

Nanocrystalline core materials for modern power electronic designs

Multi purpose soft magnetic material improves the performance of inductive components

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In the recent years, so called nanocrystalline soft magnetic materials enjoyed more and more acceptance in modern power electronic designs. Besides the undisputed excellent performance this is a result of the improved price level in combination with the availability from several sources worldwide.

Characterization and Properties

The nanocrystalline soft magnetic alloy $\text{Fe}_{73,5}\text{Cu}_1\text{Nb}_3\text{Si}_{15,5}\text{B}_7$ is available on the market since several years now under the brand names of FINEMET, VITROPERM or NANOPERM. Initially, with a quite simple but revolutionary production technology a very thin is ribbon is produced from low cost raw materials like silicon and iron. The result is a new generation of material with extraordinary soft magnetic properties. For the first time ever, almost the high flux swing of silicon steel is combined with the even improved high frequency performance of ferrites, namely low losses and high permeability. Furthermore, the new alloy provides by far a better value for the money compared to epoch making Co-amorphous alloys with similar properties, which were introduced into the market in the late 80s. Due to the high price and environmental considerations, Co-amorphous alloys are actually chosen only for special applications.

Material	alloy composition	losses (20kHz, 200mT) [W/kg]	saturation B_{sat} [mT]	magneto- striction λ_s [10^{-6}]	permeability (50Hz) $\mu_4 - \mu_{\text{max}}$	max. working temp. [°C]
grain oriented Silicon steel	$\text{Fe}_{97}\text{Si}_3$	> 1.000	2.000	9	2.000-35.000	appx.120
standard crystalline permalloy I	$\text{Ni}_{45}\text{Fe}_{55}$	> 150	1.550	25	12.000 – 80.000	130
standard crystalline permalloy II	$\text{Ni}_{54}\text{Fe}_{46}$	> 100	1.500	25	60.000-125.000	130
advanced Silicon steel	$\text{Fe}_{93,5}\text{Si}_{6,5}$	40	1.300	0,1	16.000	130
Fe- amorphous alloy	$\text{Fe}_{76}(\text{Si,B})_{24}$	18	1.560	27	6.500 – 8.000	150
high performance ferrite	MnZn	17	500	21	1.500 – 15.000	100/ 120
advanced crystalline permalloy	$\text{Ni}_{80}\text{Fe}_{20}$	> 15	800	1	150.000-300.000	130
Co-amorphous alloys a	$\text{Co}_{73}(\text{Si,B})_{27}$	5,0	550	< 0,2	100.000-150.000	90/120
Co-amorphous alloys b	$\text{Co}_{77}(\text{Si,B})_{23}$	5,5	820	< 0,2	2.000 – 4.500	120
Co-amorphous alloys c	$\text{Co}_{80}(\text{Si,B})_{20}$	6,5	1.000	< 0,2	1.000 – 2.500	120
nanocrystalline alloys I	FeCuNbSiB	4,0	1.230	0,1	20.000- 200.000	120/ 180
nanocrystalline alloys II	FeCuNbSiB	4,5	1.350	2,3	20.000- 200.000	120/ 180
nanocrystalline alloys III	FeCuNbSiB	8,0	1.450	5,5	~ 100.000	120/ 180

High-Tech Production Process

During the so-called 'rapid solidification' production process, a stream of molten metal at about 1.300°C is sprayed through a narrow ceramic nozzle directly onto a water-cooled, fast-rotating copper roller. At a speed of more than 100 km/h a continuous amorphous ribbon of only approx. 20 µm in thickness is obtained. In other words, more or less in a single step of production, such a thin ribbon can be obtained with a relatively compact machine and neither costly cold or hot rolling procedures are necessary. After toroids are wound from these ribbons, a specific annealing procedure under the presence of transversal and/or longitudinal magnetic field takes place. During that irreversible heat treatment, the amorphous structure obtained initially forms ultra-fine crystals with a typical grain size of only about 10 nm – this is why the material is called 'nanocrystalline'. By precisely controlled variation of the annealing parameters the required properties (i.e. shape of hysteresis-loop or permeability level) can be adjusted in a wide range.

Advantages and Applications

In parallel, the value for the money is getting more and more competitive compared to permalloys and ferrites. Independent from the application, the advantages gained from the use of nanocrystalline cores when designing inductive components generally are:

- significantly smaller build volume (up to more than a factor of 3)
- lower weight
- less copper losses due to reduced number of turns
- extended temperature range from –25 ... + 120°C (standard) / 180°C (special)
- bigger safety margins – more stable operation – very robust

The actual trend in Power Electronics is towards higher frequencies and smaller size or increased power density. As a result of the above-mentioned factors, a growing range of applications in power electronics was realized in the recent years and generated a growing demand, which is continuously expanding. Diversified chokes and transformers are utilized for:

- EMC / EMI filters for SMPS and inverter drives
- Switched mode power supplies
- Electrical welding power sources
- X-ray generators
- Battery chargers
- Solar generators
- AC/DC or DC/DC converters
- Power supplies in the automotive industry (42V powernet)
- Railway Transportation Systems
- Electronic Watt-Hour Meters
- Earth leakage circuit breakers (ground fault interrupters)

and many more.

One of the most important applications for the new material so far are common mode chokes for EMI filters for any kind of switched mode power converters (including variable speed drives). Here, the most significant reduction of build volume is achieved because both relevant material properties (namely permeability and flux swing) are significantly higher compared to the so far commonly used ferrites (see table).

The other main applications are power transformers in switched push-pull converters from a few 100W up to several 100kW, spike killers, magnetic amplifiers, trigger transformers for IGBT-transistors, transformer cores for mains independent earth leakage circuit breakers and current transformers in modern Electronic Watt-Hour Meters. There are many more to come in the forthcoming future – in particular in conjunction with new power converter topologies or in new systems of the automotive industry which are currently under development.

Available Products

Nanocrystalline cores are available in form of toroidal or stadium shaped tape-wound cores. The material itself is brittle and requires a protection against mechanical forces, which is either provided by plastic core boxes or a suitable heat resistive coating. Once coated or boxed, the cores are extremely robust and the major magnetic properties are highly linear and not very much dependent from temperature.

On one hand, the strip material limits the variety of mechanical core shapes but on the other hand variable toroidal core geometries can be obtained with low tooling costs. The core sizes available currently range from about 10mm up to more than 300mm of outer diameter. Basically, air-gapped or cut-core versions should also become available but these options are not yet available as a standard on the market.