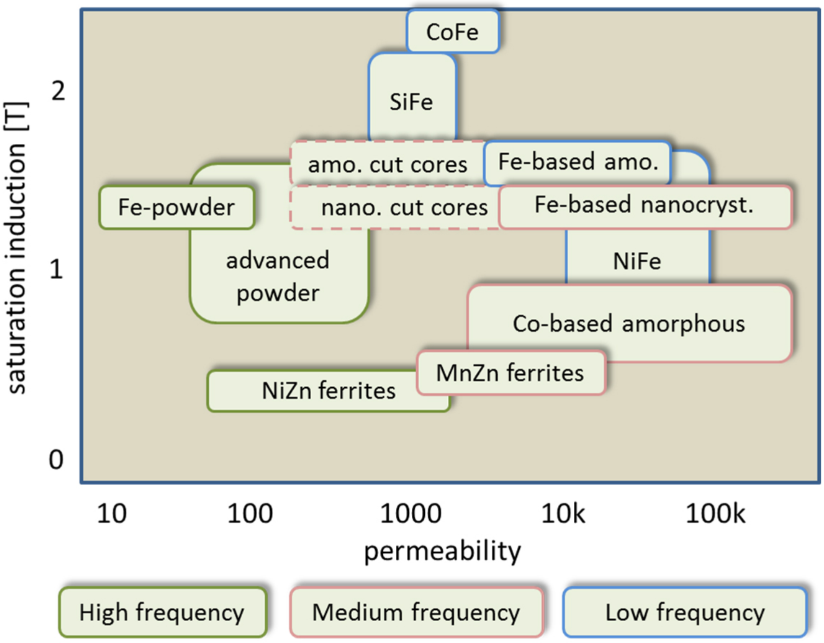
with ρ_{el} = specific resistance, x = smallest structural length of insulated material units determining eddy current paths, i.e. grain size in powder cores or tape thickness in wound cores. Real part of permeability goes down with increasing frequency when exceeding cut-off frequency; imaginary part increases at the same moment leading to high losses and low Q – see b). Since the cut-off frequency increases with increasing specific resistance and decreasing particle size of core material and initial permeability (often, only initial permeability at f → 0 or low frequency is given), powder cores and ferrites are preferred for high frequency – or more generally broad-band applications.



Typical material permeability (without gaps) vs. frequency plots. The curves represent only examples from each material class. There is a huge variety of different grades; within the classes the shown µ(f) behavior is mainly controlled by composition and grain size (for ferrites, powder) or tape thickness (tape).

b) The downside: each change of magnetization in the core is a dissipative process, i.e. creates losses. **Power loss** at given operation conditions is the area enclosed by the actual hysteresis loop, in a first approximation described by **coercivity**. In terms of application it's given as specific power losses (in power applications, leading to heating) or Q-factor (in signal applications). Mathematical and physical description of power losses is a current issue of physicists. Actually, power losses are a mix of different contributions; therefore one has always to consider the application frequency range: At low frequencies (up to the order of 10 kHz), hysteresis losses dominate; materials parameter is coercivity which is determined by intrinsic material properties, but also mechanical stress (see magnetostriction).
At higher frequencies (above the order of 100 kHz), eddy current losses dominate determined by the smallest insulated material unit as grain diameter, tape thickness etc. and the electrical conductivity of these units – the same mechanism as mentioned above for the cut-off frequency. There are a couple of other "unusual" losses in many materials, for several hysteresis loop shapes and especially near saturation. Since all these are completely different loss mechanisms, there is no optimum material for all frequencies, amplitudes (net currents), temperatures, mounting situations, etc.

c) For most power and low frequency applications, maximum operation net current, or maximum voltage-time-area, or simply maximum flux swing is the essential design parameter. It is described by **saturation induction** B_S as a material parameter, and the saturation behavior (decrease of impedance with increasing current, may be rather sharp or soft depending on material and core shape). Note that one can use full saturation induction, i.e. full flux swing, only up to a certain frequency because losses become too high exceeding that frequency. This “certain frequency” depends on the material-specific losses and B_S itself, but very generally speaking – below about 30 – 50 kHz (most power applications) B_S is a very important key property for design, above 100 kHz it’s no criterion for material selection.



