Nanocrystalline soft magnetic cores - an interesting alternative not only for highly demanding applications

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Abstract

In the past years soft magnetic cores of nanocrystalline FeCuNbSiB alloys have supplemented and to some degree even replaced soft magnetic ferrites, amorphous and NiFe cores in industrial electronics. The driving force for this development has been their unique combination of magnetic properties and more attractive prices due to an economical automated large-scale production process. Nanocrystalline cores offer design options which are not only problem solvers in critical cases, but are competitive in a "global" sense with cost savings coming not from the core itself but from an intelligent system solution. The paper will survey the production technique of the strip material, outline the properties of commercial nanocrystalline cores and discuss the most popular applications.

1. What design engineers dream of and why they are sometimes frustrated

The ideal soft magnetic alloy should have low losses (= high efficiency and no cooling requirements), a high flux density (= small, light and cheap), a high permeability when needed (= low numbers of turns, less copper, lower stray inductivity), a wide temperature range and low temperature coefficients of properties (= no safety margins necessary) as well as robustness against mechanical forces, radiation, corrosion and whatever could harm the device. To the strong relief of all material engineers, Mother Nature simply does not provide such a universal alloy. Materials with high flux densities like SiFe or CoFe have typically relatively high magnetization losses and vice versa, materials with high permeabilities are typically more sensitive towards mechanical stress (due to a property called "magnetostriction"), and if they have high permeabilities and are less sensitive against mechanical stress, then the shape is limited to toroidal or C-cores.

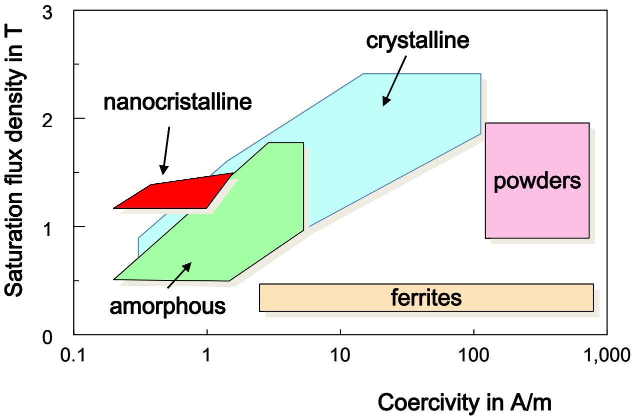

Fig. 1. Overview of soft magnetic alloys: not complete but hopefully enough to demonstrate

Consequently magnetic designers can choose from a wide variety of soft magnetic alloys, from "simple" electrical steels (grain-oriented and non-oriented SiFe) over ferrites (MnZn, NiZn) and powder composite materials (MPP, HFP, Sendust, Fe and SiFe powders) to special crystalline (NiFe, CoFe), amorphous (VITROVAC®, METGLAS®) and nanocrystalline alloys

(VITROPERM®, FINEMET®). Although the pre-selection is pretty straight forward with frequency and pre-magnetization being the main criteria, an impressive number of possible candidates remain needing careful decision making.

Perhaps the world could survive with “just” SiFe electrical steel for 50/60 Hz applications and ferrites for switched mode transformers and chokes. But what shall we do with thousands of unemployed material engineers? Seriously, the diversity of materials and the progress of properties is a precondition not only for most high-end applications (not only aircrafts and space shuttles), but can significantly contribute in energy savings, which is among the most challenging endeavors of mankind.

Improving and refining is a never ending story, even if the progress is getting smaller in percentage. However, if we would consider only 1% of all the power losses that could be saved world-wide through less magnetization losses - it could save several nuclear power plants or coal power plants (Note: this paper is intended to be strictly neutral. The author, being an engineer, will never admit that he feels always a bit uneasy in the presence of nuclear power plants). Nevertheless, even if we do not consider environmental or ethical aspects, but wouldn’t it be a great satisfaction for every design engineer when he or she would not have to pick a common standard solution, but to create something technologically advanced and innovative that sets his creation apart from all the other ordinary designs? Nanocrystalline cores could help to achieve just that and could save money to make the buyer happy (o.k., o.k., I have never seen a happy buyer in real life, it’s just imagination).

