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(54) Title: MAGNETIC CORE METHOD FOR PRODUCTION THEREOF AND EARTH LEAKAGE CIRCUIT BREAKER

(54) Bezeichnung: MAGNETKERN, VERFAHREN ZU SEINER HERSTELLUNG SOWIE FEHLERSTROMSCHUTZCHAL-
TER

(57) Abstract: The invention relates to a magnetic core made from a wound soft magnetic strip, for low frequency applications
designed to have an increased relative permeability μ_r by means of reduced mechanical tensions. The above is achieved by means of
coating at least one side of the soft magnetic strip with a static friction reducing material which is partly burnt off during the thermal
treatment of the magnetic core. The residue thereof remains such that in cross-section the magnetic core has an alternating layer of
soft magnetic material and a layer of residue of a static friction reducing material.

(57) Zusammenfassung: Ein aus einem weichmagnetischen Band gewickelter Magnetkern für Niederfrequenzanwendungen soll
eine durch die Reduktion von mechanischen Spannungen erhöhte Permeabilitätszahl μ_r aufweisen. Dazu wird das weichmagne-
tische Band auf mindestens einer Seite mit einem haftreibungsreduzierenden Material beschichtet, dass bei der Wärmebehandlung
des Magnetkerns teilweise abbrennt. Zurück bleibt sein Glührückstand, so dass sich im Querschnitt des Magnetkerns jeweils eine
Schicht aus dem weichmagnetischem Material und eine Schicht aus dem Glührückstand eines haftreibungsreduzierenden Materials
abwechseln.

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Description

Magnet core, process for producing a magnet core and residual current device

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The invention relates to a magnet core for low frequency applications which is wound from a soft magnetic strip. It also relates to a process for producing such a magnet core, and a residual current
10 device with a magnet core.

Magnet cores which are formed from a spiral-wound metal strip, so-called 'toroidal strip cores', are used, for example, in current transformers, output transformers,
15 current-compensated noise suppression chokes, residual current limiters, storage chokes, single-circuit chokes, transductor chokes and sum or differential current transformers for FI-safety switches. As such, they are used in the low frequency range at typical
20 operating frequencies of 50 to 60 Hz and at least below the kilohertz range. Unlike magnet cores used in high frequency applications, no particular attention need be paid to insulating the individual strip layers against one another to avoid eddy currents, since at low
25 frequencies the voltage between the individual strip layers is typically less than 100 μ V. At this voltage the intrinsic oxide layer on the strip surfaces is generally adequate for insulation.

30 However, the demands placed on magnet cores for low frequency applications in terms of magnetic properties are high: fault current transformers for a.c.-sensitive residual current devices, for example, must provide a secondary voltage which is at least sufficient to

trigger the magnet system of the release relay responsible for cut-off. Since the objective is to achieve the most compact current transformer design possible, as well as high induction at the typical
5 operating frequency of 50 Hz, the material used for the magnet core must above all have the highest possible relative permeability μ_r . The geometry of the magnet core itself, together with the material properties combined with the technological processing of the
10 material, by means of heat treatment, for example, have a significant effect on relative permeability.

In order to reach sufficiently high relative permeability values it was hitherto necessary to
15 achieve the lowest possible saturation magnetostriction constant λ_s of $|\lambda_s| < 2\text{ppm}$ or even $< 0.3\text{ppm}$. A further important prerequisite was to achieve the most geometrically perfect strips possible with the minimum number of structural defects. However, such a small
20 saturation magnetostriction constant λ_s can only be achieved easily with a few alloys and, in addition, it is almost impossible to achieve an exact alloy composition without impurities in industrial-scale production.

25

It would however be possible to achieve high relative permeability with numerous other alloy compositions if the magnet core were free of mechanical stresses. Mechanical stresses may be introduced into the magnet
30 core as it is wound from one or more strips and/or in the case of subsequent heat treatment. The relationship between the freedom from stress of the magnet core and

high relative permeability is mentioned in JP 63-115313, for example.

US 2005/0221126 AI discloses a method for introducing
5 stresses into strip cores in a specific manner in order to improve the magnetic properties of strip cores for high frequency applications.

