Advantages of softmagnetic nanocrystalline materials for modern electronic applications

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Abstract

During the last years softmagnetic cores of nanocrystalline FeCuNbSiB-alloys had their breakthrough in industrial electronics due to their unique combination of softmagnetic properties and an economical automated large-scale production. After a short survey on the production line the advantages of the zero magnetostriction alloy VITROPERM will be discussed regarding selected electronic devices. © 2002 Elsevier Science B.V. All rights reserved.

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1. Preconditions for favorable inductors

Modern electronic devices such as power supplies, digital telecommunication equipment, automotive or railway technique demand for magnetic cores or inductive components with compact volumes and a high universality both in magnetic properties and geometric shape. Such inductors must comply with very stringent technical requirements over a wide frequency range from quasi-static magnetization conditions up to the MHz-range even under mechanical shocks or temperature conditions reaching from arctic cold up to more than 100°C.

To realize such a performance core materials are needed that exhibit an excellent combination of softmagnetic properties as follows: saturation induction $B_s$ as high as possible to achieve highest flux density swing. To tailor hysteresis loops with a controlled level of permeability or a well-defined rectangularity the uniaxial anisotropy $K_u$ must be adjustable both in direction and amount by magnetic annealing treatment. For power applications but also to achieve good frequency properties of permeability and coercivity the hysteresis and eddy current losses must be as low as possible. Further requirements are a favorable temperature behavior and a high thermal stability. For an industrial large-scale production the material must be reliable to produce and be easy to work to cores and further to electronic components. Moreover, the raw material should be inexpensive and easy to obtain.

Until roughly one decade ago the only softmagnetic materials that exhibited such a combination of properties in a more or less pronounced manner were the Permalloys, Sendust, MnZn-ferrites and the amorphous Co-based alloys.

2. Properties of nanocrystalline alloys

During the last years in an increasing variety of applications the spectrum of softmagnetic materials has been supplemented by the nanocrystalline alloys. Owing to its high degree of reliability in production process the most prominent representative of this new class of materials is the family of the FeCuNbSiB—alloys [1,2].

As pointed out by Herzer [2] 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 causing the disappearance of the magnetocrystalline anisotropy. As such a grain is much smaller than the width of the domain walls there also is
no pinning by the grain boundaries so that the domain wall motion is not hindered at all. Another immediate consequence of the nanocrystalline two-phase-structure is a rather low magnetostriction of $\lambda_s \approx 10$ ppm, which is much lower than in the as quenched still amorphous state [2]. In certain compositions as for example Fe$_{80}$Cu$_{1}$Nb$_{3}$Si$_{15.5}$B$_{7}$ even zero magnetostriction can be obtained and with this magnetoelastic anisotropies are annihilated. As such a composition is highly interesting under magnetic and technological aspects said alloy is industrially produced on a large scale e.g. by VACUUMSCHMELZE and can be obtained commercially under the trade name VITROPERM.

With the simultaneous disappearance of crystalline and magnetoelastic anisotropies the most important conditions for excellent F- or Z-loops with lowest uniaxial field induced anisotropy are fulfilled. Further, in nanocrystalline FeCuNbSiB-alloys field induced anisotropy arises from the directional ordering of FeSi-atoms pairs as in $\alpha$-FeSi single crystals [2]. By this the kinetics is considerably slower than in amorphous materials and in consequence, as Fig. 1 shows, despite of a rather high saturation magnetization of $J_s \approx 1.2$ T lowest field-induced anisotropies can be realized in a defined manner that results in highest permeabilities but with significant better thermal stability than in amorphous alloys or even in crystalline permalloys.

3. Production process for cores

The initial material is produced as an amorphous ribbon via rapidly solidification technology. In the meantime this technique is well established for large-scale production, so that the quantity of worldwide cast FeCuNbSiB-alloys has grown to an order of magnitude of approximately 1000 tons/year.

Related to application frequency the ribbon thickness (which is responsible for lowest eddy current losses) can be varied between 15 and 25 $\mu$m while its width can be adjusted between roughly 1 and 100 mm.

To prevent an increase of the eddy current losses in the later inductor the ribbon surface is isolated by a thin mineral layer, which consists typically of MgO. Afterwards the ribbon is wound to toroidal strip wound cores just in their final dimension whereby the outer diameter can be varied between about 2 mm and several hundreds of millimeters. On automatic machines winding can be performed free of mechanical stress and flux controlled with a core size-dependent output rate up to several hundred thousand pieces per month.

The wound cores are stabilized by spot welding and stacked in a gluing magazine preparing a two step annealing treatment in a batch furnace equipped with facilities for generating strong magnetic fields oriented in the axial and tangential direction of the cores.

