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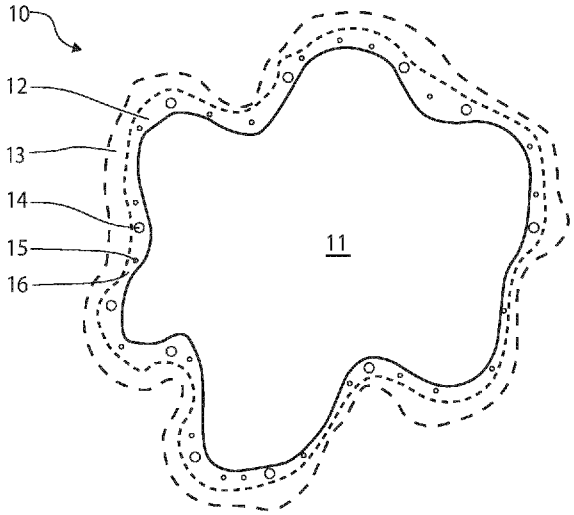


Fig. 1

(57) Abstract: Ferromagnetic powder composition comprising (i) soft magnetic iron-based core particles, and (ii) a first coating, at least partially covering and being in direct contact with the surface of the core particles, comprising a) a silicate of the general formula $(K_2O)\alpha(SiO_2)\beta$, wherein α is moles of K_2O, β is moles of SiO_2, and the β/α molar ratio is in the interval from 0.5 to 4.1, wherein the silicate is present in an amount of 0.02 to 1.0 wt% calculated based on the total weight of the ferromagnetic powder composition, b) optionally, particles of a compound comprising bismuth and oxygen having a D_{50} in the interval of 0.1 to 10 μm measured according to ISO 13320-1, and, c) a dopant dissolved as an oxo- or hydroxy- anion in the silicate (a). A second coating may be provided. Methods of producing the composition and manufacturing an object as well as objects comprising the composition.

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FERROMAGNETIC POWDER COMPOSITION AND METHOD FOR PRODUCING THE SAME

Technical field

The technology proposed herein relates generally to the field of ferromagnetic powder compositions comprising soft magnetic iron-based core particles and methods for producing ferromagnetic powder compositions.

Background

Ferromagnetic powders include soft magnetic composite (SMC) powders which comprise soft magnetic core particles, usually iron-based, with an electrically insulating coating on each particle. Such powders may be used to obtain soft magnetic components or parts, such as by compacting the powders into the desired shape. These components or parts, also known as soft magnetic composites, may be used as an alternative to laminated steel components in electric motors, generators, electromagnets in a wide range of applications.

Two key characteristics of a soft magnetic core particle and a corresponding component made from such particles, are magnetic permeability μ and core loss characteristics P_c. The magnetic permeability μ of a material is an indication of its ability to become magnetized or its ability to carry a magnetic flux. Maximum permeability (μ_{max}) is defined as the highest value of B/H, i.e., the ratio of the magnetizing force B or field intensity to the induced magnetic flux H. When a magnetic material is exposed to a varying field, energy losses occur due to both hysteresis losses and eddy current losses. The hysteresis loss (DC-loss), which constitutes the majority of the total core losses in most motor applications, is brought about by the necessary expenditure of energy to overcome the retained magnetic forces within the part made from the soft magnetic core particles and is influenced by the retentivity, or remanence B_R, and the coercivity H_C.
The retained magnetic forces within the component may be minimized by increasing the quality and purity of the soft magnetic core particles and, in particular, by heat treating the component so as to cause a release of stress caused by the compaction shear forces within the component. Energy losses are further caused by Eddy current loss (AC-loss) which is caused by the induction of electric currents in the part due to the changing flux caused by alternating current (AC) conditions. The Eddy current loss is minimized by the electrically isolating coating on each particle which thereby isolates the soft magnetic core particles from each other. Accordingly, the resistivity R of the coating becomes an

important parameter for defining the characteristics and useability of the soft magnetic core particles. The level of electrical resistivity R that is required to minimize the AC losses in a part made from soft magnetic core particles is dependent on the size distribution of the soft magnetic core particles, the size of the part, or the cross-sectional area of the magnetic flux, and the frequency of the alternating magnetic field in which the part is to be used.

EP 2 252 419 B1 generally discloses a ferromagnetic powder composition comprising soft magnetic iron-based core particles, wherein the surface of the core particles is provided with a first inorganic insulating layer and at least one metal-organic layer, located outside the first layer.

US 10,741,316 generally discloses a ferromagnetic powder composition including soft magnetic iron-based core particles, wherein the surface of the core particles is coated with at least one phosphorus-based inorganic insulating layer and then at least partially covered with metal-organic compound(s).

EP 3 411 169 B1 generally discloses a powder mixture comprising phosphorous coated iron alloy particles and phosphorous coated iron particles.

WO 2020/252551 generally concerns a particulate material comprising ferromagnetic particles covered by at least one oxide layer consisting of nanoparticles and at least one glassy layer covering the oxide layer.

BE 44 486 generally concerns a method of constructing magnetic cores by mixing particles of a magnetic material covered by an insulator with a particle separating material.

Despite the advantages brought about by the technologies described in the above cited documents, there remains a need to provide further ferromagnetic powder compositions comprising soft magnetic core particles having improved electrical, magnetic, and/or structural properties.

More particularly, there remains a need to allow heat treatment at higher temperatures while maintaining an acceptable electrical resistivity of the electrically insulating coating on each particle. Meeting this need would provide for improved ageing properties and higher resistivity for a given coercivity level and coating density/thickness level, inter alia due to an improved coverage of the coating. It would also provide for improving such properties

for harder particles, which undergo less plastic deformation during compaction and therefore require higher relaxation temperatures during the heat treatment.

Objects

First and second objects of the technology proposed herein concern the provision of ferromagnetic powder compositions and mixtures comprising soft magnetic core particles having improved electrical, magnetic and/or structural properties.

Further objects of the technology proposed herein concern the provision of ferromagnetic powder compositions and mixtures comprising soft magnetic core particles providing an improved balance between two or more of electrical, magnetic, and/or structural properties.

Further objects of the technology proposed herein concern the provision of ferromagnetic powder compositions and mixtures having improved ageing properties and higher resistivity for a given coercivity level and coating density/thickness level.

Further objects of the technology proposed herein concern the provision of ferromagnetic powder compositions and mixtures which can be used to produce objects having improved thermal ageing properties.

A third object of the technology proposed herein concerns the provision of a method of producing the ferromagnetic powder compositions and mixtures.

A fourth object of the technology proposed herein concerns the provision of a method of manufacturing an object from the ferromagnetic powder compositions or mixtures.

Fifth and sixth objects of the technology proposed herein concern an object comprising a compacted ferromagnetic powder composition or mixture as well as an object manufactured from the ferromagnetic powder composition or mixture.

Summary

At least one of the above-mentioned objects or at least one of the further objects which will become evident from the below description, are according to corresponding first and third aspects of the technology proposed herein achieved by a ferromagnetic powder composition comprising:

(i) soft magnetic iron-based core particles, and
(ii) a first coating at least partially covering and being in direct contact with the surface of the core particles, the first coating comprising:

a. a silicate of the general formula $(K_2O)\alpha(SiO_2)\beta$, wherein α is moles of K_2O, β is moles of SiO_2, and the β/α molar ratio is in the interval from 0.5 to 4.1,
    i. wherein the silicate is present in an amount of 0.02 to 1.0 wt% calculated based on the total weight of the ferromagnetic powder composition,
b. optionally, particles of a compound comprising bismuth and oxygen having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm, and,
c. a dopant dissolved as an oxo- or hydroxy-anion in the silicate (a),

and

a method of producing a ferromagnetic powder composition comprising the steps of:

(i) providing soft magnetic iron-based core particles,
(ii) contacting the soft magnetic iron-based core particles with a first aqueous solution comprising:
    a. a silicate of the general formula $(K_2O)\alpha(SiO_2)\beta$, wherein α is moles of K_2O, β is moles of SiO_2, and the β/α molar ratio is in the interval from 0.5 to 4.1,
        i. wherein the silicate is present in an amount of 0.02 to 1.0 wt% calculated based on the total weight of the ferromagnetic powder composition,
    b. optionally, particles of a compound comprising bismuth and oxygen having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm,
    c. a dopant dissolved as an oxo- or hydroxy-anion in the silicate (a), and
    d. optionally, nanoparticles having a D_{50} measured according to ISO 13320-1 of 10-200 nm, or alternatively having a specific surface area (SSA) of 6-120 m^2/g as determined according to ISO 9277:2022.

At least one of the above-mentioned objects or at least one of the further objects which will become evident from the below description, are according to a second aspect of the technology proposed herein achieved by a ferromagnetic powder composition comprising:

- the ferromagnetic powder composition according to the first aspect of the technology proposed herein, and

- a further ferromagnetic powder composition,

wherein the further ferromagnetic powder composition comprises soft magnetic iron-based core particles that are different from the soft magnetic iron-based core particles of the ferromagnetic powder composition, and

wherein preferably the soft magnetic iron-based core particles of the further ferromagnetic powder composition comprise or consist of an iron alloy having a higher electrical resistivity and/or hardness than the soft magnetic iron-based core particles of the ferromagnetic powder composition.

At least one of the above-mentioned objects or at least one of the further objects which will become evident from the below description, are according to a fourth aspect of the technology proposed herein achieved by a method of manufacturing an object from the ferromagnetic powder composition according the first aspect of the technology proposed herein or the ferromagnetic powder mixture according to the second aspect of the technology proposed herein, comprising the steps of:

(i) compacting the ferromagnetic powder composition according to the first aspect of the technology proposed herein or the ferromagnetic powder mixture according to the second aspect of the technology proposed herein in a die at a compaction pressure in the range of 300-2000 MPa, preferably 400-1200 MPa, to obtain a compacted part, and

(ii) heat treating the compacted part in a nonreducing atmosphere, preferably comprising 0-22 wt%, more preferably 0.5 to 2 wt% oxygen (O_2) at a temperature in the range of 300–800 °C, preferably 400-750 °C, more preferably 600-700 °C, to obtain the object.

At least one of the above-mentioned objects or at least one of the further objects which will become evident from the below description, are according to corresponding fifth and sixth aspects of the technology proposed herein achieved by an object comprising a compacted ferromagnetic powder composition according to the first aspect of the technology proposed herein or a compacted ferromagnetic powder mixture according to the second aspect of the technology proposed herein, and an object obtained by the method according to the fourth aspect of the technology proposed herein.

Brief description of the drawings

Figs. 1 shows a schematical cross-sectional illustration of a single particle of a ferromagnetic powder composition according to an embodiment of the first aspect of the technology proposed herein showing a soft magnetic iron-based core particle with a first coating comprising a silicate, nanoparticles,

particles of a compound comprising bismuth and oxygen and a dopant, as well as a second coating comprising at least one metal-organic compound.

