

A user guide to soft magnetic materials

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With this short guide, we want to make it easier for the designer of inductive components to choose the right core material for a certain application. Starting with the main criteria for a choice basing on the application specific function of a core, we introduce the most important material classes, hereby excluding silicon steel.

1. 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 winding; 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.

For low permeable cores (powder cores) and cores with gaps, the magnetic field cannot be considered to be guided completely along l_{Fe} in the magnetic material. This leads to deviating results for the field H with significant consequences discussed later.

- 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:

- 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

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

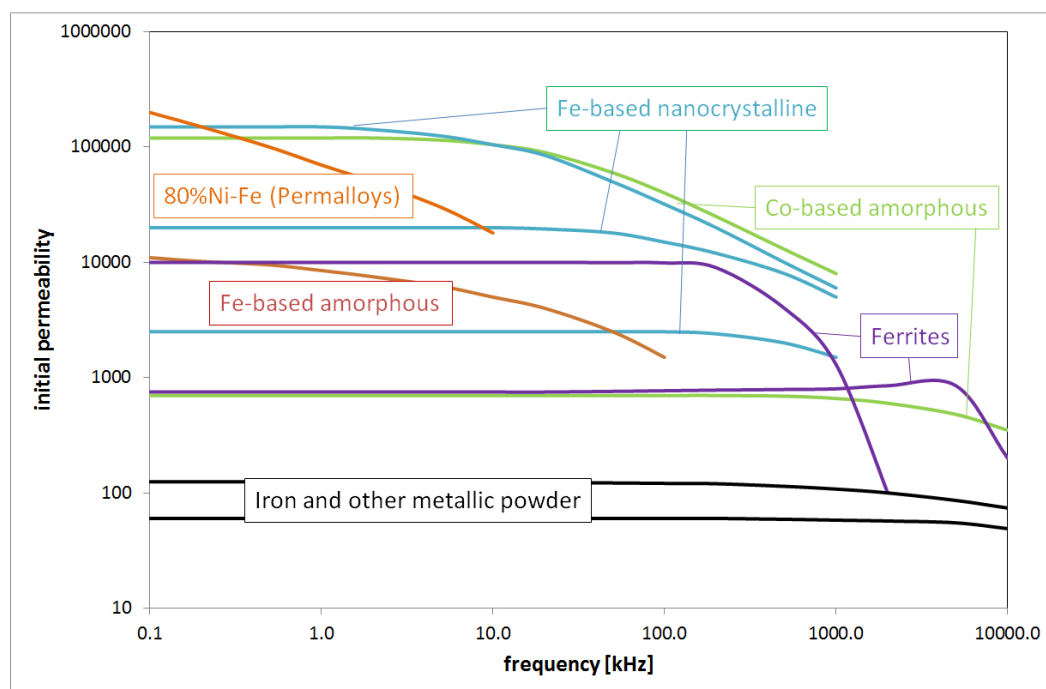
with A_{Fe} being the core's cross section. Note that l_{Fe} is often calculated wrongly: it's not the arithmetic mean value of all magnetic path lengths – the latter must be weighted with the magnetic field strength. The error of wrongly calculated inductance can easily exceed 10% for compact cores.

In case of low materials permeability (<500) or gaps or certain core / winding designs, where the field and the flux is not guided by the magnetic material completely, the field and flux parts through air (stray flux) have to be considered leading to an “effective permeability” and/or modified l_{Fe} .

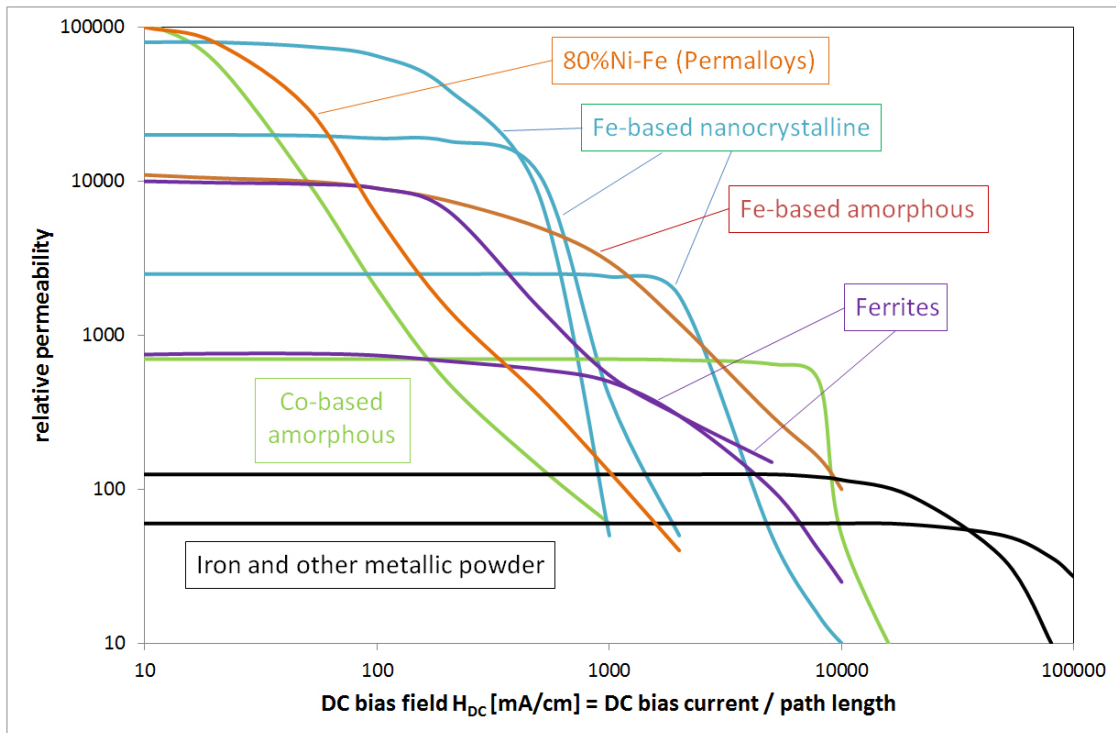
The frequency behavior of μ , and therefore L , is determined by a cut-off frequency

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

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 next point. 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 $f \rightarrow 0$ or low frequency is given), powder cores and ferrites are preferred for high frequency – or more generally broad-band applications.