During the first annealing stage which is performed at a temperature between 540 $^\circ$C and 580 $^\circ$C the nanocrystalline phase arises. In this state the material exhibits a 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 thousands.

To gain flat or rectangular hysteresis loops on which we focus here, a second annealing stage has to be performed under a magnetic field which must be strong enough to saturate the material at all. Thus a controlled uniaxial anisotropy $K_u$ will be induced depending both on the orientation of the field relative to the axes of the wound ribbon and on the annealing temperature.

If the anisotropy stands perpendicular to the ribbon axes a flat loop will arise whereby the initial permeability can be definitely adjusted even by large-scale production in a considerable wide range between about 15,000 and 150,000 by a simple variation of the field annealing conditions. Simultaneously the ratio of remanence to saturation $B_R/B_s$ changes between about 2% and 10% depending on the ratio $K_u/K_{\text{disturb}}$, ($K_{\text{disturb}} =$ sum of superimposed disturbance anisotropies) which for good linearity properties should be much greater than one. If in contrast induced anisotropy lies parallel to the ribbon axes, the resulting loop is Z-shaped. In this case a ratio of $B_R/B_s \to 100\%$ 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 core complies with customer’s specification it will be encapsulated or epoxy coated, labeled and made ready for shipment.
4. Applications for nanocrystalline cores

Due to their unique combination of favorable magnetic properties nanocrystalline cores are now well established in a wide field of applications [3–5], of which the most important are summarized in Table 1. The major areas are: switched mode power supplies, digital telecommunications with emphasis on ISDN systems, installation techniques at 50/60Hz and since very recently applications in the automotive electronics. Additionally particle accelerators should be mentioned where cores with masses up to 50 kg or even more are needed for converters or resonators. In the following paragraphs some selected applications where nanocrystalline material offers particular benefit will be discussed.

4.1. Power supplies

Since several years nanocrystalline materials are well established in the essential types of components for switched-mode power supplies (SMPS) covering a wide range of transferable energy reaching from less than 100 W for PC-applications up to clocked high power inverters for modern railway driving device with an output power of more than 1 MW. Such components are power transformers, common mode RFI chokes in filters to prevent noise emission and to protect the device against interference, magnetic amplifiers, and storage chokes and spike killers to suppress output voltage noise.

In power supply units the power transformer is the central and most costly component. Its basic function is the galvanic isolation between the primary and the secondary side of the device as well as the transformation of the output voltage. As for the maximum transferable power \( P_{\text{max}} \) holds Eq. (1)

\[
P_{\text{max}} \propto f \cdot \Delta B_{\text{opt}} \cdot A_{\text{Fe}}
\]

increasing values of frequency \( f \) and optimal flux density swing \( \Delta B_{\text{opt}} \) allow a reduction in volume (here represented by the iron cross section \( A_{\text{Fe}} \)), weight and price of the transformer inversely. In Eq. (1) clock frequency \( f \) is limited by the losses of the power IGBTs and the transformer material. As shown by Eq. (2) \( \Delta B_{\text{opt}} \) will be limited thermally by the maximum overheating temperature \( \Delta T \) and by the core losses where \( P_0 \) stands for those losses arising at a certain reference induction swing \( B_0 \), which scales with saturation induction.

\[
\Delta B_{\text{opt}} \propto B_0 \cdot \sqrt{\frac{\Delta T}{P_0}}
\]

As Fig. 2 shows, just in the regime of the operating frequencies of IGBT power semiconductors of 10–50 kHz nanocrystalline VITROPERM-alloys are superior to other transformer materials by exhibiting losses close to the ideal value of the classical eddy current theory [9]. This property combined with an upper operating temperature of more than 120 °C and a high saturation induction of \( B_s \approx 1.2 \text{T} \) gave an essential impetus for the implementation of clocked power supply topologies in the upper power range from a few kW for battery charging or medical or industrial applications up to the regime of MW in the field of modern railway traction techniques.

Furthermore the low negative temperature coefficient should be mentioned. This property protects the transformer from overheating and guarantees reliable