The object of the invention is therefore to specify a
10 magnet core wound from a soft magnetic strip for low frequency applications with a relative permeability μ increased by the reduction of mechanical stresses.

A further object of the invention is to specify a
15 process for producing such a magnet core.

This object is achieved in the invention by means of a magnet core for low frequency applications consisting of a spiral-wound, soft magnetic strip, said soft
20 magnetic strip having on at least one side a layer made of the ignition residue of a static-friction-reducing material such that layers of the soft magnetic material and layers of the ignition residue of a static-friction-reducing material alternate through the cross-
25 section of the magnet core.

The invention is based on the knowledge that mechanical stresses introduced during the winding of the magnet core or its subsequent heat treatment are caused by the
30 fact that the shape of the soft magnetic strip is not ideal. Such variations from an ideal shape are twofold:

Firstly, the surface of the soft magnetic strip is not ideally smooth, but possesses a certain surface roughness. The surface roughness varies within the micro- and nano-scale range and is subject to certain fluctuations during the industrial-scale manufacture of the strips by casting using the rapid solidification process. It varies both between individual casting batches and within a single batch due to casting wheel wear during production. Ideally, surface roughness R_a as defined in DIN 4762/ISO 4287/1, measured as the arithmetical mean of the two strip sides $(R_{a1}+R_{a2})$ /strip thickness, assumes values of approximately 1%. Typically, however, the values achieved are between 2% and 6%, and in some cases as high as approximately 15%.

Secondly, rather than achieving ideal strip geometry with exactly plane-parallel surfaces industrial-scale manufacture produces variations from this geometry in the form of bulges and/or wedge or bone shapes.

The consequences of these variations from ideal strip shape are local or whole-layer tensions in the magnet core created during the winding process by local or surface fluctuations in the thickness and surface roughness of the individual strip layers. At the same time, geometrical surface defects lead to the interlocking of the strip layers, thereby preventing the relief of mechanical stresses in the magnet core during heat treatment. The almost ubiquitous combination of surface roughness and structural defects over large surface areas leads to particularly high surface pressures at the points where the strip layers

touch, and thus to particularly high, local static friction. Due to the fundamental relationship

$$\mu_r \propto \frac{1}{\lambda_s \cdot \sigma}$$

5

between relative permeability μ_r , saturation magnetostriction constant λ_s and mechanical stress σ , if the saturation magnetostriction constant is not sufficiently small such distortions lead to inadequate and widely spread relative permeability values.

10

One fundamental concept of the invention is to compensate for micro- and nano-scale variations from ideal geometry leading to the interlocking of the strip layers and thus to distortions in the magnet core by the introduction of a static-friction-reducing material between the individual strip layers. This may be carried out either before or after the magnet core is wound, but should take place prior to heat treatment. Following heat treatment at least the ignition residue of the static-friction-reducing material remains in the magnet core, whilst at least as long as the duration of the heat treatment is sufficient any loss on ignition is consumed.

25

The magnet core disclosed in the invention is subjected to heat treatment at temperatures typically below 600°C. Adsorptively or chemically bound water and, where, applicable other solvents are lost at these temperatures, although typically not all the organic component of the static-friction-reducing material is consumed. For this reason, the term 'ignition residue'

30

is used here and below to refer to that part of the static-friction-reducing material which remains between the strip layers following heat treatment. It is not therefore necessarily only mineral substances.

5

The magnet core disclosed in the invention has a relative permeability μ_r of $400,000 \leq \mu_r \leq 800,000$. In the past such high relative permeability values were achieved by the use of magnetostriction-free materials.

10 This considerably reduced the number of suitable alloys. The magnet core disclosed in the invention offers the advantage that it is possible to relieve mechanical stresses and thus achieve a high relative permeability value with other non-magnetostriction-free
15 alloys by the use of a static-friction-reducing material which exercises a lubricating effect on the individual strip layers during heat treatment. Such alloys can thus also be used in the low frequency applications described above.