2. What makes nanocrystalline alloys unique

Nanocrystalline soft magnetic metals are a Japanese invention made by Hitachi Metals. Although it is said that they have been invented by coincidence and not by aim, the work of their researchers deserves our highest respect. Within the few players that were working on amorphous “rapidly quenched” materials was Germany’s Vacuumschmelze GmbH & Co. KG which took the challenge with one of their researchers, like Dr. Herzer who won the race by explaining in detail what makes nanocrystalline alloys so unique and special. I would like to quote Dr. Petzold who is another researcher at Vacuumschmelze, who said: “Owing to its high degree of reliability in the production process, the most prominent representative of this new class of materials is the family of the FeCuNbSiB alloys. As it was pointed out by Dr. Herzer, these materials are magnetically quasi-isotropic due to an ultrafine grain with a mean diameter of about 10–15 nm which arises in the originally amorphous matrix during an annealing treatment at 500–600°C, which causes the disappearance of the magnetocrystalline anisotropy. As such a grain is much smaller than the width of the domain walls, there is also no pinning by the grain boundaries with the consequence that the domain wall motion is not hindered. Another immediate consequence of the nanocrystalline two-phase-structure is the rather low magnetostriction of $\lambda_s < 10$ ppm, which is much lower than in the as quenched still amorphous state. In certain compositions as for example $Fe_{bal}Cu_1Nb_3Si_{15,5}B_7$, even zero-magnetostriction can be obtained which makes the magnetic properties highly insensitive against internal and external stresses.”

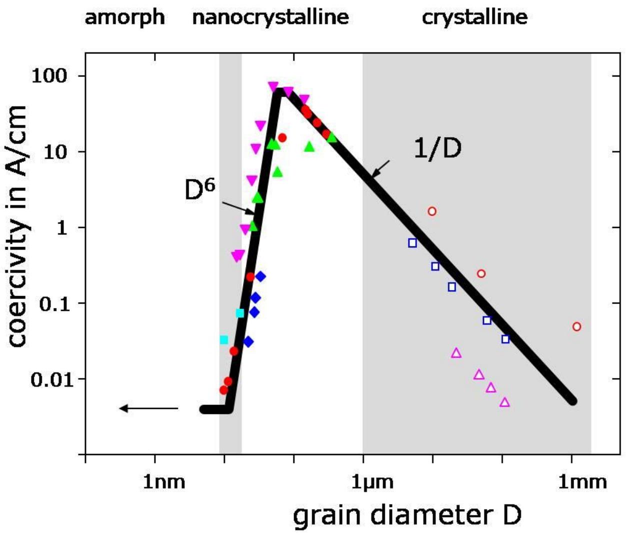

Fig. 2. The famous D^6 law from Dr. Herzer: making things smaller will sometimes surprise you

Perhaps the last few sentences sound a little too specialized for the non-technical lay person, therefore let me try to rephrase it into a “managing version” (although this might still be too sophisticated for top management☺):

Nanocrystalline metals are produced like amorphous metals by using a special rapid quenching technology. The melt is chilled into a solid state within a thousandth of a second. In order to achieve this, one dimension of the final material shape must be small in order to get the heat out of the material fast enough. Therefore amorphous strips are typically about 0,025 mm and less in thickness.

Like the amorphous strips, nanocrystalline strips are also initially amorphous. Whereas amorphous alloys loose their good magnetic properties while crystallizing at temperatures of about 500 °C, the magnetic properties of nanocrystalline materials improve after crystallization at temperatures of approximately 600 °C.

When properly annealed, nanocrystalline materials develop crystalline grains within the nanometer range in an amorphous matrix (guess what has given them the name …yap, correct!). Small grains typically are counter-productive to good soft magnetic behavior unless they are as small as 10 - 15 nanometers (which never will be the case in “normally” produced crystalline soft-magnetic material). Magnetism seems to be a bit short sighted and the grains become “magnetically invisible” if they are only small enough (see fig. 2).