Detailed description

Corresponding first and third aspects of the technology proposed herein relates to a ferromagnetic powder composition comprising:

(i) soft magnetic iron-based core particles, and
(ii) a first coating at least partially covering and being in direct contact with the surface of the core particles, the first coating comprising:
    a. a silicate of the general formula $(K_2O)\alpha(SiO_2)\beta$, wherein α is moles of K_2O, β is moles of SiO_2, and the β/α molar ratio is in the interval from 0.5 to 4.1,
        i. wherein the silicate is present in an amount of 0.02 to 1.0 wt% calculated based on the total weight of the ferromagnetic powder composition,
    b. optionally, particles of a compound comprising bismuth and oxygen having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm, and,
    c. a dopant dissolved as an oxo- or hydroxy-anion in the silicate (a);

and a method of producing a ferromagnetic powder composition comprising the steps of:

(i) providing soft magnetic iron-based core particles,
(ii) contacting the soft magnetic iron-based core particles with a first aqueous solution comprising:
    a. a silicate of the general formula $(K_2O)\alpha(SiO_2)\beta$, wherein α is moles of K_2O, β is moles of SiO_2, and the β/α molar ratio is in the interval from 0.5 to 4.1,
        ii. wherein the silicate is present in an amount of 0.02 to 1.0 wt% calculated based on the total weight of the ferromagnetic powder composition,
    b. optionally, particles of a compound comprising bismuth and oxygen having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm,
    c. a dopant dissolved as an oxo- or hydroxy-anion in the silicate (a), and
    d. optionally, nanoparticles having a D_{50} measured according to ISO 13320-1 of 10-200 nm, or alternatively having a specific surface area (SSA) of 6-120 m^2/g as determined according to ISO 9277:2022.

Accordingly, the technology proposed herein is based on the realization by the present inventors that the magnetic and electrical properties of a ferromagnetic powder composition and parts made from the ferromagnetic powder composition can be further improved by a dopant in a first coating on the soft magnetic iron-based core particles. As observed from the examples and the figure, the inclusion of the dopant in the first coating provides improved ageing properties and higher resistivity for a given coercivity level and coating density/thickness level to parts manufactured from the ferromagnetic powder composition. Specifically, these parts can be heat-treated at higher temperatures while at the same time maintaining acceptable electrical resistivity properties. In other words, the inclusion of the dopant in the first coating provides better thermal stability, and/or specific electrical resistivity for a given coercivity level and coating density/thickness level, to the glassy coating that is formed from the first coating, and any second coating applied on top thereof, when the ferromagnetic powder composition has been compacted into a part and heat treated. This enables heat treatment at higher temperatures. The heat treatment at higher temperatures provides for more fully or completely releasing the stresses induced in the part when the part is manufactured from the ferromagnetic powder composition, and thus allows the part to obtain a lower coercivity.

The improved thermal stability may alternatively be viewed as the obtaining or maintaining of an improved coverage of the glassy coating formed from first coating and any second coating on top thereof, and thus obtaining or maintaining a higher electrical resistivity of the soft magnetic iron-based core particles and hence a lower coercivity.

An additional advantage observed from parts manufactured from the ferromagnetic powder composition is the improved ageing properties. Accordingly, parts manufactured from the ferromagnetic powder composition suffer less deterioration in properties, especially resistivity and core losses, when subjected to ageing due to the environment of the part such as elevated temperatures, e.g., 30-250°C, or corrosive gases or fluids.

In the ferromagnetic powder composition, the silicate, the particles of a compound comprising bismuth and oxygen, when present, and the dopant, are all provided in the same first coating. In other words, the particles of a compound comprising bismuth and oxygen, when present, are dispersed in the silicate. The dopant is dissolved in the silicate.

Accordingly, the dopant is distributed as oxo- or hydroxy-anions in the silicate (a). Expressed differently, the oxo- or hydroxy anion of the dopant is provided, e.g. distributed, in the silicate (a). Worded differently the first coating comprises the dopant as oxo- or hydroxy-anions distributed in the silicate. The dopant is dissolved in the silicate regardless

of the state of the coating because the oxo- or hydroxy anion interacts with the silicate both in the first aqueous solution and in the first coating.

When a part produced from the ferromagnetic powder composition is heat treated, then the first coating, and any second coating applied on top thereof, react to form a glassy coating formed from the silicate and dopant with the particles of the compound comprising bismuth and oxygen, when present, dispersed therein.

The ferromagnetic powder composition comprises a plurality of soft magnetic iron-based core particles. The soft magnetic iron-based core particles comprise or consist of iron or an alloy of iron comprising at least 90% iron, preferably at least 99% iron, more preferably at least 99.5% iron. The alloy of iron may be alloyed iron Fe-Si having up to 7% by weight, preferably up to 3% by weight of silicon, or another alloy of iron selected from the groups Fe-Al, Fe-Si-Al, Fe-Ni, Fe-Co, Fe-Ni-Co, or combinations or mixtures of such alloys. The soft magnetic iron-based core particles may comprise mixtures of particles such as mixtures of iron particles and iron alloy particles or a mixture of particles made from two or more iron alloys. Preferably the soft magnetic iron-based core particles are made of essentially pure iron, i.e., iron with inevitable impurities. Preferably at least 80 wt%, more preferably at least 90 wt%, of all of the core particles have a diameter in the range 20-1000 µm, measured according to ISO 4497.

Within this range, more specific ranges may be more suitable depending on the intended use of the part, component or object that is to be produced from the ferromagnetic powder composition. Thus, for high frequency applications, such as sensors, inductors, and converters, preferably at least 80 wt%, more preferably at least 90 wt% such as at least 99 wt%, based on the total weight of the core particles, of the core particles are in the range 20-75 µm (200 mesh corresponding to a D_{50} of approximately 50-55 µm), as measured according to ISO 4497. For low to medium frequency applications, such as electric motors, generators, and converters, preferably at least 80 wt%, more preferably at least 90 wt% such as at least 99 wt%, based on the total weight of the core particles, of the core particles are in the range 45-150 µm (100 mesh corresponding to a D_{50} of approximately 95-100 µm), as measured according to ISO 4497. For low frequency applications, such as electric motors, preferably at least 80 wt%, more preferably at least 90 wt% such as at least 99 wt%, based on the total weight of the core particles, of the core particles are in the range 75-380 µm (40 mesh corresponding to a D_{50} of approximately 180-210 µm), as measured according to ISO 4497.

The soft magnetic iron-based core particles may be spherical or irregular shaped, irregular shaped particles being preferred. The AD (apparent density) may be between 2.8 and 4.0 g/cm^3, preferably between 3.1 and 3.7 g/cm^3.

The soft magnetic iron-based core particles may be water atomized, gas atomized or a sponge iron powder. Generally, water atomized soft magnetic iron-based core particles are irregular shaped.

The first coating is at least partially covering and is in direct contact with the surface of the core particles. Preferably the first coating covers all of the surface of at least 50 wt%, such as at least 75 wt% of the core particles in the ferromagnetic powder composition. More preferably, the first coating covers all of the surface of at least 90 wt%, such as at least 95 wt%, such as at least 99 wt% of the core particles in the ferromagnetic powder composition.

Expressed differently, the first coating preferably covers at least 50%, such as at least 75%, more preferably at least 90%, such as at least 95%, such as at least 99% of the total surface area of the core particles.

Typically, the first coating, and the second coating when present, has an average thickness in the range of 20-100 nm. The typical total thickness of the first and the second coatings combined is about 20-200 nm with a permeability of about 400-600. The coating thickness may be estimated from the permeability where a maximum relative magnetic permeability of about 3000 correspond to zero thickness and a maximum relative magnetic permeability of about 700 corresponds to a thickness of about 30 nm for 40 mesh core particles.

The silicate of the general formula $(K_2O)\alpha(SiO_2)_\beta$ is a potassium silicate or alternatively named K-silicate, K-waterglass, potassium waterglass or simply herein silicate.

The β/α molar ratio (i.e., the molar ratio of SiO_2 to K_2O) is in the interval from 0.5 to 4.1. Preferably, the molar ratio β/α is in the interval of 2.0 to 3.75, more preferably the molar ratio β/α is in the interval of 2.5 to 3.5.

The molar ratio β/α may thus alternatively be in the interval of 2.0 to 4.1.

The silicate is present in the amount 0.02 to 1.0 wt%, more preferably 0.05-0.5 wt% calculated based on the total weight of the ferromagnetic powder composition. Preferably, the silicate is present in the amount 0.05-0.2 wt% calculated based on the total weight of the ferromagnetic powder composition when at least 80 wt%, based on the total weight of the core particles, of the core particles are 75 μm or more, and 0.1-0.5 wt% calculated based on the total weight of the ferromagnetic powder composition when at least 80 wt%,

based on the total weight of the core particles, of the core particles are below 75 µm. The first coating may be applied as shown using an aqueous solution and it has been found that when the soft magnetic iron-based core particles are contacted with such a solution, substantially all of the silicate and all of the other components, such as the particles of a compound comprising bismuth and oxygen, when present, and nanoparticles, when present, end up in the first coating. Accordingly, contents and ratios between components in the aqueous solution and the soft magnetic iron-based core particles carry over to the contents and ratios between components in the first coating and the soft magnetic iron-based core particles.

The particles of a compound comprising bismuth and oxygen are optional, but it is preferred that they are included, i.e., comprised, in the first coating as they further improve the properties of the glassy coating formed from the silicate and dopant during heat treatment. The particles of a compound comprising bismuth and oxygen, when present, are dispersed in the first coating, e.g., dispersed in the silicate. During and after heat treatment, the particles of a compound comprising bismuth and oxygen react with the silicate and are included in the formed glassy coating.

The particles of a compound comprising bismuth and oxygen preferably comprise oxides and hydroxides of bismuth. Preferably the D_{50} measured according to ISO 13320-1 is in the interval of 0.5 to 2 µm.

Preferably the content of the particles of the compound comprising bismuth and oxygen in the first coating is 0.025-0.3 wt%, preferably 0.05-0.25 wt%, more preferably 0.07-0.22 wt%, such as 0.08-0.22 wt%, such as 0.08-0.11 wt%, based on the total weight of the ferromagnetic powder composition.
Example 8 shows that these ranges of content of the particles of the compound comprising bismuth and oxygen give good results.

The content of 0.08-0.11 wt% is currently the best range for soft magnetic iron-based core particles sized as 100 mesh.

When the soft magnetic iron-based core particles are larger, e.g., of 40 mesh size, the content of the particles of the compound comprising bismuth is preferably at least 0.05 wt%, such as 0.05-0.10 wt%.

When the soft magnetic iron-based core particles are smaller, e.g., of 200 mesh size, the content of the particles of the compound comprising bismuth is preferably at least 0.15 wt%, such as 0.15-0.30 wt%.