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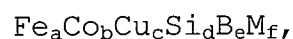
The particles of the static-friction-reducing material advantageously have a particle diameter d_p of less than 500 nm. Here the particle diameter d_p refers to the maximum diameter of a particle since the static-
25 friction-reducing particles are not necessarily spherical, but can also be cylindrical or flake-shaped, for example. Particles with diameters over 500 nm tend towards the formation of agglomerates and can form irregularly shaped, sintered bodies which render the
30 lubricating effect of the static-friction-reducing material required to achieve a high relative permeability ineffective.

In an advantageous embodiment the particles of the static-friction-reducing material have particle diameters d_p below 60 nm, in particular preferably particle diameters of 20 nm or below. This is because, as experiments have shown, a reduction in static-friction-reducing effect can be observed from particle sizes above 20 nm. If possible, therefore, particles with diameters greater than 20 nm should not be used where particularly high relative magnet core permeability is required.

The finished magnet core, i.e. the magnet core following completion of the heat treatment, typically has a nano-crystalline soft magnetic strip. However, both amorphous and crystalline strips are also conceivable depending on the intended use of the magnet core.

A number of different alloy compositions can conceivably be used for the magnet core disclosed in the invention. Since it is not necessary to eliminate the saturation magnetostriction constant, common iron-based alloys can be used, and even residual impurities which cannot generally be avoided completely can be tolerated without any undesirable effect on magnetic properties.

In one embodiment of the invention the alloy composition of the soft magnetic strip is essentially as follows:



M being at least one of the elements V, Nb, Ta, Ti, Mo, W, Zr and Hf; a, b, c, d, e and f being specified in

percent per atom; $0 \leq b \leq 20$; $0.5 \leq c \leq 2$; $6.5 \leq d \leq 18$; $5 \leq e \leq 14$; $1 \leq f \leq 6$; $d + e > 16$; $a + b + c + d + e + f = 100$ and it being possible to replace cobalt wholly or partially by nickel.

5

The iron cross-sectional area A_{Fe} of the magnet core is defined by the formula:

$$A_{Fe} = \frac{D_a - D_i}{2} \cdot h \cdot \eta ,$$

10

where D_a is the external diameter of the magnet core, D_i is its internal diameter, h is the width of the strip and η the fill factor $0\% \leq \eta \leq 100\%$, $\eta > 40\%$ being typical of magnet cores.

15

Spaces between the strip layers which necessarily result from the non-ideal strip geometry reduce the iron cross-sectional area A_{Fe} of the magnet core. To a certain extent the fill factor represents a measure of the degree of variation in the strip from an ideal, plane-parallel sheet.

20

In one embodiment after heat treatment the magnet core has a fill factor η of more than 80%, whilst in alternative embodiments the fill factor is $70\% \leq \eta \leq 80\%$ or $65\% \leq \eta \leq 70\%$.

25

The effective surface roughness RT of the strip is advantageously $1\% \leq RT \leq 12\%$, and more advantageously $1\% \leq RT \leq 6\%$ or even $1\% \leq RT \leq 4\%$. The saturation magnetostriction constant λ_s of the magnet core is advantageously less than 6 ppm and the ratio of

30

remanence induction to saturation induction B_R/B_S is greater than 40%.

In one embodiment of the invention the magnet core has
5 a remanence induction to saturation induction ratio B_R/B_S of $1\% \leq B_R/B_S \leq 30\%$ auf, in alternative embodiments it is $30\% \leq B_R/B_S \leq 80\%$ or $80\% \leq B_R/B_S \leq 97\%$.

Materials suitable for use as static-friction-reducing
10 materials are those which can be applied easily, by spraying, rolling or deposition from a solution or gas phase or by solid particle deposition from a suspension, for example, and which reduce the static friction between the individual strip layers and in
15 this manner generate a lubricating effect as the magnetic core is wound and during the relief of mechanical stresses during the subsequent heat treatment. However, there are also other requirements which a suitable static-friction-reducing material must
20 meet. For example, where possible the material should not form film-like, tension-creating layers or generate tension-creating corrosion layers as is the case, for example, with aluminium silicate, lithium silicate and magnesium oxide coatings applied from an aqueous
25 solution. In addition, the static-friction-reducing material should neither trigger undesirable surface reactions or diffusion processes within the strip, generate tension-creating shrinking effects.