“Nanocrystalline” Fe-based materials are highly “magnetostrictive” before annealing and crystallization. However, and this is truly exciting: If composition and annealing conditions are in a certain range, then the positive magnetostriction in the nanocrystalline grains exactly cancels out the negative magnetostriction in the amorphous matrix. This gives a zero-magnetostrictive alloy based on Fe with properties similar to the much more expensive amorphous Co-based alloys or crystalline permalloy alloys (80 % NiFe), but with higher flux density and a better temperature stability.

3. The production process: very straight forward and very fast

The initial material is produced as an amorphous ribbon via a special rapid solidification technology. In order to freeze-in the amorphous “structure” of the melt, cooling rates of 1 million degrees per second are necessary, which is fairly fast. The most common technology is the so-called melt-spinning technology, where the hot melt is pressed via a ceramic nozzle on a fast rotating and water cooled copper wheel. The melt almost immediately solidifies to the solid state, and after a certain contact time and contact length a thin metallic and amorphous strip is produced from the melt in only 1 step - with a velocity of about 100 km per hour.

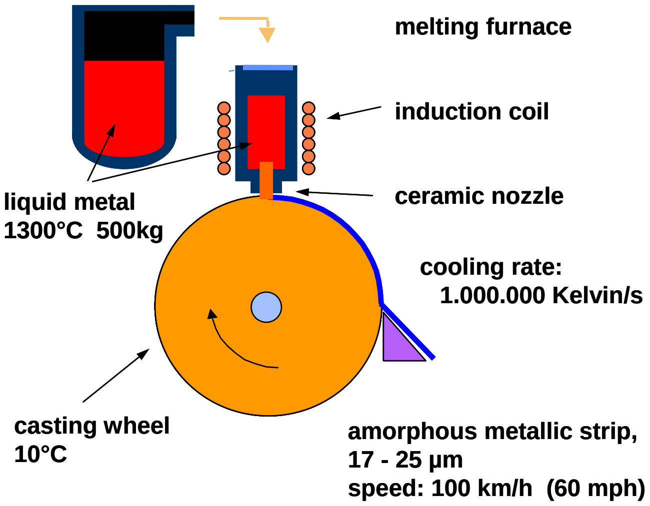

Fig. 3. Rapid Solidification Technology

In the meantime this technique is well established for large scale production, so that the quantity of worldwide cast FeCuNbSiB-alloys has been grown to a magnitude of several 1000 tons per year.

Nevertheless the technology is rather tricky since many parameters needed to be controlled extremely tightly. Imagine several 100 kg of hot melt at a temperature of 1500°C in a big furnace, while just a few meters away sophisticated catching wheels wind a thin strip with a thickness of less than a human hair and approaching with a velocity close to the speed limit on a highway. Further the strip is expected to be uniform in composition (within ± 0,1 atomic percent) and dimension, with a well defined surface both mechanical (roughness) and chemically (a bit oxide working as an electrical barrier).

It was fortunate that Vacuumschmelze started the development at a time when the former German Mark was a strong currency since machine park and development of this technology required a high capital investment.

What we have now is a thin metallic strip, fairly brittle, very hard with potentially superior soft magnetic properties - after magnetic annealing. During the annealing (and crystallization) process the strip further embrittles, which means we need to produce a magnetic core before annealing.

The possible core shapes are certainly limited, and all what is different from a simple tape-wound toroid is relatively complex to manufacture and consequently more expensive. Therefore let us make the best of these limitations and focus on toroids since they have the most uniform flux distribution of all possible core shapes, which is a precondition to make use of the full magnetic potential of the material.

The core production is again a very straight forward process. However a fully controlled, fast and automated core production with a brittle non-uniform thin strip that has sharp edges requires a few engineering skills - particularly if you want to do this fast and very cost effective without the need for a manual process in a low cost country. Even today Vacuumschmelze is still continuing to optimize the equipment - after more than three decades of production of amorphous and nanocrystalline cores in the millions. The results are high quality cores that are very uniform in their properties, from batch to batch, in summer as well as in winter.