The compound comprising bismuth and oxygen may be selected from the group consisting of bismuth(III) oxide (Bi_2O_3) and bismuth(III) hydroxide ($Bi(OH)_3$), wherein the

compound comprising bismuth and oxygen preferably is $Bi(OH)_3$. As shown in Example 9, the presence of Bi_2O_3 or $Bi(OH)_3$ particles increase resistivity. Further, as shown in Example 9, the resistivity is increased more for $Bi(OH)_3$ particles than for Bi_2O_3 particles.

The D_{50} measured according to ISO 13320-1 is defined in ISO 13320-1 as the median particle diameter used on a volumetric basis, i.e., 50% by volume of the particles is smaller than this diameter and 50% is larger.

Generally, references herein to ISO-standards are equivalent to references to SS-ISO standards where SS merely indicates that the concerned ISO standard has been adopted as a Swedish standard.

The D_{50} measured according to ISO 13320-1 can be determined using e.g., a Mastersizer 3000 from Malvern instruments.

The dopant is dissolved as an oxo- or hydroxy anion in the silicate (a). The oxo- or hydroxo-anion may be a mono- or poly-anion, preferably a mono-anion to maximize distribution in the silicate. In addition to improved distribution, the use of a mono-anion may also decrease the risk of an increase of the melting temperature of the glassy coating formed from the first coating, and any second coating applied on top thereof, during the heat treatment. Specifically, it is contemplated that an increase in melting temperature could be caused by the presence of the longer poly-anions competing with the poly-silicate ions in the glassy coating. Such an increase in melting temperature could make it more difficult to obtain a good distribution of the glassy coating.

The dopant being dissolved as an oxo-or hydroxy-anion encompasses that the dopant is an oxo- or hydroxy-anion dopant. The term dopant encompasses both compounds that form an oxo-or hydroxy-anion when dissolved in the silicate or an aqueous solution of the silicate, as well as the oxo-or hydroxy-anions themselves. As the first aqueous solution, which contains the silicate, is generally alkaline, the dopant may be a compound that forms oxo-or hydroxy-anions when dissolved in an alkaline aqueous solution.

Generally, the content of dopant may be from 0.5-30 mol%, preferably 1-30 mol%, more preferably 1-25 mol% based on the molar content of K (Potassium) in the first coating.

The contacting of the soft magnetic iron-based core particles with the first aqueous solution may be performed by mixing, e.g., in a mixer. The result of contacting the soft magnetic iron-based core particles with the first aqueous solution is that the first coating is formed on the magnetic iron-based core particles so as to at least partially cover the magnetic iron-based core particles. In other words, the method according to the third aspect of the technology proposed herein produces soft magnetic iron-based core particles coated with the first coating, i.e., the ferromagnetic powder composition

according to the first aspect of the technology proposed herein. The soft magnetic iron-based core particles coated with the first coating and optionally also coated with the second coating as described below may alternatively be referred to as coated core particles or coated soft magnetic iron-based core particles.

Preferably the first coating further comprises nanoparticles having a D_{50} measured according to ISO 13320-1 of 10-200 nm, or alternatively having a specific surface area (SSA) of 6-120 m^2/g as determined according to ISO 9277:2022.

As seen from the examples, especially example 1, inclusion of the nanoparticles further improves resistivity of the glassy coating formed form the first coating and any second coating applied on top thereof. Inclusion of nanoparticles further work well together with the dopant.

The nanoparticles, when present, are dispersed in the first coating, e.g., dispersed in the silicate. During and after heat treatment, the nanoparticles become embedded in the formed glassy coating.

The nanoparticles have a D_{50} measured according to ISO 13320-1 of 10-200 nm.

The D_{50} measured according to ISO 13320-1 is defined in ISO 13320-1 as the median particle diameter used on a volumetric basis, i.e., 50% by volume of the particles is smaller than this diameter and 50% is larger.

Generally, references herein to ISO-standards are equivalent to references to SS-ISO standards where SS merely indicates that the concerned ISO standard has been adopted as a Swedish standard.

The D_{50} measured according to ISO 13320-1 can be determined using e.g., a Mastersizer 3000 from Malvern instruments.

An alternative parameter for determining the size of the nanoparticles is the specific surface area (SSA) [m^2/g], i.e., the surface area of the particles per g of particles.

Accordingly, a D_{50} measured according to ISO 13320-1 of 10-200 nm may be equivalently replaced by a specific surface area (SSA) in the range of 6-120 m^2/g.

The SSA for the nanoparticles is preferably determined using the BET-method, which is a method for determination of the specific surface area of solids by gas adsorption.

More preferably, the SSA for the nanoparticles is preferably determined according to ISO 9277:2022.

Accordingly, a D_{50} measured according to ISO 13320-1 of 10-200 nm may be equivalently replaced by a specific surface area (SSA) of 6-120 m^2/g as determined according to ISO 9277:2022.

Preferably, the specific surface area (SSA) of the nanoparticles is 10-50, more preferably 10-30, most preferably 15-30 m^2/g. One example is 18 m^2/g. As above, these ranges are preferably determined according to ISO 9277:2022.

The specific surface area may be measured using a Micromeritics TriStar 3000 gas adsorption instrument which calculates the BET surface area.

For comparison, an average diameter for the nanoparticles may be calculated from the specific surface area if the particles are assumed to be spherical. The equation for calculating the average particle diameter in nanometres is 6000/(BET surface area in m2 /g) x (density in g/cm3). For Y_2O_3 (density 5.01 g/cm3), the specific surface areas of 120, 6, 50, 10, and 18 m2/g respectively yield the average diameters of 10, 200, 24, 120, and 67 nm respectively.

Preferably, the nanoparticles have a D_{50} measured according to ISO 13320-1 of 10 -100 nm. Most preferably the nanoparticles have a D_{50} measured according to ISO 13320-1 of 20-100 nm.

The former interval corresponds to a SSA of 12-120 m^2/g, whereas the latter interval corresponds to a SSA of 12-60 m^2/g.

The D_{50} measured according to ISO 13320-1 is preferably between 10 and 100, where 90 wt% of the particles shall have maximum diameters between 1 and 500 nm.

In the examples the nanoparticles generally have a D_{50} of 10 nm, and this size of nanoparticles have been shown to provide the best results.

Alternatively, the nanoparticles may have diameters of 1-200 nm, preferably 1-50 nm, more preferably 5-50 nm, such as 30-50 nm or such as 5-20 nm such as 10 nm.

When performing the method according to the third aspect of the technology proposed herein, it may occur that the nanoparticles as provided or obtained are agglomerated into agglomerates having a diameter above 200 nm and/or such that the agglomerated nanoparticles have a D_{50} above 200 nm. These agglomerates should preferably be fully or partially disintegrated so as to obtain, or increase the number of, nanoparticles having the desired D_{50} or diameter of 1-200 nm or smaller as preferred above because well distributed nanoparticles within the first coating is preferred. Where the nanoparticles used in the method comprises significant amounts of agglomerates, and when no further disintegration is performed on the nanoparticles, then the mol% of nanoparticles in the

first coating may preferably be increased compared to when nanoparticles comprising no or only a minor number of agglomerates and having a lower D_{50} or diameter are used.

The disintegration preferably takes place before or during the preparation of the first aqueous solution, or during the contacting of the soft magnetic iron-based core particles with the first aqueous solution. As an example, sonication may be used for disintegration.

The nanoparticles are preferably selected from the group consisting of Y_2O_3 nanoparticles, ZrO_2 nanoparticles, ZnO nanoparticles, $Mg(OH)_2$ nanoparticles, MgO nanoparticles, $CaCO_3$ nanoparticles, Al_2O_3 nanoparticles, SiO_2 nanoparticles, and TiO_2 nanoparticles, and more preferably the nanoparticles comprise or consist of Y_2O_3 nanoparticles.

The nanoparticles may comprise a mixture of nanoparticles, such as a mixture of two or more of the listed nanoparticles. Presently, preferred is however that only one type of nanoparticles, e.g., preferably Y_2O_3 nanoparticles, is present in the first coating.

The dopant is effective with numerous different nanoparticles.

As seen in example 8, numerous different nanoparticles are effective in obtaining improved magnetic and electric properties for objects manufactured from the ferromagnetic powder composition. Further, Example 8 shows that Y_2O_3 nanoparticles, also known as yttria nanoparticles and yttrium oxide nanoparticles, provides the currently considered best magnetic and electric properties.

The content of nanoparticles in the first coating is preferably 1-30 mol%, preferably 1-20 mol% based on the molar content of K (potassium) in the first coating. These general molar contents of nanoparticles provide good results, see e.g., example 8.

Preferably, the first coating comprises:

- 1-25 mol%, more preferably 8-22 mol%, most preferably 10-20 mol%, such as 20 mol% Y_2O_3 nanoparticles based on the content of K in the first coating, or
- 1-20 mol%, preferably 1-15 mol%, more preferably 1-10 mol% such as 5 mol% ZrO_2 nanoparticles based on the content of K in the first coating, or
- 1-20 mol%, preferably 5-20 mol%, more preferably 10-20 mol% $Mg(OH)_2$ nanoparticles based on the content of K in the first coating, or
- 1-20 mol%, preferably 5-20 mol%, more preferably 10-20 mol% $CaCO_3$ nanoparticles based on the content of K in the first coating, or
- 1-20 mol%, preferably 5-20 mol%, more preferably 10-20 mol% ZnO nanoparticles based on the content of K in the first coating, or

- 1-30 mol%, preferably 10-30 mol%, more preferably 15-25 mol% such as 20 mol% MgO nanoparticles based on the content of K in the first coating, or

- 1-30 mol%, preferably 10-30 mol%, more preferably 15-25 mol% such as 20 mol% TiO_2 nanoparticles based on the content of K in the first coating, or

- 1-20 mol%, preferably 5-15 mol%, more preferably 10 mol% Al_2O_3 nanoparticles based on the content of K in the first coating, or

- 1-20 mol%, preferably 1-10 mol%, more preferably 5 mol% ZnO nanoparticles based on the content of K in the first coating.

Example 8 shows that these contents of the various nanoparticles give good results. As above, different nanoparticles according to these ranges may be combined in the first coating.

Preferably the nanoparticles comprise or consist of Y_2O_3 nanoparticles and the content of nanoparticles in the first coating is 10-20 mol% based on the molar content of K (Potassium) in the first coating.

As seen in example 8, Y_2O_3 nanoparticles provides the currently considered best magnetic and electric properties.

For reference, 20 mol% Y_2O_3 particles when included in a first coating comprising 0.1 wt% potassium silicate with a β/α molar ratio of 3.4 on 5 kg of soft magnetic iron-based core particles corresponds to 0.94 g Y_2O_3 particles, i.e., 0.0188 wt% based on the weight of the ferromagnetic powder composition.