30 Suitable static-friction-reducing materials include the following: nanodispersed SiO_2 which is commercially available under the name of 'Aerosil' or 'HDK' and has a similar thermal coefficient of expansion to the

strip; nanodispersed SiO_2 with magnesium methyllate;
pigment soot; carbon nanotubes or C_{60} fullerene. In such
cases it is possible, where applicable, to avoid
corrosive surface attack by the use of water-free
5 solvents such as alcohols, ketones and ether alcohols.

As experiments have shown, it is also possible to
achieve an improvement in the magnetic properties of a
magnet core with a coating of alkylates of metals or
10 transition metals, although these layers do not have
any static-friction-reducing effect. Their effect is
due to the loosening of the magnet core when fully or
partially consumed during heat treatment. They are
therefore suitable for use as additives to the static-
15 friction-reducing material, for example. Zirconium
propylate, aluminium butylate or a magnesium methoxide
solution, for example, are suitable additives, as is
boron nitride.

20 One process disclosed in the invention for producing a
magnet core for low frequency applications comprises at
least the following steps: an amorphous, soft magnetic
strip, which may be manufactured using the rapid
solidification process, for example, is provided and
25 coated with a static-friction-reducing material. The
strip is then wound into a magnet core, typically a
toroidal strip core, and the magnet core is subject to
heat treatment in order to impart the desired magnetic
properties, the static-friction-reducing material
30 exercising a lubricating effect on the strip and
enabling the individual strip layers to slide over one
another more easily. Alternatively, it is possible to
carry out the coating process after the strip has been

wound into a magnet core, coating the magnet core using the economical process of dip coating, for example.

Both versions of the process permit the production of a
5 magnet core which is largely free of mechanical stresses and thus can have a high relative permeability value. While in the first version the stresses occurring during winding using traditional processes are avoided from the outset, in the second these
10 stresses generally continue to occur as before.

In the second version of the process, however, the static-friction-reducing material considerably facilitates the relief of mechanical stresses from the
15 magnet core during heat treatment and therefore this version of the process also provides a magnet core which is largely free of mechanical stresses.

The process disclosed in the invention therefore
20 provides at least two mechanisms for stress relief which can be used individually or in combination. These are, firstly, the loosening of the core due to the at least partial consumption of the static-friction-reducing material during heat treatment which gives the
25 core sufficient freedom for the relief of stresses, and, secondly, a lubricating effect between the strip layers which is produced by the rolling or sliding properties of spherical, cylindrical or flake-shaped particles or entire layers. Here, at the temperatures
30 occurring during heat treatment which do not exceed 600°C, the lubricating effect in particular plays a significant role, while loosening due to consumption is relatively weak. This is due to the fact that at these

relatively low temperatures it is primarily water or solvents which escape from the static-friction-reducing material, while the organic component is not generally completely consumed.

5

The process disclosed in the invention can be used to achieve a hysteresis curve either in the form of an F-loop or in the form of a Z- and R-loop. However, since it is primarily the R-loop which achieves the highest permeability values, the magnet core must be of particularly stress-free design in order to avoid damaging anisotropisms. In order to achieve an R-loop, the heat treatment is advantageously carried out field-free, i.e. in the absence of a magnetic field strong enough to have an adverse effect on the magnetic properties of the magnet core, and at a temperature T of $505^{\circ}\text{C} \leq T \leq 600^{\circ}\text{C}$.

The static-friction-reducing material can be applied by deposition from a gas phase or a solution, by solid particle deposition from a suspension or using the sol-gel process, for example.

It is advantageous to achieve a relative static-friction-reducing material surface density ρ of $10 \text{ mg/m}^2 \leq \rho \leq 600 \text{ mg/m}^2$, or better still of $20 \text{ mg/m}^2 \leq \rho \leq 300 \text{ mg/m}^2$ or even of $50 \text{ mg/m}^2 \leq \rho \leq 150 \text{ mg/m}^2$. This ensures, on one hand, that a sufficient static-friction-reducing effect is achieved and, on the other, that the layer of static-friction-reducing material does not become too thick. For if the layer is too thick, the fill factor of the magnet core drops too far during heat treatment when a significant part of the static-friction-reducing

material is consumed and the magnet core becomes too 'loose' and thus too sensitive for subsequent handling.