To prevent an increase of the eddy current losses in a preceding inductor, the ribbon surface has to be insolated by a thin mineral layer, which typically consists of MgO. Afterwards the ribbon is wound to toroidal strip-wound cores whereby the outer diameter can be varied between about 2 mm and several hundreds of millimeters. Automatic machines can perform the winding free of mechanical stress and flux controlled with an output rate up to several hundred thousand pieces per week, depending on the core size.

The wound cores are stabilized via spot welding and stacked in a stacking magazine in order to prepare them for a two step annealing treatment in a batch furnace which is equipped with facilities to generate a strong magnetic field orientation in the axial and tangential direction of the cores.
During the first annealing stage at a temperature between 540°C and 580°C the nanocrystalline phase arises. In this state the material exhibits a more round hysteresis loop with a remanence to saturation ratio of typically about 50% combined with a high initial and a high maximum permeability which can rise up to values of several hundred thousand.

For most applications more specialized shapes of the hysteresis loop are advantageous, which are either square shaped or very linear “flat” loops. This is achieved under the influence of a magnetic field. This field “induces” a controlled uniaxial anisotropy K_u (a preferred direction for the intrinsic magnetization) with the direction depending both on the orientation of the field relative to the axes of the wound ribbon, and on the annealing temperature.

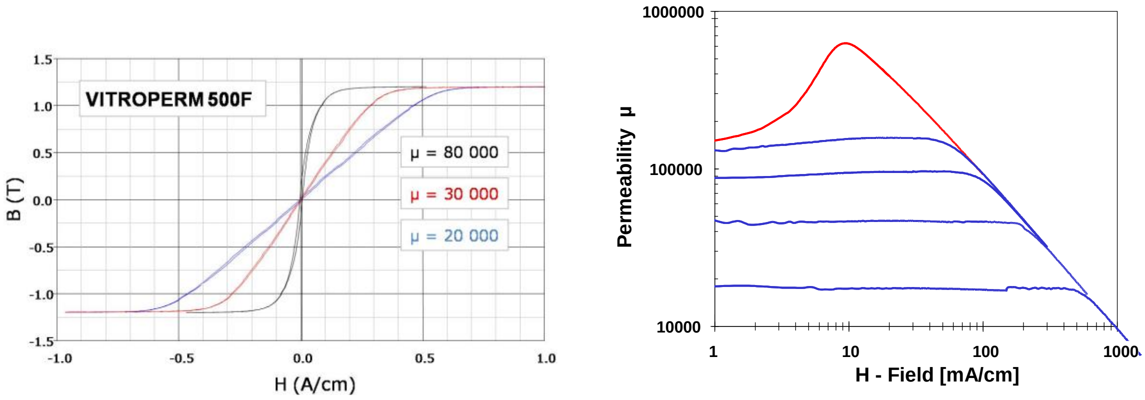

Fig. 4. Static hysteresis loops and permeability versus field strength of nanocrystalline cores with different permeability levels. The red curve on the right is the characteristic w/o magnetic field annealing (unpublished results from Dr. Petzold, Vacuumschmelze GmbH & Co. KG)

If the anisotropy stands perpendicular to the ribbon axis, a flat loop will arise whereby the initial permeability can be adjusted in a well defined manner even at large-scale production in a considerable wide range between about 15,000 and 150,000 by a simple variation of the field conditions. Simultaneously the ratio of remanence to saturation B_r/B_s changes between about 2% and 10%, as high permeability means very weak induced uniaxial anisotropy and thus small remaining disturbances in the material (stresses, impurities) are negative influences.