Preferably the dopant comprises at least one element from group 5, such as V (Vanadium) or Nb (Niobium), or comprises at least one element from group 6, such as Cr (Chromium), W (Tungsten), or Mo (Molybdenum), or comprises Al (Aluminium) or P (Phosphorus).

Preferred elements of group 5 include V (Vanadium), Nb (Niobium), and Ta (Tantalum).

Preferred elements of group 6 include Cr (Chromium), Mo (Molybdenum), and W (tungsten).

Exemplary dopants include V (Vanadium), Nb (Niobium), Ta (Tantalum), Cr (Chromium), Mo (Molybdenum), W (tungsten), and P (phosphorous). Such as V (Vanadium), Nb (Niobium), Ta (Tantalum), Cr (Chromium), Mo (Molybdenum), and W (tungsten). Such as V (Vanadium), Nb (Niobium), Cr (Chromium), Mo (Molybdenum), W (tungsten).

The group 5 and 6 elements are known to form oxo- or hydroxo-anions in alkaline water solutions. Also, Al (Aluminium) can be dissolved as a hydroxy anion in strong alkaline

solutions and thus used as a dopant. Phosphorus in the form of a phosphate, e.g., $KHPO_4$, H_3PO_4, $(NH_4)_3PO_4$ can also be used. Also Nb and Tantal can form oxo- and/or hydroxo-anions analogously to W, Mo and W.

Preferred dopants are those that are easily dissolved and stable in the silicate solution. Toxic dopants, such as ions including Cr(VI), are less preferred.

The dopant is preferably provided to the first coating by dissolving a suitable compound comprising the dopant, such as for example an oxide, in the first aqueous solution that the soft magnetic iron-based core particles is contacted with. This typically leads to the provision of ions of the dopant in the first aqueous solution.

Preferred elements for the dopant include Al, Nb, V, Mo, Cr. More preferred elements include Al and Nb.

V, vanadium, is preferably provided to the first coating by dissolving vanadium(V) oxide, V_2O_5 in the first aqueous solution that the soft magnetic iron-based core particles is contacted with. In strong alkaline water solutions, such as potassium silicate solutions, the Vanadium will form predominantly $(VO_4)^{3-}$ ions (pH>12). This will lead to the provision of VO_4^{3-} ions in the first aqueous solution. In less strong alkaline environments, the vanadium tends to form polyvanadate ions coordinating more than four oxo- or hydroxo groups, such as $(VO_3)_n^-$, analogue to polyphosphate chains. Thus, the size of the vanadate ions may vary dependent on the concentration of potassium and the pH of the silicate solution.

It is believed that the dopant ion shall preferably not exist as polyanions in the silicate prior to heat treatment in order to maximize the atomic distribution of dopants in the final glassy coating, which may theoretically increase the specific electrical resistivity of the bismuth-silicate glass.

Mo, molybdenum, is preferably provided to the first coating by dissolving Molybdenum(VI) oxide, MoO_3 in the first aqueous solution that the soft magnetic iron-based core particles is contacted with. This will lead to the provision of molybdate ions (MoO_4^{2-}), analogue with the tungstate ions, in the first aqueous solution.

W, tungsten, is preferably provided to the first coating by dissolving Tungsten(VI) oxide, WO_3 in the first aqueous solution that the soft magnetic iron-based core particles is contacted with. This will lead to the provision of tungstate ions (WO_4^{2-}), analogue with the vanadate ions, in the first aqueous solution.

Al, Aluminium, is preferably provided to the first coating by dissolving Aluminium(III) hydroxide, $Al(OH)_3$ in the first aqueous solution that the soft magnetic iron-based core

particles is contacted with. This will lead to the provision of $Al(OH)_4^-$ ions in the first aqueous solution.

Preferably:

- the dopant comprises V and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K (Potassium) in the first coating,

- the dopant comprises Nb and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises Cr and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises Mo and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises W and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises Al and the content of dopant in the first coating is 0.5-5 mol%, preferably 1-3 mol%, more preferably 1.71-2.58 mol% based on the molar content of K in the first coating, and/or,

- the dopant comprises P and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating.

More preferably, the dopant comprises V and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 10-15 mol%, based on the molar content of K in the first coating.

As shown in example 1 and 3, 10-15 mol% of V dopant yields higher resistivity for a given coercivity level and coating density/thickness level. This is believed to be caused by a better distribution of the glassy coating formed from the first coating, and any second coating on top thereof, during the heat treatment.

Alternatively, the dopant comprises Al and the content of dopant in the first coating is 0.5-5 mol%, preferably 1-3 mol%, more preferably 1.5-2.7 mol% such as 1.71-2.58 mol%, based on the molar content of potassium K in the first coating.

As seen in example 7, the provision of an Al dopant to the first coating at a concentration in this range allows higher heat treatment temperatures yielding lower coercivity while maintaining good resistivity. The effect is less than for V, but Al has less environmental effect and presents a lesser health risk.

Preferably the ferromagnetic powder composition further comprises:

(iii) a second coating at least partially covering the surface of the core particles and/or the first coating, the second coating comprising:

a. at least one metal-organic compound having the general formula

$$R_1[(R_1)_x(R_2)_y(M)]_nO_{n-1}R_1 \qquad (I)$$

or

$$R_2[M(OH)_{2(n+1)}]_{(n+1)}O_{(n)}R_2 \qquad (II)$$

wherein M is selected from the group consisting of Si, Ti, Al, and Zr; O is oxygen; R_1 is a hydrolysable group; R_2 is an organic moiety and wherein at least one R_2 contains at least one nitrogen containing group, preferably an amino group; wherein n is the number of repeating units being an integer between 1 and 20; wherein x is 0 or 1; and wherein y is 1 or 2, and x+y is 2,

wherein the content of the at least one metal-organic compound is 0.05 to 0.40 wt%, preferably 0.10 to 0.30 wt%, based on the total weight of the ferromagnetic powder composition.

The second coating further improves the electrical, structural and magnetic properties of components or parts manufactured from the ferromagnetic powder composition. Without wishing to be bound by theory, it appears that the second coating may provide lubrication and additional silicon and carbon which helps formation of the glassy coating during heat treatment.

R_1 may be an alkoxy-group having less than 4, preferably less than 3 carbon atoms. R_2 is an organic moiety, which means that the R_2-group contains an organic part or portion. R_2 preferably includes 1-6, more preferably 1-3, carbon atoms. R_2 may further include one or

more hetero atoms selected from the group consisting of N, O, S and P. The R_2 group may be linear, branched, cyclic, or aromatic. R_2 may include one or more of the following functional groups: amine, diamine, amide, imide, epoxy, hydroxyl, ethylene oxide, ureido, urethane, isocyanato, acrylate, glyceryl acrylate, benzyl-amino, vinyl-benzyl-amino. The R_2 group may alter between any of the mentioned functional R_2-groups and a hydrophobic alkyl group with repeatable units.

When n=1 the metal-organic compound is a monomer (formula I) or a dimer (Formula II). If the metal-organic compound is a monomer it may be selected from the group of trialkoxy and dialkoxy silanes, titanates, aluminates, or zirconates. The monomer of the metal-organic compound may thus be selected from 3-aminopropyl-trimethoxysilane, 3-aminopropyl-triethoxysilane, 3-aminopropyl-methyl-diethoxysilane, N-aminoethyl-3-aminopropyl/ethyl/methyl-alkoxy-silane such as N-aminoethyl-3-aminopropyl-trimethoxysilane and N-aminoethyl-3-aminopropyl-methyl-dimethoxysilane, 1,7-bis(triethoxysilyl)-4-azaheptan, triamino-functional propyl-trimethoxysilane, 3-ureidopropyl-triethoxysilane, 3-isocyanatopropyl-triethoxysilane, tris(3-trimethoxysilylpropyl)-isocyanurate, 0-(propargyloxy)-N-(triethoxysilylpropyl)-urethane, 1-aminomethyl-triethoxysilane, 1-aminoethyl-methyl-dimethoxysilane, or mixtures thereof.

When n=2-20 the metal-organic compound is an oligomer. An oligomer of the metal-organic compound may be selected from alkoxy-terminated alkyl-alkoxy-oligomers of silanes, titanates, aluminates, or zirconates. The oligomer of the metal-organic compound may thus be selected from methoxy, ethoxy or acetoxy-terminated amino-silsesquioxanes, amino-siloxanes, oligomeric 3-aminopropyl-methoxy-silane, 3-aminopropyl/propyl-alkoxy-silanes, N-aminoethyl-3-aminopropyl-alkoxy-silanes, or N-aminoethyl-3-aminopropyl/methyl-alkoxy-silanes or mixtures thereof.

Examples of suitable metal-organic compounds in particular include Dynasylan® 1146 and Dynasylan® SIVO 203 from Evonik Industries AG, or XIAMETER™ OFS-6020 Silane from Dow Chemical Company.

Water-borne amino- or multifunctional silane systems are also comprised by the metal-organic compound, such as the corresponding Dynasylan® HYDROSIL products supplied by Evonik industries AG. In these products the hydrolysable alkoxy-groups have almost fully been replaced with hydroxyl groups, i.e., as per Formula (II), while the functionality is similar, e.g., hydrophobic alkyl-groups in combination with amino- or diamino-alkyl-groups. Examples include the Dynasylan® HYDROSIL 2627, 2776, and 1151 silane systems. Examples of such compounds can be 1,3-Bis(3-aminopropyl)disiloxane-1,1,3,3-tetrol or (3-aminopropyl)({[(propyl)dihydroxysilyl]oxy})silanediol.

It is further contemplated that a part, or all, of the particles of a compound comprising bismuth and oxygen and having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm, which are optionally comprised by the first coating, may be provided in the second coating also or instead.

Example 8 shows that a variety of metal organic compounds in the second coating can be used successfully in the ferromagnetic powder composition.

Preferably, the at least one metal-organic compound has the general formula (I). Alternatively, the at least one metal-organic compound has the general formula (II).

The ferromagnetic powder composition preferably further comprises:

(iv) a lubricant, preferably a particulate lubricant.

Including a lubricant in the ferromagnetic powder composition improves compaction and leads to an increased density and strength of an object manufactured from the ferromagnetic powder composition. The lubricant may be selected from the group consisting of primary and secondary fatty acid amides, trans-amides (bisamides) or fatty acid amides or alcohols. The lubricating moiety of the lubricant may be a saturated or unsaturated chain containing between 12-22 carbon atoms. The lubricant may preferably be selected from stearamide, behenyl alcohol, erucamide, stearylerucamide, erucyl-stearamide, behenyl alcohol, erucyl alcohol, ethylene-bisstearamide (i.e., EBS or amide wax). Preferably the lubricant is an amide wax. Preferably is also a mixture of stearamide or behenyl alcohol and an amide wax. One example is 0.1 wt% stearamide combined with 0.3 wt% amide wax.

