A user guide to soft magnetic materials (part 2 of 4)

Selecting the right material class: key considerations with amorphous and nanocrystalline materials

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 and μ vs. f graphs shown in the first part of the guide. 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.
- Within powder cores, mainly the operation frequency and space considerations determine the preferred material.
- Low permeable (μ = 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). Here we use ferrites or tape cores. Within these classes, usage mainly depends on frequency for power applications:
    - For 50 Hz, laminations or wound cores of steel may be used, but it is being substituted more frequently by Fe-amorphous and even nanocrystalline material for efficiency reasons.
    - 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 Bs, higher permeability) can't be utilised for power applications and cheaper ferrites become the preferred material, as long as the shape allows for it.
- 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, nanocrystalline cores are a useful solution due to taking up less space, however the compromise is that the customer often needs to be willing to pay a higher component price for the reduced space.
- Any application with low net current, but high impedance for signal processing or EMI, needs 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.

Fe-based amorphous and nanocrystalline

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 taped – 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 2606SA1. 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 2606SA1 (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 μ(H) behavior for μ > 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 μ(H), μ(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. We can be curious if the production costs can 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 offers with VITROPERM® 270, 250 and 220 materials for permeabilities between 1800 and 8000 (occupied also by Ferrites with much lower B_S), mainly for current transformers and CMCs with high non-symmetric currents.

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. These materials have never got commercial relevance. Hitachi Metals have launched recently FT-8 with $B_S = 1,32$ T and $\mu = 5000$, but $\lambda_S = 8$ ppm for medium frequency, high current applications.

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