For this reason, layer thicknesses d of the static-
5 friction-reducing material prior to heat treatment of d
 $< 5 \mu m$, preferably of $d < 1 \mu m$ or even $d < 0.5 \mu m$ or
 $d < 0.2 \mu m$ are advantageous.

The process disclosed in the invention has the
10 advantage that it permits the production of a magnet
core with particularly favourable magnetic properties,
in particular with a high relative permeability value,
without great technical difficulty. The process
eliminates dependence on special, often costly alloy
15 compositions and renders the complete removal of
impurities in the alloy unnecessary. At the same time,
it renders superfluous complex selection procedures
designed to achieve the most perfect strip surfaces
possible. Thus the process disclosed in the invention
20 can be used to reduce the production costs for toroidal
strip cores by simple means. In addition, since
compensation is provided for structural defects in the
strip, it is also possible to avoid the undesirable
excessive spread of relative permeability values.

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The magnet core disclosed in the invention is
particularly suitable for use in a residual current
device since, due to its high relative permeability, it
provides an adequately high secondary voltage to
30 trigger the magnet system of the release relay
responsible for cut-off.

Embodiments of the invention are explained in greater detail below with reference to the attached drawings.

5 Fig. 1 shows a schematic cross-section through a magnetic toroidal strip core.

10 Fig. 2a shows a schematic section of a plurality of strip layers in the toroidal strip cores described in the first step of the process disclosed in the invention.

 Fig. 2b shows the same section after a subsequent process step.

15 Fig. 2c shows the same section after a further process step.

20 Fig. 3 shows various embodiments of the process disclosed in the invention in tabular form.

Identical parts are designated by the same reference numerals in all figures.

25 Fig. 1 shows a cross-section through a magnet core (1), or more exactly through a magnetic toroidal strip core, consisting of numerous strip layers 3. The magnet core 1 is wound from a soft magnetic, typically amorphous strip 2 onto a cylinder 4, which is later removed. The
30 strip 2 does not present ideal geometry with smooth, exactly plane-parallel surfaces 5. In fact, its thickness varies locally causing surface roughness, and in addition the strip 2 may present geometric defects

such as bulges and/or wedge- or bone-shaped cross-sectional areas. In Fig. 1 the surface roughness of the strip 2 is illustrated by hooks 6.

5 Due to the lack of ideal geometry presented by the strip 2 as caused by the hooks 6 and other irregularities, when the magnet core 1 is wound the static friction between the individual strip layers 3 which is significantly higher than would be presented
10 by an ideal strip leads to mechanical stresses in the magnet core 1. These mechanical stresses could be relieved during the heat treatment of the magnet core 1 following winding. However this is completely or at least partially prevented by the sustained interlocking
15 of the strip layers 3.

Fig. 2 shows steps of a process as disclosed in the invention for producing a magnet core 1. In the version of the process illustrated, first the magnet core 1 is
20 wound, then its strip layers 3 are coated with a static-friction-reducing material by dip coating, for example. However, it is equally possible to coat the strip prior to winding, either by dipping or by a continuous process, for example. The magnet core 1 is
25 then subjected to heat treatment during which the static-friction-reducing material is partially or extensively consumed. Here the freedom from stresses of the magnet cores 1 is achieved both by the lubricating effect of the static-friction-reducing material and by
30 a loosening of the magnet cores due to the partial consumption of the static-friction-reducing material, since the magnet core 1 is able to expand during heat treatment.

Fig. 2a shows a section from the wound magnet core with three strip layers 3 of the soft magnetic strip 2. Due to the considerable enlargement and in the interests of simplification, the strip layers 3 are represented as
5 being flat rather than curved. The surface 5 of the strip 2 is not perfectly flat, but has micro- and nano-scale geometrical defects in the manner of surface roughness which is indicated by hooks 6. Superimposed on these 'short-wave' oscillations are 'long-wave'
10 structural defects extending along and across the strip. As a result, spaces 7 form between the strip layers 3 as the magnet core is wound. These spaces are undesirable because they reduce the iron cross-sectional area of the magnet core and, in addition,
15 lead to mechanical tensions.