The lubricant may be present in an amount of 0.05-0.80 wt%, preferably 0.20-0.40 wt% of the ferromagnetic powder composition. If a very low amount of lubricant is added in the composition (0.05 to 0.20 wt%), the compaction and ejection can be facilitated by using die wall lubrication (DWL). The low amount of internal lubricant will improve compact density, permeability and mechanical strength.

The second aspect of the technology proposed herein concerns a ferromagnetic powder composition comprising:

- the ferromagnetic powder composition according to the first aspect of the technology proposed herein, and

- a further ferromagnetic powder composition,

wherein the further ferromagnetic powder composition comprises soft magnetic iron-based core particles that are different from the soft magnetic iron-based core particles of the ferromagnetic powder composition, and

wherein preferably the soft magnetic iron-based core particles of the further ferromagnetic powder composition comprise or consist of an iron alloy having a higher electrical resistivity and/or hardness than the soft magnetic iron-based core particles of the ferromagnetic powder composition.

This is advantageous in that it allows the magnetic and electrical properties of components or parts manufactured from the ferromagnetic powder composition to be further adjusted. If, as preferred, the soft magnetic iron-based core particles of the further ferromagnetic powder composition comprise or consist of an iron alloy having a higher electrical resistivity than the soft magnetic iron-based core particles of ferromagnetic powder composition, then the ferromagnetic powder mixture will have an even lower core loss at higher frequencies. The soft magnetic iron-based core particles of the further ferromagnetic powder composition are typically also harder and may thus provide further improvements in properties.

The soft magnetic iron-based core particles of the further ferromagnetic powder composition preferably comprise or consist of an iron alloy selected from the group consisting of FeSi, FeAl, FeSiAl, FeNi, FeCo, and FeNiCo, or combinations or mixtures of such alloys. Especially preferred are FeSi (typically 3-6.8 wt% Si) and FeSiAl (also known as Sendust; typically 9 wt% Si and 6 wt% Al, or alternatively 3.5wt% Si and 3wt% Al).

The content of the further ferromagnetic powder composition may be up to 60 wt% such as 30-60 wt%, but is typically from 10-50 wt%, such as from 20-40 wt%, such as 20-30 wt%, based on the weight of the ferromagnetic powder mixture with the ferromagnetic powder composition according to the first aspect of the technology proposed herein making up the remainder. Further, for medium or low frequency application, the content of the further ferromagnetic powder composition is preferably low or non-existent so as to not decrease density, magnetic induction and permeability. To the contrary, for high frequency application, the content of the further ferromagnetic powder composition may instead be increased up to 90 wt%.

In the powder mixture the soft magnetic iron-based core particles of the ferromagnetic powder composition preferably comprises or consists of essentially pure iron, i.e., iron with inevitable impurities.

Preferably the further ferromagnetic powder composition further comprises a coating or surface treatment on the soft magnetic iron-based core particles therein. The coating or surface treatment preferably comprises the first, and optionally also the second, coating as described above. Typically, however, when comprising an iron alloy, the soft magnetic iron-based core particles of the further ferromagnetic powder composition may be coated

or treated with another coating, such as by being treated with phosphoric acid diluted in acetone.

The soft magnetic iron-based core particles or the further ferromagnetic powder composition preferably have the same particle sizes as the soft magnetic iron-based core particles of the ferromagnetic powder composition according to the first aspect of the technology proposed herein as described further above.

The method according to the third aspect of the technology proposed herein may further comprise one or more of the steps of:

(iii) drying the coated soft magnetic iron-based core particles, and/or
(iv) contacting the coated soft magnetic iron-based core particles with at least one metal-organic compound as described above, and/or
(v) mixing the coated soft magnetic iron-based core particles with a lubricant as described above.

Step (iii) is preferably performed after step (ii). Step (iii) may be performed by heating the soft magnetic iron-based core particles while stirring.

Step (iv) is preferably performed after step (ii) or (iii), and before step (v).

Step (v) is preferably performed after step (iii) and step (iv).

The fourth aspect of the technology proposed herein relates to a method of manufacturing an object from the ferromagnetic powder composition according the first aspect of the technology proposed herein or the ferromagnetic powder mixture according to the second aspect of the technology proposed herein, comprising the steps of:

(i) compacting the ferromagnetic powder composition according to the first aspect of the technology proposed herein or the ferromagnetic powder mixture according to the second aspect of the technology proposed herein in a die at a compaction pressure in the range of 300-2000 MPa, preferably 400-1200 MPa, to obtain a compacted part, and
(ii) heat treating the compacted part in a nonreducing atmosphere, preferably comprising 0-22 wt%, more preferably 0.5 to 2 wt% oxygen (O_2) at a temperature in the range of 300–800 °C, preferably 400-750 °C, more preferably 600-700 °C, to obtain the object.

The compaction may be cold die compaction, warm die compaction, or high-velocity compaction, preferably a controlled die temperature compaction (50-120°C) with an unheated powder is used. During the compaction, the coated soft magnetic iron-based core particles are pressed together and deformed so as to adhere to each other and form

the compacted part. During the heat treatment the particles of the compound comprising bismuth and oxygen together with the nanoparticles and the silicate in the first coating and the amino and/or alkyl groups of the metal-organic compound of the second coating form an evenly distributed bismuth-silicate glass on the surface of the soft magnetic iron-based core particles which provides the desired electrical resistivity between the individual particles of the compacted and heat treated ferromagnetic powder composition in the finished object. Additionally, the heat treatment relieves the stress formed during the compaction.

The heat treatment process may be in vacuum, non-reducing, inert or in weakly oxidizing atmospheres, e.g., 0.01 to 3 wt% oxygen in nitrogen. In one embodiment, an essentially pure nitrogen atmosphere is used as a non-reducing atmosphere. In one embodiment with addition of 0-22 wt% oxygen, preferably 0.5-2 wt% oxygen. Higher temperature, above 680-700 °C, may require lower oxygen levels such as 500-3000 ppm (0.05-0.3 wt%). Generally, the oxygen levels may be higher during the initial heating, e.g., delubrication. Optionally, the heat treatment is performed in an inert atmosphere and thereafter exposed quickly in an oxidizing atmosphere, such as 0.5-22 wt% oxygen/nitrogen mixtures or in steam/nitrogen mixtures, to build a superficial crust of higher strength and/or corrosion resistance. The temperature may in one embodiment be up to 800°C. Heat treating the compacted part at a temperature in the range 300–800 °C means that the temperature compacted part is exposed to a temperature in the range 300–800 °C. This is typically done for a time period sufficient to cause the compacted part to be heated to a temperature in the range 300–800 °C, such as for example 20-120 minutes.

Typically the heat treating is performed in three phases: a delubrication stage at about 300-400°C during which the compacted part is heated up towards the curing stage, a curing stage at about 350-450°C (first temperature and time) in which the first coating is cured so as to cause the formation of the electrically insulating glassy coating (the silicate and any present silane is being polymerised to form the silicate glass) from the first, and second coating, when present, and a relaxation stage at 600-700°C (second temperature and time) in which the glassy coating flows out to cover the core particles and the stresses from the compaction was released. The temperature in the range of 300–800 °C given for step (ii) above corresponds to this last (second) temperature. The first and second time period may typically be 0-60 minutes each, such as 1-60 minutes.

The compacted part is further preferably heat treated at a temperature below the glass crystallisation temperature of the first coating. This is because crystallisation of the silicate in the coating layer may decrease the resistivity and mechanical strength of the silicate and the first coating. Further, crystallisation of the silicate in the first coating may cause

cracks in the glassy coating formed by the first coating and the second coating during the heat treatment.

The heat treatment may comprise a delubrication stage, wherein the temperature during said delubrication stage may be between 400 and 500°C, such as 420-480°C, such as 430-470°C. The atmosphere in the delubrication stage may be an inert atmosphere, such as an N_2(g.) atmosphere.

Preferably step (ii) comprises heat treating the compacted part at a (second) temperature of at least 650°C, more preferably at least 670°C to substantially or fully eliminate the stress in the compacted part. The temperature where maximum elimination of stress in the compacted part occurs is called the maximum relaxation temperature.

Preferably step (ii) accordingly comprises heat treating the compacted part at a (second) temperature of 670-700 °C, preferably 680-700 °C.

For heat treating at higher second temperatures, e.g., between 700°C and 750°C or 750°C and up to 800°C, it is preferred that a thicker first coating, i.e., a higher wt% of the silicate, such as 0.25 wt%, is used as such thicker coating provide acceptable remaining resistivity while having the potential to provide even better ageing properties. This also applies to ferromagnetic powder mixture comprising harder or alloyed particles which benefit from being treat at these higher second temperatures as that allows a higher degree of relaxation of the comparative less degree of plastic deformation during the compaction. In particular finer powders, e.g., 200-300 mesh, may advantageously be coated with the thicker first coating as the resulting lower permeability is generally acceptable for the type of passive components in which these finer powders are typically used.

As seen in example 1, the inclusion of the dopant allows these high heat treatment step temperatures with corresponding low coercivity while maintaining acceptable resistivity and thus acceptable core loss.

The heat treatment may further comprise an initial preoxidation step in ambient air at between 200 and 250°C for 1-30 h, such as 2-18 h. This improves electrical resistivity.

In particular, the heat treating step (ii) may comprise the preoxidation step followed by delubrication at 400-500 °C in inert atmosphere (e.g. nitrogen), followed by curing and stress relaxation treatment at between 600 and 700 °C in between 5000 and 15000 ppm oxygen. This improves mechanical strength (TRS) without sacrificing the magnetic properties such as resistivity, coercivity and core loss significantly.

Corresponding fifth and sixth aspects of the technology proposed herein concern an object comprising a compacted ferromagnetic powder composition according to the first aspect of the technology proposed herein or a compacted ferromagnetic powder mixture according to the second aspect of the technology proposed herein, and an object obtained by the method according to the fourth aspect of the technology proposed herein.

The object may alternatively be referred to as a part or a component. The object may be selected from the group consisting of a soft magnetic component of a sensor, inductor, converter, transformer, electric motor, and a generator.

Examples

In the following examples various ferromagnetic powder compositions comprising soft magnetic iron-based core particles according to the first aspect of the technology proposed herein were produced by coating the soft magnetic iron-based core particles with various first and second coatings as per various embodiments of the method according to the third aspect of the technology proposed herein. The ferromagnetic powder compositions were then used to produce test parts or test objects which were compacted and heat treated according to various embodiments of the method according to the fourth aspect of the technology proposed herein. The finished test parts were finally investigated for relevant properties such as resistivity Res and permeability μ-max.