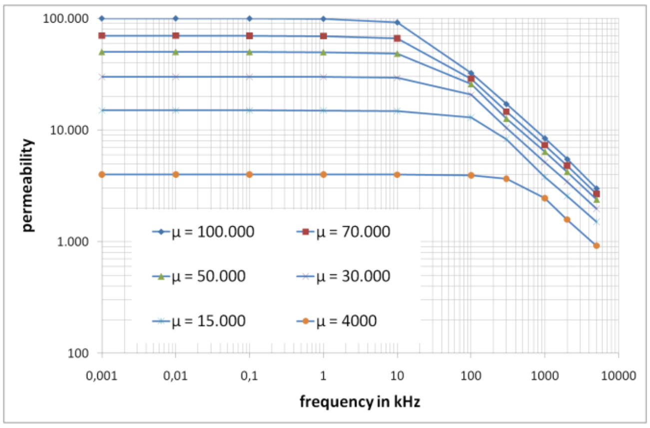

Fig. 5. Permeability versus frequency of nanocrystalline cores with different permeability levels

Such flat loops offer a unique combination of high permeability with high linearity. If in contrast the induced anisotropy is aligned parallel to the ribbon axis, the resulting loop is square shaped. In this case a ratio of B_r/B_s close to 100% is desired whereby in industrial practice values of B_r/B_s can rise up to more than 90%.

Finally the magnetic properties of each single core are measured by a computer controlled testing sequence. If the cores comply with the specification they will be encapsulated or epoxy coated, labeled and made ready for shipment.

4. What nanocrystalline cores are good for and why

Suppose you are designing a lowest cost power supply with no restrictions in seize, efficiency, temperature range or environmental impact. Then nanocrystalline cores will probably not be your first choice. However, if you are required to consider frame conditions, you should at least have them in the back of your mind as a technically very interesting option. Let us survey a few commercial applications of nanocrystalline cores and let us list a few reasons for each case why they are so interesting.

4.1. MagAmp chokes - analog, but highly efficient and robust

I like to start with something fairly exotic in our digital world, named Magnetic Amplifier or MagAmp. A MagAmp is a saturable reactor which is used to control one or several output voltages of switched mode power supplies. Using a simple control circuit such a choke adjusts the output voltage by blocking more or less “time-voltage” area. Interestingly the magnetization losses of MagAmps are lowest at the maximum current. MagAmps are therefore especially suitable for high current outputs with low voltages. Apart from the high efficiency in such cases MagAmps are also extremely reliable.

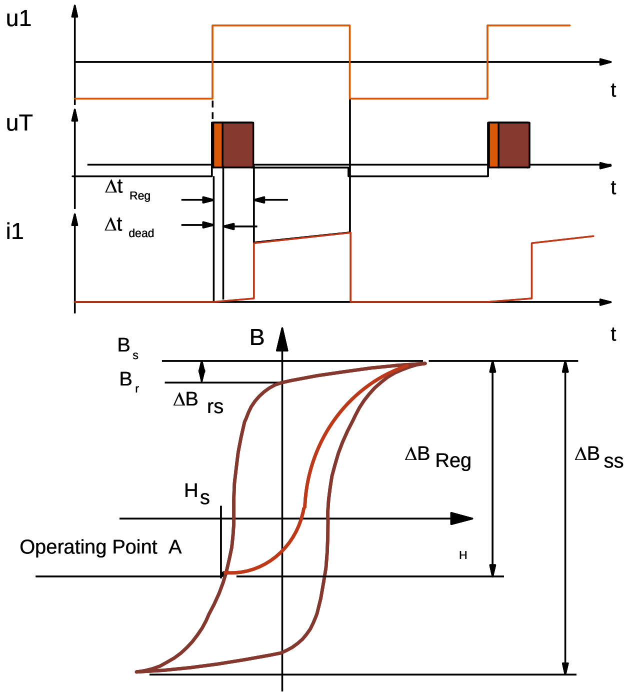

Fig. 6. Basic principle of a MagAmp: During the magnetization from operating point A to saturation, the voltage drops across the MagAmp choke. This part of the wave is removed from the full square wave. Since the operating point can be manipulated (via the regulation circuit), the part which is taken away can be regulated and therefore also the output voltage.