Table 1
Main applications for nanocrystalline alloys

<table>
<thead>
<tr>
<th>Application area</th>
<th>Application</th>
<th>Material requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supplies</td>
<td>Power transformer [4,5]</td>
<td>( P_0; B_s )</td>
</tr>
<tr>
<td></td>
<td>Common mode choke [4,6]</td>
<td>( \mu(f); B_s )</td>
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<tr>
<td></td>
<td>Storage choke [7]</td>
<td>( \mu(H_{\text{DC}}); B_s; P_{\text{le}} )</td>
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<td></td>
<td>PFC-choke [7]</td>
<td>( \mu(H_{\text{DC}}); P_{\text{le}} )</td>
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<tr>
<td></td>
<td>Drive transformer [4]</td>
<td>( P_{\text{le}} ) linearity</td>
</tr>
<tr>
<td></td>
<td>Magnetic amplifier [8]</td>
<td>( \Delta B_{\text{RS}}; P_{\text{le}}; B_s )</td>
</tr>
<tr>
<td></td>
<td>Pulse power core [4]</td>
<td>( B_s; P_{\text{le}} )</td>
</tr>
<tr>
<td>ISDN telecomm.</td>
<td>Signal transformer ( S_0 ) [4]</td>
<td>( \mu(f); \mu(H_{\text{DC}}) )</td>
</tr>
<tr>
<td></td>
<td>Common mode choke [4,6]</td>
<td>( \mu(f); B_s )</td>
</tr>
<tr>
<td>Installation techniques</td>
<td>Earth leakage circuit breaker (AC-sensitive) [4]</td>
<td>( \mu_s; \mu_{\text{max}}; \mu(T); B_s )</td>
</tr>
<tr>
<td></td>
<td>Earth leakage circuit breaker (Pulse sensitive) [4,5]</td>
<td>( \mu_s; \mu(T); P_{\text{le}}; B_s ) linearity</td>
</tr>
<tr>
<td></td>
<td>Current transformer [4,5]</td>
<td>( \mu_s; B_s ) linearity</td>
</tr>
<tr>
<td>Automotive electronics</td>
<td>DC/DC-Converter [7]</td>
<td>( \mu(H_{\text{DC}}); B_s; P_{\text{le}} ) (flakes!)</td>
</tr>
</tbody>
</table>
operation at intrinsic temperatures of $-40^\circ$C up to $120^\circ$C. The consequence is a further reduction of volume finally resulting in a weight to power ratio of only a few hundred g/kW which is smaller than a factor of 30 as it is typical for crystalline transformer materials.

For the application in personal computers or industrial devices SMPS with an output power range up to 1 kW are demanded. Generally such devices are featured by multiple independent regulated output voltages stabilized by a magnetic amplifier (MagAmp) containing a core with a rectangular hysteresis loop which acts as saturable choke as follows: As long as the working point remains in the steep region of the loop the current is blocked by the inductor. However, as soon as the choke is magnetized to saturation its impedance decreases abruptly by several orders of magnitude and the choke becomes conductive. Depending on the duration ratio of the blocking to conducting time a pulse width regulation can be realized by which the output voltage is stabilized fast and exactly against abrupt changes of the external load.

For good regulation characteristics a MagAmp core needs a residual flux density swing $\Delta B_{RS}$ from remanence to saturation induction as small as possible which requires that $K_u \gg K_{\text{disturb}}$ is fulfilled. Moreover, due to a high clock frequency range of typically 100–300 kHz the core losses must be as low as possible. However, a high amount of $K_u$ oriented parallel to the ribbon axes excludes low magnetization losses because there exists a strong dependence of the anomalous eddy current losses from the domain wall energy [10]. This conflict can only be solved by minimizing $K_{\text{disturb}}$ by the simultaneous elimination of the magnetocrystalline and magnetoelastic anisotropy as can be reached e.g. in amorphous Co-based alloys or in nanocrystalline alloys as VITROPERM. Therefore Fig. 3 shows rather low losses over a wide range of $\Delta B_{RS}$, whereby an optimum can be reached by appropriate annealing conditions. Additional advantage comes from the high saturation induction facilitating a high flux density swing $\Delta B$ which in combination with an extended temperature range up to 120°C allows a significant reduction in core weight, volume and costs compared to other MagAmp materials e.g. the Co-based amorphous materials or ferrites.

4.2. Digital telecommunications

During the last decade ISDN telecommunication network has been well established in many countries of the world. As Fig. 4 shows the network termination as well as the terminal equipment like telephone, telefax, PC, etc. are connected to the $S_0$-bus by $S_0$-transformers.
to get galvanic isolation. Furthermore EMC-chokes [6] are used to suppress RFI noise.

The basic requirements for $S_0$-transformers are compliance with an impedance template as sketched in Fig. 4 even under DC-bias currents coming from electrical remote supply, which guarantees operation of consumer terminal equipment even under a local current failure. As in digital telecommunication devices the degree of integration advances increasingly, the volume of the components and in consequence the core size must be as compact as possible.

Said requirements can only be fulfilled simultaneously if the core material shows highest permeabilities up to high frequencies combined with a high stability against DC-premagnetization fields whereby the second precondition needs a F-shape loop with pronounced linearity and a high saturation induction. However, as already shown in Fig. 1 for amorphous alloys this condition stands in contradiction to the requirement for a high permeability and in consequence regarding core size compromises have to be accepted.