More specifically, the test parts used in the examples were produced in the following steps:

Step 1: Soft magnetic iron-based core particles were mixed (10 min) with an aqueous solution of a silicate of the general formula $(K_2O)\alpha(SiO2)\beta$ (potassium silicate K12, Sibelco Nordic AB, β/α molar ratio of about 3.35, solids content 35 wt%) at a concentration (based on dry matter content) of about 0.11 wt% (0.165 wt% and 0.275 wt% also tested) to form the first coating on the core particles. Particles of a compound containing bismuth and oxygen, specifically $Bi(OH)_3$ at 0.08 wt% (0.11 wt% and 0.205 wt% was also tested) unless specified otherwise, were also included in the aqueous solution.

Where nanoparticles were included in the first coating, then these were Y_2O_3 particles (nominally 10 nm) at 20 mol% based on the content of K, unless otherwise specified.

The aqueous solution further contained one or more additional compounds or additives of interest as specified for each sample. After the initial mixing, the core particles where dried while being stirred at 60°C for 1 h, followed by further drying without stirring at 120°C.

Step 2: The mixture from step 1 was mixed with a silane (oligomeric diaminofunctional silane Dynasylan® 1146 from Evonik Industries AG, 2.0 g and 1 g H_2O (corresponding to 2 g silane per kg of core particles coated with the first coating) unless otherwise specified for 5 min so as to form the second coating, and the resulting mixture was dried at 50°C for 2 h to produce a finished ferromagnetic powder composition comprising coated soft magnetic iron-based core particles.

Step 3. A lubricant (0.4 wt% amide wax unless otherwise specified) was added to the ferromagnetic powder composition in order to facilitate producing the test part, and the ferromagnetic powder composition was then shaped and compacted (800 MPa with a die temperature of 100°C) into test parts which were heat treated as detailed for each sample to release stress from the compaction to form the finished test parts.

The soft magnetic iron-based core particles were a water atomized annealed iron powder having dimensions according to 100 mesh and an apparent density of 3.32 g/cm^3 unless otherwise stated.

The heat treatment was performed in three stages in a pre-heated furnace. The three stages comprised a delubrication stage at about 300-400°C during which the compacted part was heated up towards the curing stage, a curing stage at about 350-450°C (first time and temperature given for each sample) in which the first and second coatings were cured so as to cause the formation of an electrically insulating silicate glass from the first and second coatings, and a relaxation stage at 600-700°C (second time and temperature given for each sample) in which the stress from the compaction was released and improved coverage of the glassy coating was obtained. The oxygen partial pressure during the heat treatment was 15000 ppm (1.5 wt% oxygen in nitrogen) unless otherwise specified.

The finished test parts (OD55/ID45/H5 mm magnetic square toroids) were subjected to test to determine inter alia:

Electrical resistivity (Res) – how the material resists electric current [μΩm]. Measured using 4-point probe method with 20 mm distance between measuring points.

Coercivity* (H_c) at 10 kA/m [A/m]

Maximal permeability* (μ-max) – the maximum value of the ratio between the magnetization that a material obtains in response to an applied magnetic field [unitless].

Total core loss* (at 1T/1kHz) – total core loss for a test part obtained for a given induction and frequency [W/kg].

*For the measurement of magnetic properties, the square toroids were wound with 100 drive and 100 sense turns of resin coated copper wire (diameter 0.63 mm) and measured using a Brockhaus MPG 200D. References: IEC 60404-4 (DC measurements) and IEC 60404-6 (AC-measurements).

Further measurements included:

Square toroid density (d) – density of the square toroid test part [g/cm^3].

TRS – Transverse rupture strength according to SS-EN ISO 3325:2000, on bars with dimensions of 30x12x6 mm [MPa].

AD – Apparent density according to ISO standard 3923-1:2018 measured as the ratio between the dry mass and apparent volume of the powder sample [g/cm^3].

FLOW – Hall flow according to SS-EN ISO 4490:2018 [seconds].

GS – Green strength, measured as TRS but on test parts prior to heat treatment [MPa].

Example 1: Initial experiments with and without nanoparticles and dopant

Example 1 tested the effects of adding a dopant to a first coating containing a silicate and particles of a compound comprising Bismuth and oxygen. For further exploration, also nanoparticles were added to the first coating.

Table 1A: No dopant or nanoparticles

Sample	Constitution and conditions	Res	Hc	µ-max	Total Core loss
No dopant, no nanoparticles, 0.11 wt% silicate					
1-1	450/650°C (30/30min) @ 15000 ppm	2158	138.3	547	78.9
1-1	450/670°C (30/30min) @ 15000 ppm	25	136.6	543	Very high

The results in Table 1 illustrates the problems encountered when heat treating at higher temperatures. Whereas the sample part had a resistivity of 2158 µΩm when heat treated at up to 650°C, heat treating at the higher temperature of 670°C resulted in an about 86 times lower resistivity of 25 µΩm. Such a low resistivity is unacceptable for almost all applications.

Table 1B: With dopant

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
With 10 mol% V dopant (V_2O_5), no nanoparticles, 0.11 wt% silicate					
1-2	450/650°C (30/30min) @ 15000 ppm	5649	136.8	555	78.3
1-2	450/670°C (30/30min) @ 15000 ppm	309	137.1	561	Not measured

The results in table 1B indicates that the V dopant had improved the resistivity of the sample at the heat treatment at 650°C to 5649 μΩm, i.e., about 2.6 times that of sample 1-1. More importantly, the resistivity for the higher temperature heat treatment of 670°C is now 309 μΩm, which is more than 12 times higher than for sample 1-1 and only about 18 times lower than for sample 1-2 at the lower temperature of 650°C. Accordingly, the addition of the V dopant has affected the thermal stability of the coating on the core particles.

Table 1C: With nanoparticles

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
With 20mol% Y_2O_3 nanoparticles, no dopant, 0.11 wt% silicate					
1-3	450/650°C (30/30min) @ 15000 ppm	14841	134.8	510	81.5
1-3	450/670°C (40/30min) @ 5000 ppm	1758	132.1	522	81.3

The results in table 1C indicate that the addition of nanoparticles to the first coating increases resistivity (14841 μΩm for sample 1-3 at 650°C being about 6.9 times larger than the 2158 μΩm for sample 1-1 at 650°C). When the heat treatment is carried out at the higher temperature, 670°C, the resistivity is 1758 μΩm which is about 8.4 times smaller than for the lower temperature. Comparing tables 1A-1C it appears that the

dopant might have a higher impact on the thermal stability whereas the nanoparticles may have a higher impact on the general resistivity level.

Table 1D: With dopant and nanoparticles

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
With nanoparticles, with dopant, 0.11 wt% silicate					
1-4	5 mol% V_2O_5 + 10 mol% Y_2O_3 450/650°C (30/30min) @ 15000 ppm	22711	136.1	495	82.6
1-5	10 mol% V_2O_5 + 20 mol% Y_2O_3 450/650°C (30/30min) @ 15000 ppm	27216	139.9	465	83.5
1-4	5 mol% V_2O_5 + 10 mol% Y_2O_3 450/670°C (40/30min) @ 5000 ppm	7158	130.6	507	80.6
1-5	10 mol% V_2O_5 + 20 mol% Y_2O_3 450/670°C (40/30min) @ 5000 ppm	9345	133.0	483	80.8

The results in Table 1D indicate that the nanoparticles and dopant together provide high resistivity at both the lower and the higher heat treatment temperature. Moreover, the results indicate that the dopant provides for retaining a higher proportion of the resistivity when using the higher temperature. As an example, the resistivity at the 670°C heat treatment for the addition of 10 mol% V dopant, i.e., 9345 μΩm, is about 5.3 times larger than for sample 1-3 at the same temperature.

Table 1E: Higher silicate concentration and other temperatures

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
With 20 mol% Y_2O_3 nanoparticles, without dopant, 0.165 wt% silicate					
1-6	420/640°C (50/40min) @ 12000 ppm	32893	141.5	407	85.5

1-7	450/680°C (40/35min) @ 5000 ppm	1605	133.4	415	83.2
With 20 mol% Y_2O_3 nanoparticles, with 10 mol% V_2O_5, 0.165 wt% silicate					
1-6	420/640°C (50/40min) @ 12000 ppm	37613	139.2	406	84.6
1-7	450/680°C (40/35min) @ 5000 ppm	4187	133.3	421	82.2

Tables 1E shows results obtained for a higher concentration of silicate, i.e., a thicker first coating. The results show, similar to table 1D, that the addition of the dopant provides for retaining a higher proportion of the low temperature treatment resistivity also when using the even higher temperature of 680°.

In summary, these results show that the addition of the dopant alone, or preferably together with nanoparticles, provides better thermal stability and higher resistivity for a given coercivity level and coating density/thickness level.

Based on these results, it was decided to use a ferromagnetic powder composition wherein the first coating comprised 20 mol% Y_2O_3 nanoparticles and the silicate concentration was 0.11wt%, as a general reference when further evaluating the effect of the dopant in the following examples.

Example 2: The addition of a V dopant in the first coatings ensures an acceptable electrical resistivity also after heat treating at elevated temperatures.

Example 2 further tested the effects of adding a V dopant (in the form of V_2O_5) to the aqueous solution of the silicate in step 1 when producing the coated soft magnetic iron-based core particles in step 2. All samples further contained, in the first coating, Y_2O_3 nanoparticles (nominally 10 nm) at 20 mol% (based on the molar weight of K) and bismuth hydroxide ($Bi(OH_3)$) at a concentration of 0.12 wt%.

Table 2: Addition of V dopant

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
Heat treatment: 420/640°C (50/40 min), 12000 ppm					

Ref 1B	Reference 1B, no dopant	35295	141.5	407	85.5
2-1	Ref 1B + 5 mol% V dopant	24557	139.2	413	85.0
2-2	Ref 1B + 10 mol% V dopant	32589	139.2	406	84.6
2-3	Ref 1B + 15 mol% V dopant	28865	138.2	402	84.0
Heat treatment: 450/660°C (40/40 min), 12000 ppm					
Ref 1B	Reference 1B, no dopant	12989	133.1	410	83.7
2-1	Ref 1B + 5 mol% V dopant	10718	135.5	420	83.8
2-2	Ref 1B + 10 mol% V dopant	12734	135.7	413	83.7
2-3	Ref 1B + 15 mol% V dopant	12396	131.4	413	78.5
Heat treatment: 450/680°C (45/35 min), 5000 ppm					
Ref 1B	Reference 1B, no dopant	1605	133.4	415	83.2
2-1	Ref 1B + 5 mol% V dopant	3342	132.6	428	82.3
2-2	Ref 1B + 10 mol% V dopant	4187	133.3	421	82.2
2-3	Ref 1B + 15 mol% V dopant	6214	134.2	413	82.1
Heat treatment: 450/700°C (40/30 min), 5000 ppm					
Ref 1B	Reference 1B, no dopant	242	131.4	412	86.2
2-1	Ref 1B + 5 mol% V dopant	680	129.7	430	83.4
2-2	Ref 1B + 10 mol% V dopant	1889	131.6	419	82.7
2-3	Ref 1B + 15 mol% V dopant	2864	132.5	420	81.9

As seen from the results, the progressively higher maximum temperature in the heat treatment step provided progressively lower coercivity for the samples. This applied also to the samples in which the V dopant had been added. These latter samples however, and in contrast to the reference 1B sample, maintained an acceptable resistivity even at the highest maximum temperature of 700°C. Furthermore, the results show that the electrical resistivity increased with increasing content of dopant for each heat treatment. Adding the V dopant, preferably at least 5 mol%, more preferably 10 mol% or even more

preferably 15 mol%, to the solution used to obtain the first coating thus provides that parts manufactured from the ferromagnetic powder compositions can be heat treated at higher maximum temperatures, e.g. 680 and 700 °C so as to obtain coercivity values in the range of 132 to 134 while maintaining electrical resistivity values in the range of 1889 to 6214.