Fig. 2b represents the section from the magnet core after the strip 2 has been coated with a static-friction-reducing material 8. The static-friction-reducing material 8 sheathes the strip 2 and thus forms
20 intermediate layers 10 between the strip layers 3, resulting in a layer sequence comprising alternating layers of soft magnetic strips 2 and static-friction-reducing material 8. The new surface 9 of the strip 2
25 is significantly smoother than the original, and as such significantly closer to an ideal surface. If the layer is composed of spherical or cylindrical particles or of graphitic layers, it already has a marked lubricating effect which facilitates the sliding of the
30 strip layers and thus relieves stresses in the core.

After coating, the magnet core is heat-treated in a retort or continuous furnace. Fig. 2c indicates that

during this heat treatment the static-friction-reducing material is partially or extensively consumed. What remains is essentially the ignition residue 11 of the static-friction-reducing material which now forms the
5 intermediate layers 10 between the strip layers 3. The material lost due to consumption leads to a loosening of the magnet core. If the ignition residue also has the aforementioned lubricating effect, these two fundamental mechanisms both contribute to the relieving
10 of stresses in the core.

Fig. 3 is a table representing various embodiments of the invention. In addition to nano-dispersed SiO_2 , carbon nanotubes, fullerene and pigment soon are also
15 used as static-friction-reducing materials for coating. Layers of MgO , zirconium propylate and aluminium butylate are also examined. Ensembles of 50-100 core are coated and heat treated. The magnetic properties, in particular relative permeability μ_r at a frequency of
20 50 Hz, are then measured. The range of relative permeability is specified as $2s/\langle \mu_r \rangle$, where s is standard deviation.

As a comparative example, ensembles of uncoated
25 reference cores were produced using the traditional process. The table shows that static-friction-reducing layers of nano-dispersed SiO_2 in particular result in high levels of relative permeability. Layers of MgO , zirconium propylate or aluminium butylate cause slight
30 tensions or are largely passive. These layers can nevertheless lead to improved magnetic properties of strip cores since the extensive consumption of the

layer during heat treatment will permit the loosening of the core and thus the relief of mechanical stresses.

Nano-dispersed SiO_2 with small additions of MgO as an
5 additive also permits the loosening of the core due to
consumption during heat treatment, although the
percentage of MgO must be kept low enough to prevent
the coating from presenting any tension-creating
effect. Thus the positive effects of SiO_2 and MgO
10 coating can be combined.

It has been shown that the particle size of nano-
dispersed SiO_2 plays a not un-negligible role. Tests
using finely dispersed SiO_2 with a particle size of 500
15 nm or 1000 nm show a clear deterioration in magnetic
properties, in particular a reduction in permeability
to values around 200,000. A slight, though not yet
significant deterioration in magnetic properties can
also be measured at a particle size of 60 nm and above.
20 Furthermore, the concentration of the SiO_2 in the
dispersion also influences the magnetic properties of
the core. In concentrations of more than approximately
8%, as opposed to concentrations of 1.5% to 5%, it is
possible to measure slight deteriorations which
25 increase further at higher concentrations.

Carbon nanotubes, fullerene and pigment soot do not
form tension-creating layers. They exercise a
lubricating effect which can be exploited as the core
30 is being wound and also as it relaxes during heat
treatment.

List of reference numerals

- 1 Magnet core
- 2 Strip
- 5 3 Strip layer
- 4 Cylinder
- 5 Surface
- 6 Hook
- 7 Space
- 10 8 Static-friction-reducing material
- 9 Coated surface
- 10 Intermediate layer
- 11 Ignition residue