One attempt to display material’s properties in two dimensions: Usual plot of saturation induction B_S vs. any parameter indicating the degree of soft magnetism like coercivity, anisotropy energy, or permeability – here the latter indicating also the preferred frequency range.

Furthermore, since saturation behavior is undefined for many core materials and depends on core shape, and saturation induction B_S decreases with increasing temperature, the design for a component should be based on just 65-80% of room-temperature B_S value.
Consider the influence of number of turns: the more turns of wire, the higher the inductance (to the 2nd power), and the lower the max current (linear). Conclusion: For small exciting currents (signal and sensor applications), look for high permeability and apply rather high number of turns – and you may use small cores. Always consider the winding capacity. - For high net currents (AC + DC), you need rather big cores (long magnetic path) using material with high saturation induction, low permeability and low number of turns – and high magnetic cross section to gain impedance.
Closely related is the energy which can be stored as field energy in inductive components, which is essential for storage chokes or flyback transformers:

$$W = \frac{1}{2} L \cdot I_{\max}{}^{2}$$

Here again high B_S and rather low permeability is required.

d) Magnetostriction (**saturation magnetostriction** λ_S) is frequently under- or overestimated. It's the relationship between volume change and magnetization (cause-and-effect chain applies in both directions!). Since many materials, especially those made from tape, are anisotropic, volume change can be elongation in one direction and shrinkage in another one. Magnetostriction is considered to be the origin of noise and in worst case mechanical resonances, but this applies only for closed magnetic loops within the core (no gap). Cut cores, E-core systems etc. provide a couple of additional mechanisms creating noise, which have nothing to do with magnetostriction. On the other hand, any mechanical stress on the core like mounting forces (potting, gluing, clamping…) or vibrations affect the B(H) behavior – and accordingly L(I) and especially coercivity and losses. Since relative influence of magnetostriction grows with permeability, it should be near zero (can mean <0,3 ppm for certain applications) for high permeable cores especially with high linearity or loss requirements – or remarkable effort has to be spent for mechanical decoupling of cores from environment.

Most mentioned parameters can be modified by introducing a piece of low permeability into the magnetic path – usually an air gap. This is a common method to use superior properties of high permeable material like high B_S (Fe-based amorphous or nanocrystalline material) or low high frequency losses (ferrites), but provide low effective permeability needed for certain applications. Linearity may be improved with an appropriate core design. Stray flux is created, however, introducing extra losses and leakage inductance.

Thirdly, what else has to be considered when designing an inductive component and choosing a core material?

- The structure (morphology) of material: For ferrites it is clearly – it's principally a ceramic material, consisting of sintered grains. All other common materials are metallic alloys which can be produced as tape (tape wound core), powdered and pressed tape (for amorphous and nanocrystalline material) or pressed metal powder (for crystalline material). 50% NiFe-alloys can be produced, for example, as tape or as powder (high-flux). Due to the granular structure with electrically and magnetic insulating grain boundaries, the latter have much lower permeability, but almost the same saturation induction compared to the metal tape.
- The complete set of environmental conditions in all possible operation cases and lifetime (mechanical, temperature). Especially operation temperature relative to Curie temperature T_C appears to be an essential parameter for materials choice: B_S decreases with increasing temperature until vanishing at T_C; magnetic parameters get instable reaching T_C in short-term and long-term (ageing). Since cores are often coated, impregnated or encapsulated in plastic or metallic cases, all these additional materials and adhesives have to be considered in terms of their behavior regarding low and high temperature, vibration, pressure, etc.
- Core shape – determined by space, winding design and stray flux considerations.
- Last but not least – price: the bigger the core size, the better the performance (bigger impedance, bigger current resilience, lower losses) but the higher the cost, weight and space consumption. Core price consists of materials and production costs. Material costs are dominated by main magnetic element Fe, Ni, and/or Co – and eventually expensive additives like Nb for nanocrystalline materials. Powder cores and ferrites are cost effective for high volumes; else tooling costs must be considered.