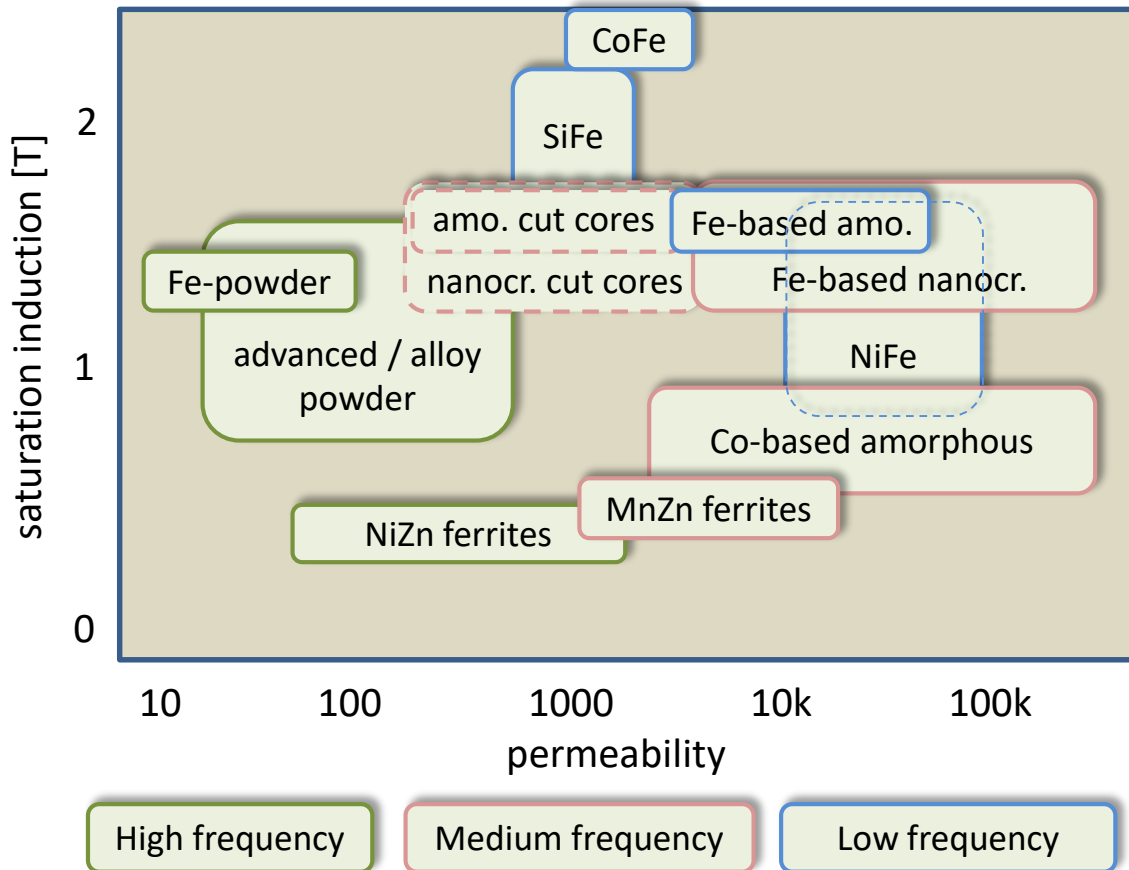
Typical material permeability (without gaps) vs. frequency plots. The curves represent only examples from each material class. There is a huge variety of different grades; within the classes the shown $\mu(f)$ behavior is mainly controlled by composition and grain size (for ferrites, powder) or tape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



Typical relative material permeability (without gaps) vs. bias current plots. The curves represent only examples from each material class. The behavior, especially in the saturation range (permeability drops down) depends on materials grade, but mainly on core dimensions and mechanical conditions.

- 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.
- 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 like shown in the permeability vs. DC bias graph, may be rather sharp or soft depending on material and core shape). The higher B_s , the lower μ , and the more linear the $B(H)$ behaviour is, the longer at the bias scale the permeability is stable.

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.

- 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. There is an interesting approach to add also energy consumption (losses) over lifetime to the costs, this could lead to more expensive, but also more efficient parts. 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.

2. Selecting the right material class: key considerations

After identifying the key properties of the materials required for specific applications, it is possible to formulate the initial step of selecting the material class. This is done by considering the B_s vs. μ , μ vs. f and μ vs. H_{DC} , graphs shown above. Most applications require cores with a round or flat hysteresis loop, where permeability (numbers refer to 50 Hz; almost equal to 10 kHz value for $\mu < 50.000$) is a useful parameter:

