A user guide to soft magnetic materials (part 3 of 4)

Ferrites

Soft magnetic 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 1,000°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 / cm^2. 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 1,400°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 μ(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.

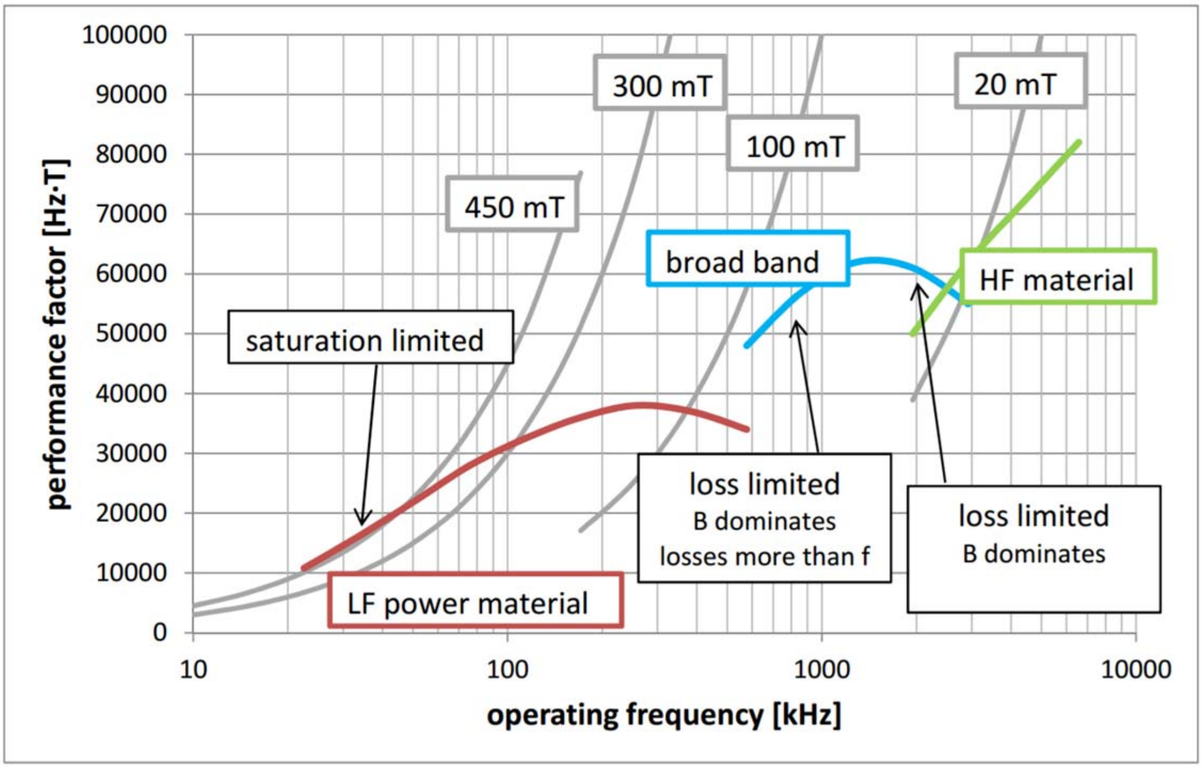
Materials selection and applications

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 favorised 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/cm^3) 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 T_C > 220°C, better >250°C, rather high B_S, 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, und 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.

Conclusion

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.