The first switched mode MagAmps used permalloy tape-wound cores with square hysteresis loops. More than three decades ago, permalloys have been replaced by amorphous Co-based cores due to their higher squareness and lower losses. About one decade ago, nanocrystalline cores started to replace amorphous cores as they are simply cheaper and feature a higher temperature stability. Still nowadays amorphous and nanocrystalline cores are used for output regulation e. g. in computer power supplies.

A closed magnetic circuit is necessary to enable a square hysteresis loop. Every air gap, even if it is extremely small, significantly reduces the remanence ratio. Consequently all MagAmp cores are toroidal which allows nanocrystalline alloys to bring in the full weight of their excellent magnetic properties.

Another magnetic property next to the high remanence ratio is negatively impacted by air gaps (how they are unavoidable with e. g. E, U or pot cores) - that is permeability.

This brings us to an application where permeability is essential for efficiency and weight. I speak of common mode chokes, which are highly efficient to reduce common mode noise of switched mode devices - from power supplies to various converters.

4.2. Common Mode Chokes - efficient damping up to 180 °C

Typical common mode chokes are made with ferrite cores, often with standard cores and a design approach that is geared to simply increase the core size and the number of turns until the noise level is sufficiently brought down to a permitted level (I'm joking of course, the design process is a highly sophisticated multidimensional approach that uses every imaginable kind of intelligent simulation software). Ferrite solutions - independent from the design process - typically feature a pronounced resonance frequency range with excellent damping behavior in this range. More complex noise conditions e. g. with peaks in different frequency ranges are often approached and solved with two-stage filters.

Nanocrystalline cores offer much higher permeabilities than ferrite cores. This permits similar inductance levels in the lower frequency range <100 kHz with less number of turns compared to ferrites. This saves copper and increases efficiency. At higher frequencies the damping behavior is less determined by the inductivity but more by winding properties like winding capacities. Again, a lower number of turns means less winding capacity, which is of advantage. In total, nanocrystalline chokes feature a pronounced broad-band damping behavior which can be realized with small core or choke sizes.

Consequently they can be a problem solver if space is limited. Sometimes they can enable a one stage filter topology instead of a two stage with ferrite chokes, or they save space which can be a cost saving option, or they improve the efficiency and the competitiveness of a device. Furthermore their excellent properties are stable within a wide temperature range from - 40°C to over 130°C with a short time use up to 180°C without losing much of the damping effect. Try this with a ferrite choke, and you will see the difference.

Typical applications are industrial power supplies, drives and solar converters on the one side, where efficiency and a small size are important, on the other side all applications where a wide temperature range, small size, optimized weight and robustness are not only important but essential. These are e. g. automotive, aircraft, spacecraft and defense applications.

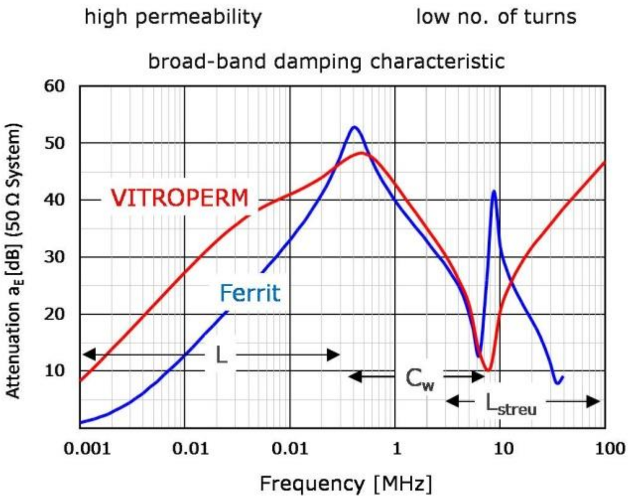

Fig. 7. Damping behavior of nanocrystalline common mode chokes - small size, broadband, almost no degradation at high temperatures

4.3. Precise current sensing - not missing a milliamp

Current transformers (CT) deliver an electrically isolated image of the primary current via a transformer core, a secondary winding and a shunt resistor. If this image shall not be just a rough guess, and if amplitude and phase errors shall be within a certain range, the core material should have a high permeability at already very low currents and it should have low losses.