- Any application requiring energy storage needs small effective permeability (<150) and preferably high B_s , i.e. powder cores or gapped ferrites or even gapped tape cores. Gaps, however, can occasionally cause problems to occur due to fringing flux (see below).
- Within powder cores, mainly the operation frequency and space considerations determine the preferred material.
- Low permeable ($\mu = 700 - 3000$) Co-amorphous material provides high linearity $\mu(H)$ and $\mu(f)$ until several 100 kHz and low losses, resulting in low total harmonic distortion. Despite being costly, they are used for special applications in signal conversion and for DC-tolerant current transformers for Wh-meters.
- Transformers need medium permeability (3.000 – 50.000). Low permeable nanocrystalline material has been developed to enter the market in last decade as an alternative. Here we use ferrites or tape cores. Within these classes, usage mainly depends on frequency for power applications:
 - For 50 / 60 Hz, laminations or wound cores of electrical steel (SiFe) are used. New steel grades have been developed in last years to cover also the range up to few kHz, especially the attractive market for mid frequency transformers. On the other hand, amorphous and partially nanocrystalline materials replace steel for higher efficiency.
 - Fe-amorphous works well up to some 10 kHz, but nanocrystalline is superior (but more expensive) due to smaller losses and less noise. If space doesn't matter, and no permeability above 20.000 is needed from other reasons, ferrites can be used.
 - Above 50 – 100 kHz, the advantages of amorphous and nanocrystalline materials (high B_s , higher permeability) can't be utilised for power applications and cheaper ferrites become the preferred material, as long as the shape allows for it.
 - Saturation induction, a measure for the potential miniaturisation of a component, decreases in the order Fe-Si steel → Fe-amorphous → Fe-nanocrystalline → Ferrites. Losses decrease in the same order. The transition from one class to the next in terms of frequency is defined by the losses, i.e. at a certain frequency losses become too high to use the higher B_s , and the next class becomes more attractive. Any improvement of loss level for a certain class shifts this transition to higher frequencies. This is one driving force for materials development.
- Within ferrites, amorphous and nanocrystalline classes, there's a great variety of materials showing different permeability vs. frequency, temperature and current behavior.
- For Common Mode Chokes, both, ferrites and nanocrystalline cores are useful. Ferrites have some advantage for attenuation at some 100 kHz, while nanocrystalline show more broadband attenuation, and the chokes can be designed smaller and with lower copper resistance and winding capacitance.

- Any application with low net current, but high impedance for signal processing or EMI, need high permeability (>50.000). For these and sensor applications requiring certain linearity (permeability independent on current) at medium up to highest permeability (>100.000) such as non-DC tolerant current transformers or RCCB, nanocrystalline is the current choice, replacing NiFe alloys.

Cores with defined rectangular hysteresis loop are used in switching applications like MagAmps. Usually tape wound cores annealed in magnetic fields are used. Permeability is not an appropriate unit to describe these cores. Because of this, and due to their limited importance, we will only focus on cores with natural (as it is) or flat (induced with special treatment) hysteresis loops.

Next, we explore the most commonly used material classes describing their production process, resulting morphology and properties in connection with the application properties discussed in part one. We will also look at their sub-classes, reviewing their specific properties and preferred usage.

3. Fe-based amorphous and nanocrystalline tape

Production, resulting morphology and properties

The tape as a raw material is produced in a single step when the metallic melt is cast onto a rotating cooled wheel – so-called rapid solidification process. The cooling rate is very high (about 10^6 K/s) and the material stays amorphous like a glass, often referred as “metallic glass”. The atomic disorder is responsible for the superior soft magnetic properties: magnetization is not coupled to an “easy axis” determined by the crystal lattice and its changes are simple and require little energy.

The as-cast tape has a typical thickness of 15 – 30 μm . It is wound subsequently to a toroidal or other shaped core and annealed – often in a magnetic field – to release stress and induce a magnetic anisotropy, creating the shape of hysteresis loop and finally parameters like permeability, its linearity and coercivity. The so-called amorphous materials have good properties already in the as-cast state, which are improved and only slightly modified during annealing without changing the morphology.

The nanocrystalline cores undergo a structural change during annealing: nanocrystals of few nm size are formed in a residual amorphous matrix. Although they are crystalline having an easy axis, their orientation is disordered and averaged out due to the small size compared to the size of magnetic domains. Hence the magnetic properties are determined mainly by induced anisotropy or its absence, leading for example to small coercivity which is similar to amorphous materials.

Being metals, these materials are good electrical conductors. When the core is attached with wire windings, the magnetic field is always in the direction of the tape, resulting in eddy currents in the cross section plane of the tape. Therefore the eddy current power losses are proportional to the second power of tape thickness if the layers are insulated, demonstrating the impact of tape thickness and insulation for medium and high frequency applications. Usually the tape has a certain insulating oxide surface withstanding inter-layer voltages (voltage measured with one turn, divided by the number of tape layers) of some tenths of Volts. For high-voltage or high-frequency applications, however, additional tape insulation must be applied.

Since the tape is solidified at the casting wheel, the surface has a roughness in the order of few μm , a relatively high percentage. When winding the core, the filling degree in the total volume is reduced. A so-called filling or lamination factor of 75 – 90% (much lower than known from rolled tape as steel or NiFe alloys) needs to be used when calculating effective cross section, effective flux density etc. Compared to calculation from weight, area and density of a tape piece, tape thickness is significantly higher when measured mechanically.

Another unique property of amorphous material is the hardness, flexibility and – unfortunately – the brittleness of unprotected cores. Because of this, the sharp edges and the fact that any deformation of material leads to deterioration of magnetic properties if magnetostriction is not zero, cores must be packed into protection housings (plastic or metallic cases), coated, or wrapped – the latter in combination with impregnation. Coating and impregnation lead to mechanical stress and therefore impact on magnetic properties, even for the so-called zero-magnetostriction materials. Since the relative influence of this effect increases with increasing permeability, cores with highest permeability (>100.000) are usually offered only in housings with proper fixation.

Amorphous and nanocrystalline materials contain (as main element) one or more ferromagnetic transition metals: Iron, Cobalt or Nickel. To create the glassy state and to make it castable, so-called glass forming elements like Silicon, Boron and Carbon have to be added. Additional elements are used to adjust casting properties, solidification behavior and surface properties, magnetostriction, permeability, saturation induction and – in case of nanocrystalline materials – the crystallisation properties, including crystallisation temperatures, grain size and distance.

Many Cobalt based amorphous materials with superior soft magnetic properties have been invented and used over recent decades. Today, they play just a minor role due to the high Cobalt price compared with Iron, the predominant base for most materials today.