The successively lower coercivity values obtained for higher amounts of V points towards less stress being introduced in the coated soft magnetic iron-based core particles. Without wishing to be bound by theory, one possible mechanism is that the addition of the V_2O_5 compound to the solution used to obtain the first coating, and the subsequent surmised inclusion of VO_4^{3-} ions in the first coating, provides a more thermally stable first coating which is less susceptible to the formation of cracks during the heat treatment. The improved thermal stability may have different reasons. Without wishing to be bound by theory the dopant may i) enhance the specific electrical resistivity of the bismuth silicate glass. Higher specific resistivity of the glass would allow the use of a higher relaxation temperature that would decrease the viscosity of the formed glass that could facilitate an improved coverage of the particle surfaces. The effect of dopant may also ii) decrease the glass forming temperature, and/or iii) decrease the viscosity of the glass that may in turn facilitate the distribution and particle coverage of the glass, and/or iv) cause less change in volume during the heat treatment or cooling protocol, which thereby may cause less formation of cracks. Cracks would expose the soft magnetic iron-based core particles to oxidation that would cause a relative enhancement of coercivity during the heat treatment but also as a result of ageing during usage in an application involving elevated temperatures.

The distribution of the first coating is further facilitated by the nanoparticles, which inter alia acts are believed to prevent the formation of cracks during the drying of the first coating.

Regardless of the mechanism, the results show the advantage of including the V dopant in the first coating.

Example 3: Further experiments using different dopants

Further experiments were made to determine whether the dopant used in Example 2 could be replaced by other dopants while providing the same or similar improvement of the properties of the test part. Experiment parameters and results are presented in table 3.

Table 3: Other dopants

Sample	Constitution and conditions	Res	ΔRes (%)	Hc	μ-max	Total Core loss
Heat treatment: 420/640°C (50/40 min), 12000 ppm						
Ref 1B	Reference 1B, no dopant	35295	100	141.5	407	85.5
2-1	Ref 1B + 5 mol% V dopant (V_2O_5)	24557	100	139.2	413	85
3-1	Ref 1B + 5 mol% W (WO_3) dopant	19947	100	141.8	402	85
3-2	Ref 1B + 5 mol% Mo (MoO_3) dopant	16965	100	141.5	400	85.3
3-3	Ref 1B + 2.5 mol% Al ($Al(OH)_3$) dopant	25653	100	140.2	419	85.2
Heat treatment: 450/680°C (45/35 min), 5000 ppm						
Ref 1B	Reference 1B, no dopant	1605	5	133.4	415	83.2
2-1	Ref 1B + 5 mol% V dopant	3342	14	132.6	428	82.3
3-1	Ref 1B + 5 mol% W (WO_3) dopant	1283	6	134.0	414	83.2
3-2	Ref 1B + 5 mol% Mo (MoO_3) dopant	3206	19	137.5	408	83.3
3-3	Ref 1B + 2.5 mol% Al ($Al(OH)_3$) dopant	3616	14	135.4	426	83.1
Heat treatment: 450/700°C (40/30 min), 5000 ppm						
Ref 1B	Reference 1B, no dopant	242	0.7	131.4	412	86.2
2-1	Ref 1B + 5 mol% V dopant	680	3	129.7	430	83.4
3-1	Ref 1B + 5 mol% W (WO_3) dopant	-	-	-	-	-
3-2	Ref 1B + 5 mol% Mo (MoO_3) dopant	408	2	132.1	420	85.1

3-3	Ref 1B + 2.5 mol% Al ($Al(OH)_3$) dopant	413	2	130.2	432	83.5

As seen from the table, both the Mo (MoO_3) dopant and the Al ($Al(OH)_3$) dopant provides a higher resistivity than the reference at the heat treatment at 450/700°C. These dopants thus, similarly to V, allows heat treatment at higher temperatures to reach lower coercivity values while retaining acceptable resistivity values. W provides a similar, albeit lower, resistivity compared to the reference at 450/680°C but retains more of if its initial resistivity (6% vs 5% for the reference). It should also be noted that at the two highest temperatures all samples with dopants had a higher remaining resistivity percentage than the reference.

Example 4: Different amounts of nanoparticles

Further experiments were made to investigate the results obtained using dopants with different amounts of Y_2O_3 nanoparticles. Experiment parameters and results are presented in table 4.

Table 4: Different amounts of nanoparticles

Sample	Constitution and conditions	Res	Hc
Heat treatment: 450/670°C (45/35 min), 5000 ppm, 0.11 wt% silicate			
4-1	0.08% $Bi(OH)_3$, 0.4% Amide wax, 5 mol% Y_2O_3, 10 mol% V dopant.	11078	133.1
4-2	0.08% $Bi(OH)_3$, 0.4% Amide wax, 10 mol% Y_2O_3, 10 mol% V dopant.	9345	133.0
4-3	0.08% $Bi(OH)_3$, 0.4% Amide wax, 5 mol% Y_2O_3, 10 mol% Mo dopant.	8959	134.1
4-4	0.08% $Bi(OH)_3$, 0.4% Amide wax, 10 mol% Y_2O_3, 10 mol% Mo dopant.	4850	131.8

As seen from the table, the dopants are effective also with different amounts of nanoparticles.

Example 5: Effects of thermal ageing

Further experiments were made to determine the effect of thermal ageing on the properties of the test parts. As detailed by table 5A below, test parts manufactured from the powder produced with the 420/640°C, 450/680°C, and 450/700°C heat treatments were further held at 260°C for 5 days.

Table 5A: Effects of thermal ageing

Sample	Constitution	After thermal ageing at 260°C for 5 days		
		Res after / before ageing, % remaining	Hc after / before ageing, % increase	Core loss @ 1T/1kHz after / before ageing, % increase
Heat treatment: 420/640°C (50/40 min), 12000 ppm				
Ref 1B	Reference 1B, no dopant	2751 / 35295, 8%	153 / 141.5, +8%	90.1 / 85.5, +6%
5-1	Ref 1B + 5 mol% V_2O_5 dopant	2719 / 24557, 11%	150.4 / 139.2, +8%	89.7 / 85.0 = +6%
5-2	Ref 1B + 10 mol% V_2O_5 dopant	1919 / 32589, 6%	155.2 / 139.2, +11%	91.0 / 84.6 = +8%
5-3	Ref 1B + 15 mol% V_2O_5 dopant	1249 / 28865 = 4%	158.5 / 138.2 = +15%	92.6 / 84.0 = +10%
Heat treatment: 450/680°C (45/35 min), 5000 ppm				
Ref 1B	Reference 1B, no dopant	1182 / 1605, 74%	144.9 / 133.4 = +9%	87.9 / 83.2, +6%
5-1	Ref 1B + 5 mol% V_2O_5 dopant	1533 / 3342, 46%	144.5 / 132.6, +9%	87.3 / 82.3, +6%
5-2	Ref 1B + 10 mol% V_2O_5 dopant	1789 / 4187, 43%	145.4 / 133.3, +9%	86.9 / 82.2, +6%
5-3	Ref 1B + 15 mol% V_2O_5 dopant	1588 / 6214, 26%	150.4 / 134.2, +12%	88.5 / 82.1, +8%
Heat treatment: 450/700°C (40/30 min), 5000 ppm				

Ref 1B	Reference 1B, no dopant	191 / 242, 79%	145.4 / 131.4, +11%	92.5 / 86.2, +7%
5-1	Ref 1B + 5 mol% V_2O_5 dopant	450 / 680, 66%	150.8 / 129.7, +16%	91.2 / 83.4, +9%
5-2	Ref 1B + 10 mol% V_2O_5 dopant	947 / 1889, 50%	149.5 / 131.6, +14%	89.2 / 82.7, +8%
5-3	Ref 1B + 15 mol% V_2O_5 dopant	933 / 2864, 33%	150.9 / 132.5, +14%	89.1 / 81.9, +9%

As shown in the table, samples comprising the V dopant provided better ageing properties with higher resistivity values.

Further XRD experiments were made to examine the ratio of Fe-oxides vs Fe on the surface of the powder particles, as seen in table 5B below. The quantitative analysis of the crystal phases was made by Rietveld analysis using the Highscore Plus software from Malvern Panalytical. The analyzed specimen were the flat surfaces of the compacted test bars after being subjected to the different heat treatments.

Table 5B: XRD results of thermal ageing

Sample	Constitution	Surface Fe-oxide content before ageing at 260°C for 5 days
Heat treatment: 450/680°C (45/35 min), 5000 ppm		
Ref 1B	Reference 1B, no dopant	79%
5-1	Ref 1B + 5 mol% V dopant	23%
5-2	Ref 1B + 10 mol% V dopant	43%
5-3	Ref 1B + 15 mol% V dopant	50%

3-1	Ref 1B + 5 mol% W dopant	58%
3-2	Ref 1B + 5 mol% Mo dopant	27%

As shown in the table, the samples that did not include a dopant had higher FeOx/Fe-ratio than the samples that included a dopant. Consequently, a low ratio facilitates an improved ageing resistance of the heat-treated component thanks to an improved coverage of the glassy coating. This applied to all the tested dopants.

Example 6: Further experiments with increased amount of silicate in first coating

Further experiments were made to evaluate effects of dopant and further increased amount of silicate in the first coating. Experiment parameters and results are presented in table 6 below.

Table 6: Effects of silicate amount in the first coating

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
Heat treatment: 420/640°C (50/40 min), 12000 ppm					
Ref 1B	Reference 1B, no dopant	35295	141.5	407	85.5
6-1	Reference 1B, no dopant, 0.275 wt% silicate instead of 0.165 wt%	43242	142.4	390	89.2
2-2	Ref 1B + 10 mol% V_2O_5 dopant	32589	139.2	406	84.6
6-2	Ref 1B + 10 mol% V_2O_5 dopant, 0.275 wt% silicate instead of 0.165 wt%	65696	138.7	293	88.4
Heat treatment: 450/680°C (45/35 min), 5000 ppm					

3-1	Ref 1B + 5 mol% W dopant	58%
3-2	Ref 1B + 5 mol% Mo dopant	27%

As shown in the table, the samples that did not include a dopant had higher FeOx/Fe-ratio than the samples that included a dopant. Consequently, a low ratio facilitates an improved ageing resistance of the heattreated component thanks to an improved coverage of the glassy coating. This applied to all the tested dopants.