Some demanding applications are e.g. electronic energy meters - simply driven by the desire of the energy providers to charge their customers not a cent more than what they are truly consuming☺. Nanocrystalline cores are meanwhile widely used in such devices. They have replaced permalloy cores due to their higher initial permeability, better linearity, lower temperature coefficients, and last but not least also lower alloy costs.

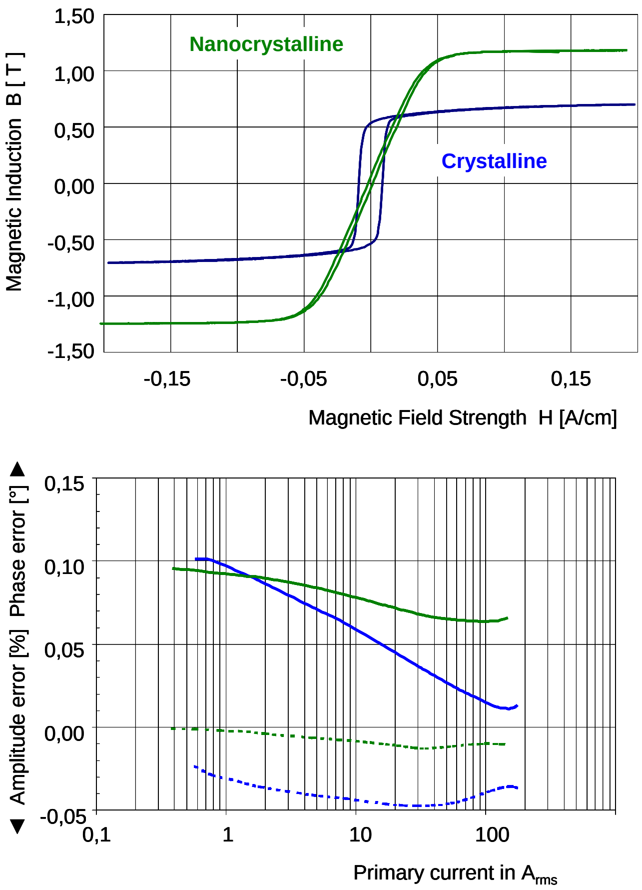

Fig. 8. Basic differences between crystalline and nanocrystalline high-permeability alloys for precise current transformers

European designers of energy meters face a special problem though. The IEC standards require testing with a "rectified" sinusoidal current, which means that the CT is only magnetized in one direction. Due to their high permeability and inductivity, even low remanence high permeability cores saturate after only a few cycles. Although this would open "energy saving" options to engineers with a certain "criminal" energy, technical inventions in this direction have been rigorously dried out by introducing low permeability CT's with highly linear hysteresis loops. They exhibit of course a high phase error; however as the phase error is constant due to the linearity of the magnetic properties it can easily be compensated by electronic means.

The first "DC" CT's were only possible with relatively expensive Co based amorphous cores, since it has not been possible to anneal standard nanocrystalline alloys down to permeabilities less than about 15.000 - which is still too high to meet the IEC standards. Meanwhile tailored nanocrystalline alloys are available that are allowing permeabilities of 4.000 and less. Another interesting option with standard alloys is to apply mechanical stress during the annealing process, which will result in permeabilities down to about 1000 and less (if the stress is properly applied).

For a magnetic enthusiast it is certainly a little bit frustrating that electronic energy meters can be designed with alternative technologies like shunts or Rogowski coils (which are air coils without magnetic flux concentrating material). If I am still alive to see the replacement of the old Ferraris-type energy meters by advanced smart meters in Germany (as it has already happened in countries like USA, Italy, India and others...), I will surely insist on getting a meter that is using the CT technology with nanocrystalline cores ☺.