Fe-based amorphous sub classes and their applications

The most popular and successful material is a Fe-Si-B alloy introduced by Metglas® as 2605SA1. The major benefit is the high saturation induction of 1,56 T and permeability of some 10.000 when annealed in magnetic field to get a linear hysteresis loop, or >100.000 when annealed without field. Thanks to its low power losses compared with electrical steel, it is superior for low frequency applications, mainly as distribution transformers for 50 or 60 Hz. The cores are often used with distributed gap, or as cut cores to reduce effective permeability. The main drawback is the high magnetostriction of 27 ppm.

Other variations have been developed to reach higher saturation induction (by adding Cobalt), or lower losses at higher frequencies. Nevertheless, quantitatively 2605SA1 (in Asia known also as 1K101) plays the dominant role in the market of rapid solidified tape wound cores, not least due to the relatively low price arising from the cheap raw materials, good castability and high production efficiency, as well as overcapacities.

Fe-based nanocrystalline sub classes and their applications

This class was invented in 1988 at Hitachi Metals as Finemet®, and developed to a commercially successful material in the 1990s mainly by Hitachi Metals and VACUUMSCHMELZE®. Large-scale production of cores with well-defined and reproducible properties requires a higher degree of theoretical knowledge and practical know-how on the manufacturing processes both for tape and cores. Note that there far less sources for tape than core producers – the core market is based on about five established and experienced and about 10 smaller tape manufacturers worldwide.

There exists a dominating sub-class also for nanocrystalline materials: FT-1 introduced by Hitachi Metals, and advanced FT-3 (known also as VITROPERM® 500 and 800 from VAC). Besides iron they contain Silicon, Boron, Niobium and Copper. Copper and Niobium are responsible for the formation process of nanocrystals, which are actually α -FeSi. FT-1 has a B_s of 1,26 T and can reach permeabilities of some 100.000 at 50 Hz; but it shows a magnetostriction of 2 ppm.

FT-3 contains little less Iron, making it more difficult to cast and leading to little lower B_s of 1,2 T. In return, magnetostriction can be adjusted to zero, and coercivity is lower, making it superior for all applications which require the highest permeability and linearity, with the lowest losses. Best soft magnetic properties are maintained when coatings or impregnation are applied. Highest maximum permeabilities up to 1.000.000 at 50 Hz used for AC-type RCCB cores can be achieved when excluding any surface crystallization and when annealing without any external disturbance introducing anisotropy energy, like magnetic fields, mechanical pressure etc.

The variety between these established alloys is floating today: a couple of producers offer nanocrystalline materials in that composition range (in Asia often known as 1K107) – mainly adjusting the Silicon and Boron content – combining it with different annealing technology. To adjust magnetostriction stable $<0,5$ ppm, low permeability <30.000 , linear $\mu(H)$ behavior for $\mu > 100.000$, and to maintain high permeability at high frequencies, however, does not come without challenges; not all producers are able to achieve a specific quality or properties.

Main applications for FT-3 type material are cores for RCCB completely replacing NiFe in last decade, cores for ANSI current transformers, CMC cores, signal and gate drive transformer cores and power transformer cores as toroids or cut cores. Cheaper FT-1 type or similar materials can be used for these applications, if compromises in terms of stability and reproducibility can be made. It is not surprising that automotive applications are the strongest growing market for high-quality FT-3 type cores.

Hysteresis loop and all resulting magnetic properties, such as $\mu(H)$, $\mu(f)$, coercivity and losses, are adjusted by the annealing process, mostly in a magnetic field. The minimum permeability achievable in that near-zero-magnetostriction sub-class is about 18.000. This is too high for applications like storage chokes, flyback transformers or DC-tolerant current transformers. Using so-called creep-induced anisotropy developed some years ago, on a commercial base driven by Imphy Alloys / Mecagis / Arcelor Mittal, it is possible to reach permeabilities as low as 100, requiring high-sophisticated production technology: the tape must be annealed under tensile stress of some 100 MPa and wound to cores in a continuous process – with the high brittleness of the tape. Cores with permeability of some 100 or few 1000, high linearity and excellent temperature stability, but increased losses compared with field annealed cores, are available in the market today. In last years, production costs could be reduced to a degree that nanocrystalline cores become competitive in these applications against powder or Co-based amorphous cores.

Another option to decrease permeability is addition of a second transition element (Ni and/or Co), introducing, however, magnetostriction of some ppm. VACUUMSCHMELZE started with VITROPERM® 270, 250 and 220 materials for permeabilities between 1800 and 8000 (occupied also by Ferrites with much lower B_s) about 15 years ago, mainly for current transformers and CMCs with high non-symmetric currents. Today, this approach is used by a couple of manufacturers, and also the remaining gap between 8000 and 18.000 is closed. So, nanocrystalline material is principally available for the whole range between 100 and 1.000.000 at 50 Hz.

Recent developments of nanocrystalline materials

Attempts have been made to increase significantly saturation induction, with little loss of the other advantageous properties, on an Iron + Zirconium / Hafnium base or with addition of Phosphorus. Other approaches use ultra-fast annealing of amorphous materials which normally crystallise with large grains. All these materials have never got commercial relevance. Hitachi Metals have launched FT-8 with $B_s = 1,32$ T and $\mu = 5000$, but $\lambda_s = 8$ ppm for medium frequency, high current applications.

Acal BFi very recently started to offer two new materials: one material with similar properties like FT-1 but 1,4 T and 3 ppm magnetostriction, and a 1,7 T material with a property profile between FT-1 and 2605SA1 in terms of losses, permeability and magnetostriction.

Another challenge is the reduction of tape thickness to increase the accessible frequency range compared to ferrites. Again Hitachi Metals were the commercial pioneer with FT-3K50T, achieving $\mu = 30.000$ at 100 kHz, followed by all relevant ribbon producers.

4. Ferrites

Ferrite cores are used mainly in HF and broadband applications with higher permeabilities as a result of low losses and low saturation induction. Core shapes are highly standardized; accessories like bobbins as well. This seems to allow easy usage – when the optimum material is found among the huge variety of manufacturers and their material grades.