Claims

1. Magnet core for low frequency applications
consisting of a spiral-wound, soft magnetic strip,
5 said soft magnetic strip having on at least one
side a layer comprising the ignition residue of a
static-friction-reducing material such that layers
of soft magnetic material and ignition residue of
a static-friction-reducing material alternate
10 through the cross-section of the magnet core.
2. Magnet core in accordance with claim 1,
the magnet core having a relative permeability μ_r
where $400,000 \leq \mu_r \leq 800,000$.
- 15 3. Magnet core in accordance with claim 1 or 2,
the particles of the static-friction-reducing
material having a particle diameter d_p where d_p
< 500 nm.
- 20 4. Magnet core in accordance with claim 1 or 2,
the particles of the static-friction-reducing
material having a particle diameter d_p where d_p
< 60 nm.
- 25 5. Magnet core in accordance with claim 1 or 2,
the particles of the static-friction-reducing
material having a particle diameter d_p where d_p
 ≤ 20 nm.
- 30 6. Magnet core in accordance with one of claims 1 to
5,
the soft magnetic strip being nano-crystalline.

7. Magnet core in accordance with one of claims 1 to 5,
the soft magnetic strip being crystalline.
- 5 8. Magnet core in accordance with one of claims 1 to 5,
the soft magnetic strip being amorphous.
- 10 9. Magnet core in accordance with one of claims 1 to 8,
the soft magnetic strip essentially comprising the alloy composition
 $\text{Fe}_a\text{Co}_b\text{Cu}_c\text{Si}_d\text{Be}_e\text{M}_f$,
15 M being at least one of the elements V, Nb, Ta, Ti, Mo, W, Zr and Hf; a, b, c, d, e and f being
specified in percent per atom; $0 \leq b \leq 20$; $0.5 \leq c \leq 2$; $6.5 \leq d \leq 18$; $5 \leq e \leq 14$; $1 \leq f \leq 6$; $d + e > 16$ and $a + b + c + d + e + f = 100$; and cobalt
20 being able to be wholly or partially replaced by nickel.
10. Magnet core in accordance with one of claims 1 to 9,
25 the magnet core having a fill factor of $> 80\%$ after heat treatment.
11. Magnet core in accordance with one of claims 1 to 10,
30 the fill factor η being $70\% \leq \eta \leq 80\%$.
12. Magnet core in accordance with one of claims 1 to 10,

the fill factor η being $65\% \leq \eta \leq 70\%$.

13. Magnet core in accordance with one of claims 1 to 12,
5 the magnet core having an effective surface roughness RT where $1\% \leq RT \leq 12\%$.
14. Magnet core in accordance with one of claims 1 to 12,
10 the effective surface roughness RT being $1\% \leq RT \leq 6\%$.
15. Magnet core in accordance with one of claims 1 to 12,
15 the effective surface roughness RT being $1\% \leq RT \leq 4\%$.
16. Magnet core in accordance with one of claims 1 to 15,
20 the magnet core having a saturation magnetostriction constant λ_s where $\lambda_s < 6$ ppm.
17. Magnet core in accordance with one of claims 1 to 16,
25 the magnet core having a remanence induction to saturation induction ratio B_R/B_S of $B_R/B_S > 40\%$.
18. Magnet core in accordance with one of claims 1 to 16,
30 the magnet core having a remanence induction to saturation induction ratio B_R/B_S of $1\% \leq B_R/B_S \leq 30\%$.
19. Magnet core in accordance with one of claims 1 to 16,

the magnet core having a remanence induction to saturation induction ratio B_R/B_S of $30\% \leq B_R/B_S \leq 80\%$.

- 5 20. Magnet core in accordance with one of claims 1 to 16,
the magnet core having a remanence induction to saturation induction ratio B_R/B_S of $80\% \leq B_R/B_S \leq 97\%$.

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21. Magnet core in accordance with one of claims 1 to 20,
the static-friction-reducing material provided being nano-dispersed SiO_2 .

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22. Magnet core in accordance with one of claims 1 to 20,
the static-friction-reducing material provided being nano-dispersed SiO_2 with magnesium methyllate.

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23. Magnet core in accordance with one of claims 1 to 20,
the static-friction-reducing material provided being pigment soot.

25

24. Magnet core in accordance with one of claims 1 to 20,
the static-friction-reducing material provided being carbon nanotubes.

30

25. Magnet core in accordance with one of claims 1 to 20,

the static-friction-reducing material provided being C₆₀ fullerene.