4.4. Nanocrystalline cores in life saving devices

Most countries require the installation of so-called “Ground Fault Current Interrupters” (GFCI) in homes and apartments, particularly in the bath rooms. These devices simply switch off the main voltage circuit in the case of an electrical accident (e.g. an absentminded physicist using a hairdryer while sitting in the bathtub). The main component of a GFCI is a differential current transformer.

Most European countries go even further. They request the GFCI to switch the voltage off without allowing electrical amplification. Since human beings typically do not have the physical constitution to withstand a current more than 30 mA for a longer time, the GFCI devices need to trigger before such a current is flowing (over the human body to earth). This is not much, if no amplification is allowed. Consequently the current transformer needs to be highly sensitive in order to supply the necessary energy out of < 30 mA to trigger for example a relay.

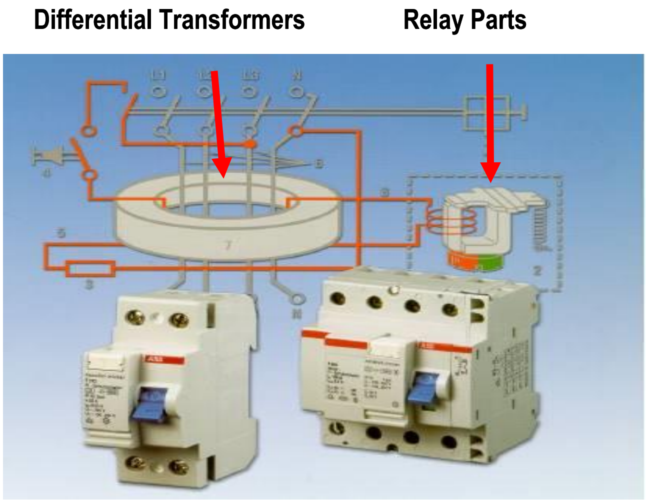

Fig. 9. Basic GFCI design (European version)

Highly specialized permalloy cores have been used in differential transformers, but meanwhile they have been replaced to a great extend by nanocrystalline cores. They are more sensitive, the device can be designed smaller, and again costs were a driving factor. Meanwhile at least one nanocrystalline core can be found in almost every European household, although not many of the residents are aware of it. However, for a few of them it might be a blessing while they relax in the bathtub.

4.5. A few other applications at a (very short) glance

Other applications are various types of (switched mode) power transformers, especially for higher powers in rough environments or at higher temperatures, as well as pulse power applications, signal sensing and transforming in power line applications and more. Nanocrystalline cores also circle the earth, either in air planes or in higher altitudes like in satellites. They work in sophisticated research devices or medical equipment, and they withstanding rough environments in mining or defense applications. However, they are also used in urban industrial devices like wind-generators, solar converters, PC power and household appliances.

Nanocrystalline cores are produced from a thin metallic strip which reduces the availability of varieties to a simple ring since it is by far the most economical choice. Although winding a toroid is more challenging than bobbin winding, it is compensated by the unique combination of soft-magnetic properties which the nanocrystalline alloys offer in a wide frequency and temperature range. I am not aware of any other magnetic material that is being used at 50 or 60Hz with better magnetic properties than permalloys, and has a better damping behavior up to 30 MHz compared to ferrites in common mode chokes.

Conclusion

Nanocrystalline cores are available in standard sizes ranging from 6 mm to more than 250 mm, and are offered either in plastic protection boxes or with epoxy coating. They are also offered with different permeability levels that are already tailored and optimized for various previously mentioned applications. Although they may appear like a specialty to some magnetic designers, but mass applications like GFCI’s and electronic energy meters have proven their competitiveness thanks to their superior magnetic properties. Nanocrystalline cores simply increase the options for design engineers, they can solve problems which otherwise could be real problems and, when properly used, they are commercially competitive, either directly or indirectly creating function related cost saving options.

About the author: Mr. Wengerter has worked for over two decades with Vacuumschmelze GmbH & Co. KG and started as an application engineer for amorphous and nanocrystalline products, from where he advanced into senior management positions. He is now managing director at Sekels GmbH.

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