Ferrites are principally a ceramic material, i.e. sintered grains of non-metallic (semiconducting) oxides. Their general composition is MFe_2O_4 , with M being the metals which provide the nomenclature for the material. For soft magnetic cores, there are two big groups, so-called Mn-Zn ferrites (base composition $Mn_xZn_{(1-x)}Fe_2O_4$) and Ni-Zn ferrites ($Ni_xZn_{(1-x)}Fe_2O_4$).

Production, resulting morphology and properties

The first manufacturing step is the preparation of a powder with desired composition. The raw materials are metal oxides; oxides of other elements are also added to modify the properties of grains and of the grain boundaries, which will be created later. Different ferrite materials are defined at this initial production step.

The metal oxide composition is mixed appropriately and then fired at approximately 1000°C to create flakes. These are then subsequently milled into a fine powder.

The powder is pressed into different shapes under high pressure in the order of 1 ton / cm². For each core size, a pressing tool is necessary consisting of at least two parts. The resulting so-called “green bodies” are then sintered at up to 1400°C under defined atmosphere. During many hours or even days, some grains will grow at the cost of others, the free volume between the grains disappears, i.e. the bodies are compacted and shrink significantly, and grains are connected and separated finally by thin grain boundaries with different chemical and structural properties. The most critical property of these boundaries are the insulating properties and thus, these act as capacitor with the neighboring grains. It is worth noting that structural changes which occur during this sintering process determine the final properties. This is an essential difference to metal powder cores.

There are three critical process parameters which control the final properties:

- **Temperature-time profile** - this determines the grain growth, i.e. their final size in the order of some μm , and the properties of grain boundaries.
- **Atmosphere** - i.e. oxygen partial pressure. This determines the oxidation state of iron and – together with the mentioned additives - the magnetic properties of the resulting material.
- **Shrinkage** – controlled by powder properties, pressing process and temperature-time profile. The volume reduction doesn't result just in a simple shrinkage of the green body, but may also change the shape, especially for complicated shapes. This shrinkage can be calculated or simulated in advance, but sometimes the result is surprising and the tool must be corrected.

After sintering, most parts will require machining to obtain defined dimensions and even surfaces. Principally all types of machining, including grinding, drilling and sewing can be applied, therefore allowing parts to also be machined from a simple sintered block, a big advantage for prototyping.

Finally, cores can be coated with different materials to insulate and protect them.

Generally, the possibility to form parts quickly with pressing tools, even with complicated shapes, and machine them with standard equipment makes ferrite core production cost effective for high volumes. A set of standard shapes like toroids, different shapes derived from E and U cores, rods, plates and even beads with voids or integrated leads has been established. For small and medium volumes, however, this advantage disappears due to tooling and setup efforts and costs.

Final magnetic properties are the result of both the grain and boundary properties, as well as the interaction of them:

Low frequency hysteresis loop

and hence initial permeability, saturation induction and hysteresis losses determining low frequency power losses is defined by the composition and microstructure. Since no preferred direction of magnetization is induced during manufacture, ferrite cores have usually a round hysteresis loop: Linearity $\mu(H)$ is low, permeability shows a maximum at a certain field, i.e. current. Some material grades with rather rectangular loop (high remanence) are known as exception, so-called saturable cores. Initial permeability of usual Mn-Zn ferrites is 600 – 20.000 at 25°C, and 15 – 2000 for Ni-Zn ferrites. B_s is 320 – 550 mT and 220 – 420 mT, respectively. This is the lowest saturation induction range among all commercially used soft magnetic materials – and the biggest disadvantage of ferrites limiting the usage at low frequencies.

Curie temperature

T_C is 100 – 300°C, for some Ni-Zn materials up to 500°C. This is rather low compared with other materials and often a disadvantage because it determines maximum application temperature: B_s decreases continuously towards T_C ; operation is not possible near T_C . Permeability increases usually with temperature and has the maximum near T_C .

Resistance

The bulk material i.e. the grains, is a semiconductor with much lower conductivity than the other metallic materials. The grain boundaries are insulators and act as strong resistor at low and medium frequencies, determining the total resistance and – more important – restrict the maximum eddy current paths. These are actually the grain size, which thus determines the eddy current losses at medium frequencies. The eddy current losses are very small due to small size and poor conductivity of grains; losses are dominated by hysteresis losses. Resistivity decreases, however, rapidly with increasing temperature which makes important parameters like permeability and power losses highly temperature controlled. Moreover, grain boundaries act as capacitors at high frequencies (> 1 MHz depending on their thickness and structure). From a certain frequency, permeability drops and losses increase more than expected from a one-phase system. Often permeability even increases close to the start of the drop.

The temperature dependence of permeability and losses

Are the most significant feature of ferrites, one of the most important differences to other materials, and one of the reasons for the big amount of different material grades: Adjusting grain and grain boundary properties allows adjusting temperature behavior more or less independently from the basic properties.

Mechanical properties

The consequence of ceramic structure and strong shrinkage during sintering: Big cores may show visible or hidden cracks which usually are detected by manufacturer. Nevertheless, cores are sensitive against forces; therefore the maximum size is limited.

All in all the interaction between the two different structures (the bulk and boundary) makes the properties of ferrites with their dependence on temperature, field (current), and frequency much more complex than properties of other materials – and opens the opportunity to tailor materials for certain applications.