As can be derived from Fig. 5 these problems can be solved again by VITROPERM in an excellent manner. Despite of a high saturation induction which favors a higher stability against DC-premagnetization than can be realized by amorphous alloys or ferrites, the initial permeability e.g. at 10 kHz can be varied definitely between a lower limit of about 15,000 and upper values near 100,000 by a variation of the annealing conditions. This again allows further reduction in core size and makes the component very interesting concerning circuit design and marketing aspects. In consequence $S_0$-transformers with VITROPERM have turned out to be a serious competitor for amorphous cores and ferrites with an increasing market share of several millions of pieces per month.

4.3. Installation techniques

Besides differential-current transformers for pulse current sensitive earth leakage circuit breakers that are discussed e.g. in Ref. [5], presently current transformers for electronic energy meters are the major application in the field of 50/60 Hz-technique for high permeability nanocrystalline cores with flat hysteresis loop.

In electronic electricity meters for the 50/60 Hz AC power supply the calculation of the power consumption is realized by continuously multiplying the values of the detected current and voltage at any time. To achieve a reasonable precision even in circuits with a mainly inductive load the requirements on the phase error of the current transformer are rather high. Thus, the quality of the transformer can be described by the ratio $(R_{Cu} + R_{load})/\omega L$ [9] $(R_{Cu}, R_{load}$: ohmic resistance of secondary winding and load; $L$: ($\propto \mu$) inductance of the secondary side of the current transformer) which is proportional to the phase shift $\phi$ and should be as small as possible. In consequence the core material has to show over a wide range of induction highest and constant permeability as well as smallest magnetization losses. As can be seen from Fig. 6 the error of amplitude $F(I)$ of VITROPERM can be neglected. Moreover, the high constancy of the phase error $\tan \phi$ vs. $I_{prim}$ curve makes it possible to reduce the phase error by more than a factor 4 by an electronic calibration of the evaluation system. This is a special advantage of the high linearity of the hysteresis loop which is a unique feature of VITROPERM and amorphous alloys with zero magnetostriction.

4.4. Automotive electronics

New developments in automotive electronics as for example 1 kW DC/DC-converters for the 14/42 V dual

![Fig. 5. Permeability vs. DC-premagnetization curves of nano-crystalline cores with varied permeability (VITROPERM) in comparison with amorphous Co-based alloys (VC = VITRO-VAC).](image)

![Fig. 6. Transformer characteristics calculated from typical material data. Core dimensions: 16 $\times$ 10 $\times$ 6; $N_{prim} = 1$; $N_{sec} = 4000$; diam Cu = 0.07 mm; $R_{load} = 200 \Omega$.](image)
voltage system call for chokes with high storage energy, optimized design in shape, lowest losses and favorable thermal properties. This can be fulfilled in principle by air gapped cores with low permeability but also by powder cores as e.g. Sendust revealing excellent losses and representing the special case of a distributed air gap. Recently the latter group has been supplemented by nanocrystalline flake cores consolidated by press additives [11]. By a variation of the particle size and the compacting conditions the permeability can be adjusted with good reproducibility between about 10 and several thousands.

Now under development are chokes made from nanocrystalline flake powder molded complete with copper coil and a high temperature plastic resin to the final shape of the component. One of the most important advantages of this procedure is that the properties of the initial material as high saturation induction or lowest coercivity and core losses remain unchanged. Typical values of the low frequency permeability are about 50 whereby the frequency dependent release up to 1 MHz is less than 10%. Regarding the losses the molded component of nanocrystalline flakes can be classified between powder cores of Molypermalloy [12] and Sendust [13].

An additional advantage is that this new technology makes use of almost the whole component volume for the magnetics, allows a fully automated production process and as Fig. 7 shows opens a high variety of shapes and designs. Moreover, molded chokes are excellent for use in heat sink applications. In contrast to normal components with a simple compound of resin the high thermal conductivity of VITROPERM-powder component insures good coupling between the magnetic materials, copper windings and heat sink. Thus compared to classic solutions the temperature rise can either be reduced or the design will result in a reduction of volume by 40% or even more.

5. Conclusions

As pointed out by selected examples, due to their unique combination of softmagnetic properties and a high thermal stability nanocrystalline VITROPERM alloys comply with the fundamental requirements for high performance inductors for a wide range of modern electronic devices in a unique manner. The major benefit of this class of high tech materials is a miniaturization of the inductors in volume combined with a high degree of universality in shape and electric properties. This allows a reduction in size for the complete device and in many cases solutions being impossible with conventional magnetic alloys. On the other side the reliability and cost optimization of the production process brought the price of the product in a range being highly competitive with classical crystalline alloys and ferrites. In consequence increasing demand arises from market pushing the worldwide production rate in the range estimated to 1000 tons/year with growing tendency.

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