- 5 26. Magnet core in accordance with one of claims 1 to 25,
an alkylate of a metal or transition metal being provided as an additive to the static-friction-reducing material.
- 10 27. Magnet core in accordance with one of claims 1 to 25,
boron nitride being provided as an additive to the static-friction-reducing material.
- 15 28. Process for producing a magnet core for low frequency applications comprising the following steps:
- provision of an amorphous, soft magnetic strip;
- coating of the strip with a static-friction-reducing material;
20 - coiling of the strip into a magnet core;
- subjection of the magnet core to heat treatment, the static-friction-reducing material exercising a lubricating effect on the strip.
- 25 29. Process for producing a magnet core for low frequency applications comprising the following steps:
- provision of an amorphous, soft magnetic strip;
30 - coiling of the strip into a magnet core;
- coating of the strip layers forming the magnet core with a static-friction-reducing material;

- subsection of the magnet core to heat treatment,
the static-friction-reducing material exercising
a lubricating effect on the strip.

- 5 30. Process in accordance with claim 28 or 29,
the heat treatment being carried out field-free in
the absence of a magnetic field.
- 10 31. Process in accordance with one of claims 28 to 30,
the heat treatment being carried out at a
temperature T where $505^{\circ}\text{C} \leq T \leq 600^{\circ}\text{C}$.
- 15 32. Process in accordance with one of claims 28 to 31,
nano-dispersed SiO_2 being used as the static-
friction-reducing material.
- 20 33. Process in accordance with one of claims 28 to 31,
nano-dispersed SiO_2 with magnesium methyllate being
used as the static-friction-reducing material.
- 25 34. Process in accordance with one of claims 28 to 31,
pigment soot being used as the static-friction-
reducing material.
- 30 35. Process in accordance with one of claims 28 to 31,
carbon nanotubes being used as the static-friction-
reducing material.
36. Process in accordance with one of claims 28 to 31,
 C_{60} fullerene being used as the static-friction-
reducing material.
37. Process in accordance with one of claims 28 to 36,

an alkylate of a metal or transition metal being used as an additive to the static-friction-reducing material.

- 5 38. Process in accordance with one of claims 28 to 36, boron nitride being used as an additive to the static-friction-reducing material.
- 10 39. Process in accordance with one of claims 28 to 38, the surface coverage density ρ of the static-friction-reducing material being $10 \text{ mg/m}^2 \leq \rho \leq 600 \text{ mg/m}^2$.
- 15 40. Process in accordance with one of claims 28 to 38, the surface coverage density ρ of the static-friction-reducing material being $20 \text{ mg/m}^2 \leq \rho \leq 300 \text{ mg/m}^2$.
- 20 41. Process in accordance with one of claims 28 to 38, the surface coverage density ρ of the static-friction-reducing material being $50 \text{ mg/m}^2 \leq \rho \leq 150 \text{ mg/m}^2$.
- 25 42. Process in accordance with one of claims 28 to 41, the layer thickness d of the static-friction-reducing material prior to heat treatment being $d < 5 \text{ }\mu\text{m}$.
- 30 43. Process in accordance with one of claims 28 to 41, the layer thickness d of the static-friction-reducing material prior to heat treatment being $d < 1 \text{ }\mu\text{m}$.
44. Process in accordance with one of claims 28 to 41,

the layer thickness d of the static-friction-reducing material prior to heat treatment being $d < 0.5 \mu\text{m}$.

- 5 45. Process in accordance with one of claims 28 to 41,
the layer thickness d of the static-friction-reducing material prior to heat treatment being $d < 0.2 \mu\text{m}$.
- 10 46. Process in accordance with one of claims 28 to 45,
the static-friction-reducing material being applied
by deposition from the gas phase or from a
solution.
- 15 47. Process in accordance with one of claims 28 to 45,
the static-friction-reducing material being applied
using the sol-gel process.
- 20 48. Process in accordance with one of claims 28 to 45,
the static-friction-reducing material being applied
by solid particle deposition from a suspension.
49. Residual current device with a magnet core in
accordance with one of claims 1 to 27.