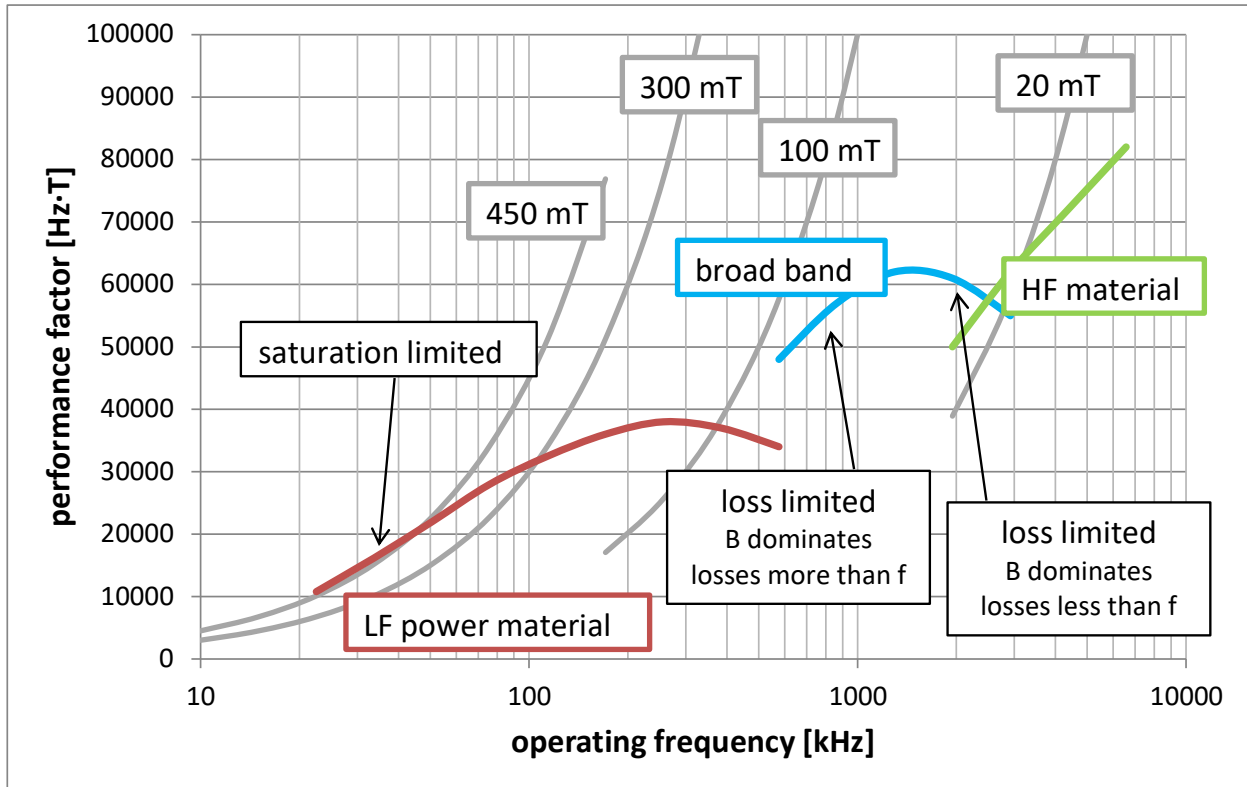
Materials selection and applications

From the initial material composition and the process parameters, there is a huge variety of different material sorts, even from one manufacturer, and it's not easy to compare and select materials of different manufacturers. Moreover, not all core shapes are available for each material. Therefore the designer, looking for an optimum core, needs to follow an empiric search route. Manufacturers usually provide some materials lists with significant materials parameters which should be used as first guidance.

1. The most important parameter is the frequency range of application. Recommendations of suppliers range from as low as 100 kHz up to 50 MHz. So a couple of suitable materials can be selected.
2. This selection may be restricted further if the designer knows already the core shape to be used. It is worth to note that effective permeability is reduced compared with material permeability when choosing assembled cores having a gap like EE combinations.
3. Next criterion is the maximum operation temperature which limits T_c (T_c should be clearly above maximum temperature) and B_s . For "small" frequencies (up to 80 kHz), the full saturation induction can be used without having problems with losses (saturation limited operation). At higher frequencies, losses become too high and limit the induction swing (loss limited mode).
4. Often the so-called performance factor (PF) vs. frequency plot is used to visualise the optimum choice of materials in power applications: PF is the product of frequency and maximum induction B_{max} without exceeding a given loss level indicating the potential power of a transformer. In the saturation limited frequency range, B_{max} is simply B_s ; actually the core shape should be considered as well to avoid partial saturation of cores. The PF(f) plot is a simple line with slope 1 – and the lines are very similar for different materials, determined only by material specific B_s . Above a certain frequency in the range of 80 kHz, cores cannot be operated until B_s due to increasing losses; the core operation is loss limited, and the PF(f) plot becomes more flat.

Losses depend stronger on B than on f, therefore increasing frequency and reducing amplitude by the same factor reduces losses. In other words, having a defined loss level allows higher performance factors at higher frequencies, the PF(f) plot has a positive slope. At a certain frequency (obviously reflecting the above mentioned favoured frequency range), the curve goes down because losses depend stronger on f than on B. This is visible also in the loss curves of the manufacturers: P_v vs B plots become flatter at higher frequencies. These PF(f) plots appear to be simple to use, but the designer has to be aware that they are valid just for a defined maximum loss level (for example 500 mW/cm³) defined by ambient temperature, operation temperature and cooling, and

operation temperature itself determining B_s and P_v . Allowing higher losses may have influence on maximum operation temperature (or cooling design) or reverse, which changes material selection basing on T_c . Changing operation temperature causes different losses and B_s which change the PS(f) plots etc. – finally it’s an iterative process which needs to go into detailed material curves.



5. Permeability is important when a certain inductance and / or maximum current (considering also B_s) are sought – but this is a common design issue for all materials.
6. Fine tuning criterion – or one of the first steps - may be the evaluation of temperature dependence of permeability and losses. Manufacturers spend much effort to optimize it for certain applications: power ferrites, for example, have the loss minimum in the expected operation temperature range. High losses at lower temperature are no problem; actually it’s a self-controlling system up to the temperature where losses rise again. Other applications seek for constant properties in a broad temperature range.
Finally, introduction of additional air gaps in toroids or U- or E-based core shapes open a wide field to adjust effective permeability, current resilience, and hence storable energy. Gaps can be created easily by machining.

Both manufacturers and designers define groups of materials with optimized properties for certain applications. And in each group, there are “standard” materials and more exotic ones.

Power ferrites

Are mainly Mn-Zn ferrites with TC > 220°C, better >250°C, rather high BS, medium permeability of few Thousands, and medium losses allowing saturation limited mode until 200 – 400 kHz. Loss minimum is around 100°C, and the main difference between materials is overall level and temperature dependence of permeability. These ferrites are used in many shapes for transformers and chokes.

Their real advantage is in the loss limited mode (>> 100 kHz): the low saturation induction compared with other materials, especially nanocrystalline material, is no design disadvantage, i.e. the size of components is similar for all material classes. The ferrites benefit from little lower losses and low price. In the saturation limited mode, the cores and components are definitely bigger in size than those made from other material classes – here the benefit can be convenient shape and price. Power optimized ferrites are used also in automotive applications, where space and weight reduction and high operation temperatures are a topic.

Signal and pulse transformer materials

Have higher permeability >10.000; T_C and B_S don't play an important role. Materials for EMI suppression and for CMCs are similar.

Ni-Zn ferrites

With lower permeability, but lower losses are used mainly for HF and wideband applications, again in many shapes including rods, tubes, and plates.

Rods and plates

Are increasingly used as antennas, shields, absorbers or flux guides, actually driven by wireless charging, inductive heating and signal transmission. For this, mostly wideband (low loss) material is used, both Mn-Zn and Ni-Zn.

Recent developments

We do not expect “new” materials to become available or created in near future, but certain properties are likely to be improved further to give combinations of properties optimized for certain – sometimes new – applications:

- SMPS frequency increases, modules become smaller. So power ferrites are developed with lower losses at increased switching frequencies and temperatures around 100°C.
- Automotive power applications seek for materials with operating temperatures of at least 155°C and low losses at 120 – 150° - appropriate materials have been already developed, and this will be continued.
- Density and therefore apparent B_S and even μ are improved by higher pressure for shaping before sintering.
- For CMCs and similar designs, new shapes are available allowing winding without magazine-based machines (wire must be transferred into a store before winding) for toroids, and without bobbins for other shapes.
- Rather new applications like inductive charging will drive new developments regarding materials and shapes for energy transmission itself, shielding and flux guidance, EMI topics and power conversion.

5. Powdercores

Powder cores consist of soft-magnetic metallic powder, mostly iron and its alloys (mixed with nickel, molybdenum, silicon and others), embedded in a binder material. The powder mix is pressed into desired shapes, but as it is not sintered, grains stay isolated. As a result, all these cores contain a so-called distributed air gap resulting in low permeability and soft saturation behaviour. The different compositions of powder, grain size and densities of the particles within the core allow for a wide range of permeability (10 to 550) and other material properties. Most materials are derived from known tape materials like Fe-Si or different NiFe alloys. The five most popular types of powder cores are Iron powder, Molypermalloy Powder (MPP), High Flux, Sendust (Kool M μ) and XFlux. In case of specific features manufacturers are able to offer blends of materials combining positive characteristics of the 5 main materials.

Production, resulting morphology and properties

The first step in the production of the powder cores is the preparation of the raw materials. Iron or iron alloys are melted and merged together to get a material with a specific composition and purity.

These metallic blocks are physically reduced in size by different procedures (rolling, cutting, milling) until the desired level of powdered grains is achieved. Different size grains are separated by sieving processes. The final powder is then composed by those grains which are insulated from each other by a binder material within a chemical process.

The powder is inserted into a mould, which determines the form of the powder core, and then compressed in one direction. After pressing, cores are annealed and cooled down with a specific temperature-time profile. After this process the bare cores are finished.

They undergo etching and grinding processes to give them their final shape. Finally, cores are coated and painted. These secondary operations influence mechanical properties (eg toroid cores can be more easily wound with bevelled edges) as well as the magnetic properties (eg smoothing the surface of E-cores to avoid additional parasitic air-gaps).

The most interesting property of the majority of powder cores is that they have low permeability due to distributed gaps. Eddy currents are small due to small grain size and effective insulation of the grains. Both features result in flat $\mu(f)$ behaviour and high saturation fields, so large currents can be applied without saturating the core.

Materials

Molypermalloy Powder (MPP)

MPP powder is an alloy of around 80% nickel, 17% iron and 3% molybdenum. The high amount of nickel influences the electrical and magnetic behavior and also the price, which is high compared with other materials.

The maximum available permeability of MPP cores is $\mu=550$, significantly higher than other powder cores. The cores have the lowest losses of all powder cores and a very good inductance stability under DC-bias and also higher temperatures.

High Flux

High Flux powder contains approximately 50% iron and 50% nickel. Cores made from this powder reach an overall permeability of 14-160. The mixture enables a very high flux level (double compared with MPP) through the core before reaching saturation, which gives the core its name. This characteristic makes High Flux cores an ideal solution for high DC-bias chokes. Often, it enables the designer to reduce the core size, if it is used instead of MPP or Sendust material. The material has more losses compared with MPP and Sendust but less than XFlux under the same excitation conditions. Recent process optimizations have been able to reduce power losses in High Flux material, reaching similar levels of MPP.

Sendust (KoolM μ)

Sendust powder is based on an alloy of roughly 85% iron, 9% silicon and 6% aluminium. The material is relatively low cost as it doesn't contain nickel. The permeability range is between 14 and 125. The soft saturation of Kool M μ cores starts at relatively low current. The losses in the material are low, which makes them the preferred choice for the usage in storage chokes in relatively high-frequency SMPS.

Recently, improved variants of Sendust have been deployed to the market. They extend the application field of sendust to applications showing higher currents (DC Bias improved) and higher operational frequencies (power losses reduced at frequency above 500Khz)

Silicon-iron (XFlux, Fluxsan)

The iron-silicon alloy, with approximately 6.5 % silicon, leads to a very stable inductance over DC bias in the range of high-flux cores. As they contain no nickel, they are the cheaper alternative if losses are not critical.

Due to the relatively large loss generation in the XFlux cores, they are mostly used when frequency doesn't exceed 30 kHz or if the amplitude of the high-frequency part of the current through the component is limited.

Iron powder

Iron-powder cores offer a permeability of between 4 and 100. Most iron-powder cores use an organic binder, which is susceptible on thermal ageing under high temperatures. Iron powder cores are cheaper compared with other powder cores, but lead to more core losses compared with Sendust, High Flux and MPP cores.

The pressure during the pressing process is moderate, which makes iron powder cores available in many different shapes, such as E-cores, pot-cores and rods. Large iron powder E-cores or pot cores, which can be gapped in their middle leg in addition to the distributed air-gap within the material, offer the possibility to decrease effective permeability further and enable the cores to be stable at even higher currents.

The following table compares the technical characteristics of the different powder core types.

Comparison of powder-core materials (Origin: Magnetics Inc.)

| | MPP | High Flux | Kool Mμ | Si-Fe | Iron powder |
|--|------------|------------------|-------------------------------|--------------|------------------------|
| Permeability | 14-550 | 14-160 | 14-160 | 19-125 | 4-100 |
| Saturation (B sat) | 0,7 T | 1,5 T | 1,0 T | 1,6 T | 1,2-1,4 T |
| Frequency Response - 60u flat to... | 6 MHz | 3 MHz | 5 MHz | 3 MHz | 1 MHz – 1GHz |
| AC core loss | Lowest | Moderate | Low | High | Highest (and variable) |
| DC bias | Better | Best | Good | Best | Good |
| Alloy composition | Fe Ni Mo | Fe Ni | Fe Si Al | Fe Si | Fe |

Amorphous or nanocrystalline powder

A special group of powder material is made from amorphous or nanocrystalline tape. After annealing, the tape is milled to get flake-shaped particles. This shape makes it difficult to press mechanically stable bodies with reasonable permeability. Special binders and processes are necessary.

Main advantages are rather high saturation induction and good losses. Depending on particle shape and pressing technique, properties may be anisotropic.

6. Powder vs. gapped ferrites

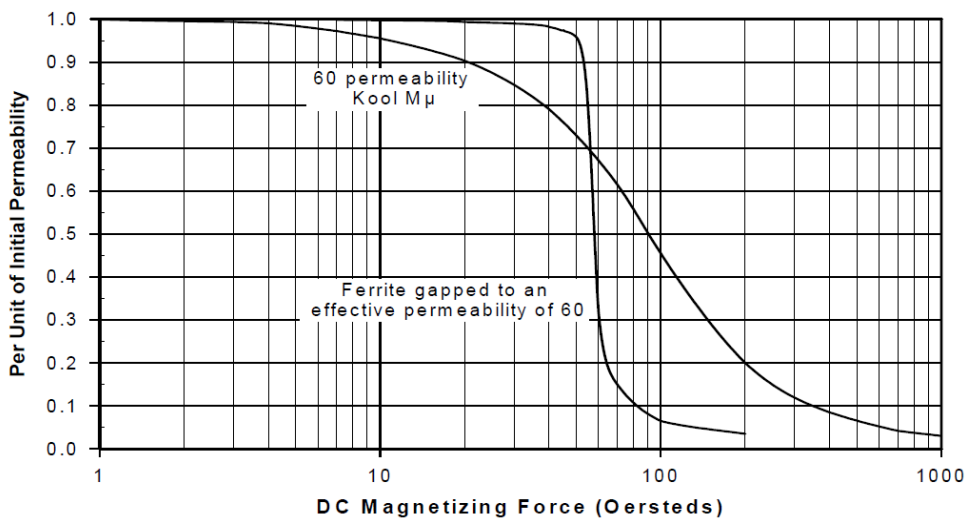
The manufacture of ferrite and metal powder cores sounds very similar, but there are big differences between both classes, not only due to different composition leading to, for example, different saturation induction. Different annealing conditions (temperature is much higher for ferrites) lead to a shrinking of the green body of ferrites, which is a challenge for achieving defined shapes or a dense body with small grain-grain distances. Ferrites reach higher permeabilities and are mechanically more stable.

Powder cores, as well as gapped ferrites, are able to store energy as their inductance is stable up to specific current.

Thanks to this property, both can be used as storage, differential mode filter chokes or for damping reasons under a DC-bias. Also the effective (overall) permeability of a gapped ferrite core is often in the same range as the permeability of the powdered cores ($\mu=4-500$). Both core types can be used under relatively high frequencies of several 10ths of a kHz, as the cores have a high resistivity. At higher frequencies, ferrites or Sendust powder cores are the preferred solution.

A very important difference between gapped ferrites and powder cores is the saturation behaviour. The saturation of a ferrite core is reached with a flux density of 0.3 to 0.5 T, depending on material and temperature. Powder cores lose their permeability at much higher flux levels of 0.7 to 1.5 T. Not only is the maximum flux different, but also the current-inductance characteristic of the chokes made by those cores, due to the particle structure of the powder cores. The reason is distributed gaps in the direction of the flux and in any other direction; therefore the saturation of the powder cores is soft in comparison with a gapped ferrite (see the following figure, origin: Magnetics Inc.). This is because some particles in the powder will saturate earlier, due to their position and so lose their permeability. In a gapped ferrite structure, the biggest part of the ferrite material will saturate at the same excitation, as the material is relatively equally fluted by the magnetic flux.

Comparison of saturation behaviour of a powdered core (distributed gap) and a gapped ferrite (Origin: Magnetics Inc.)



A further advantage of the distributed gap within the material compared with a gapped core is the avoidance of fringing flux around the gap, which is shown in the figure below. The AC-part of the fringing flux entering the high-conductive copper winding of the choke could lead to losses due to high-induced eddy currents. Powdered cores can reduce fringing flux, enabling the designer to place the winding closer to the core and save space.

Comparison of fringing flux of a powder core (left) and a gapped structure (Origin: Magnetics Inc.)