Example 6: Further experiments with increased amount of silicate in first coating

Further experiments were made to evaluate effects of dopant and further increased amount of silicate in the first coating. Experiment parameters and results are presented in table 7 below.

Table 6: Effects of silicate amount in first coating

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
Heat treatment: 420/640°C (50/40 min), 12000 ppm					
Ref 1B	Reference 1B, no dopant	35295	141.5	407	85.5
6-1	Reference 1B, no dopant, 0.275 wt% silicate instead of 0.165 wt%	43242	142.4	390	89.2
2-2	Ref 1B + 10 mol% V_2O_5 dopant	32589	139.2	406	84.6
6-2	Ref 1B + 10 mol% V_2O_5 dopant, 0.275 wt% silicate instead of 0.165 wt%	65696	138.7	293	88.4
Heat treatment: 450/680°C (45/35 min), 5000 ppm					

Ref 1B	Reference 1B, no dopant	1605	133.4	415	83.2
6-1	Reference 1B, no dopant, 0.275 wt% silicate instead of 0.165 wt%	5539	134.7	303	86.2
2-2	Ref 1B + 10 mol% V_2O_5 dopant	4187	133.3	421	82.2
6-2	Ref 1B + 10 mol% V_2O_5 dopant, 0.275 wt% silicate instead of 0.165 wt%	22582	133.9	298	85.8
Heat treatment: 450/700°C (40/30 min), 5000 ppm					
Ref 1B	Reference 1B, no dopant	242	131.4	412	86.2
6-1	Reference 1B, no dopant, 0.275 wt% silicate instead of 0.165 wt%	954	131.2	310	85.3
2-2	Ref 1B + 10 mol% V_2O_5 dopant	1889	131.6	419	82.7
6-2	Ref 1B + 10 mol% V_2O_5 dopant, 0.275 wt% silicate instead of 0.165 wt%	9240	130.7	301	87.0

As seen from the table, the higher concentration of silicate provides a generally increased resistivity at the cost of a lower μ-max.

Example 7: Further experiments using $Al(OH)_3$ as dopant

Aluminium, e.g., from $Al(OH)_3$, is an interesting dopant in that it has less environmental impact and presents a lesser health risk than V_2O_5. Accordingly, further experiments were made to evaluate effects of dopant and increased amount of silicate in the first coating. For these experiments, a silicate solution having a higher β/α ratio (3.82) was used to compensate for the decrease in β/α ratio when the $Al(OH)_3$ was dissolved with the help of extra KOH. Experiment parameters and results are presented in table 7 below.

Table 7: Further experiments with $Al(OH)_3$

Sample	Constitution and conditions	Res	Hc	μ-max	Total Core loss
Heat treatment: 420/640°C (50/40 min), 12000 ppm					
Ref 2	Reference 2, no dopant, 0.11% silicate, module 3.35, 0.4 wt% Awax	30062	136.8	491	82.1
7-1	Reference 2 + 0.85 mol% $Al(OH)_3$	12180	138.2	505	82.4
7-2	Reference 2 + 1.71 mol% $Al(OH)_3$	20526	138	481	82.3
7-3	Reference 2 + 2.58 mol% $Al(OH)_3$	10016	138.9	478	83.4
Ref 3	Reference 3, no dopant, 0.165% silicate, module 3.35	34339	137.7	427	83.6
7-4	Reference 3 + 1.71 mol% $Al(OH)_3$	35168	140.2	399	85.2
7-5	Reference 3 + 2.58 mol% $Al(OH)_3$	29266	140.7	401	85.2
Heat treatment: 450/660°C (40/35 min), 12000 ppm					
Ref 2	Reference 2, no dopant, 0.11% silicate, module 3.35	1166	132.3	503	81.1
7-1	Reference 2 + 0.85 mol% $Al(OH)_3$	663	133.9	518	82.3
7-2	Reference 2 + 1.71 mol% $Al(OH)_3$	864	132.8	493	81.9
7-3	Reference 2 + 2.58 mol% $Al(OH)_3$	609	135.4	492	83.5
Ref 3	Reference 3, no dopant, 0.165% silicate, module 3.35	259	136.2	438	86.9
7-4	Reference 3 + 1.71 mol% $Al(OH)_3$	1596	136.9	406	84.1
7-5	Reference 3 + 2.58 mol% $Al(OH)_3$	2287	137.1	405	84.3

As seen from the table, the Al dopant provided better resistivity than the reference at the higher temperature and higher silicate concentration. At the lower silicate concentration, the Al dopant provided lower but comparable resistivity to the reference.

Example 8: Variations of non-dopant constituents

Further experiments were made to evaluate variations in the other components of the first coating in the absence of the dopant. Heat treatment was 450/650°C (30/30min). The results are shown in table 8 below:

Table 8: Variations of non-dopant constituents

Sample	Constitution and conditions	GS	TRS	d	Res	μ-max	Hc	Total core loss
No nanoparticle or dopant results in a comparatively low resistivity.								
8-1	Ref0: (0.1 wt% Bi_2O_3), no nanoparticles, no dopant	-	-	-	1435	456	135.0	81.2
Different compounds of bismuth and oxygen and different concentrations provide comparable resistivity values with a preference for $Bi(OH)_3$.								
8-2	ref1: 0.1 wt% Bi_2O_3 + 20 mol% Y_2O_3, AD3.32	9.1	58	7.46	9072	477	138.2	79.9
8-3	ref2: 0.08 wt% $Bi(OH)_3$ + 20 mol% Y_2O_3	9.6	56	7.46	13253	475	138.9	79.4
Different sizes of nanoparticle have a limited effect on resistivity although smaller sizes are preferred.								
8-4	20 mol% Y_2O_3 nominally 30-50 nm.	10.8	55	7.49	7699	535	133.0	Not measured
8-5	20 mol% Y_2O_3 experimentally determined as 200 nm	11.2	64	7.47	13519	525	133.0	Not measured
Different types and concentration of nanoparticle provide different, but generally useable, resistivity results compared to 20 mol% Y_2O_3.								
8-6	10 mol%Y_2O_3 + 0.1 wt% Bi_2O_3	-	-	-	657	665	131.3	78.2

8-7	As ref3 but 1 mol% ZrO_2 instead of 20 mol% Y_2O_3	9.0	57	7.49	1844	525	131.4	76.1
8-8	As ref3 but 2.5 mol% ZrO_2 instead of 20 mol% Y_2O_3	9.0	68	7.48	8333	502	133.3	76.7
8-9	As ref2 but 10 mol% ZrO_2 instead of 20 mol% Y_2O_3	9.1	58	7.46	2080	526	133.8	78.0
8-10	As ref1 but 10 mol% $Mg(OH)_2$ instead of 20 mol% Y_2O_3, and AD3.34	8.4	51	7.46	4154	514	133.6	77.9
8-11	As ref1 but 20 mol% $Mg(OH)_2$ instead of 20 mol% Y_2O_3, and AD3.34	9.1	55	7.46	5760	518	135.6	78.4
8-12	As ref2 but 10 mol% $CaCO_3$ instead of 20 mol% Y_2O_3	11.3	67	7.48	2536	553	137.5	79.7
8-13	As Ref3 but 2.5 mol% ZnO instead of 20 mol% Y_2O_3	9.0	60	7.49	7208	522	132.3	76.4
8-14	As ref1 but 20 mol% ZnO instead of 20	9.3	55	7.47	2567	522	137.7	78.6

	mol% Y_2O_3, and AD3.34							
8-15	As ref3 but 20 mol% MgO instead of 20 mol% Y_2O_3	8.0	60	7.49	13568	504	133.6	76.9
8-16	As ref3 but 20 mol% TiO_2 (anatase) instead of 20 mol% Y_2O_3	9.0	65	7.49	12322	494	131.9	76.8
8-17	As ref3 but 10 mol% Al_2O_3 instead of 20 mol% Y_2O_3	9.0	63	7.48	8737	514	138.0	77.7
Different metal-organic compounds in the second coating provide similar resistivity values.								
8-18	Ref (0.15% Dynasylan® 1146)	-	66	7.48	12166	501	134	82.4
8-19	0.15% Dynasylan® HYDROSIL 2776 (water-borne)	-	44	7.50	11231	508	131	82.1
8-20	0.30% Dynasylan® HYDROSIL 2776 (water-borne)	-	57	7.49	13549	529	131	82.1
Different core particle dimensions, 450/650°C (30/30min)).								
8-21	40 mesh, AD3.0, 0.05 wt% silicate with β/α=3.2, 20 mol% Y_2O_3 + 0.04 wt% $Bi(OH)_3$	18.3	67.6	7.53	696	631	124	104

8-22	As sample 9.22 but 100 mesh, AD 3.0 g/cm^3, 0.2 wt% silicate with β/α=3.2, 20 mol% Y_2O_3 + 0.08 wt% $Bi(OH)_3$	24.3	71.9	7.41	1719	375	181	105

As seen from the above results, the non-dopant constituents of the ferromagnetic powder composition can be varied widely.

Example 9: Schematic cross-sectional illustration of the particles of the ferromagnetic powder composition

Based on the examples above, Fig. 1 shows a highly schematical cross-sectional illustration of a single particle 10 of a ferromagnetic powder composition according to an embodiment of the first aspect of the technology proposed herein. The particle 10 comprises a soft magnetic iron-based core particle 11 covered by a first coating 12 comprising a silicate. A second coating 13 is also shown and comprises a metal-organic compound. Particles of a compound comprising bismuth and oxygen and having approximate diameters of about 1 µm, one of which is designated the reference numeral 14, are shown dispersed within the first coating 12. Additionally, nanoparticles having an approximate diameter of about 10-200 nm, one of which is designated the reference numeral 15, are also shown dispersed within the first coating 12. Finally, as designated by the reference numeral 16, a dopant is schematically shown dissolved in the silicate of the first coating 11.

Fig. 1 shows the particle prior to heat treatment, i.e., prior to the ferromagnetic powder being compacted and heat treated to manufacture an object as per the method according to the fourth aspect of the technology proposed herein. During heat treatment the particles of the compound comprising bismuth and oxygen 14 together with the nanoparticles 15 and the silicate with its dissolved dopant 16 in the first coating 12 and the amino and/or alkyl groups of the metal-organic compound of the second coating 13 are believed to form an evenly distributed glassy coating (bismuth-silicate glass) which provides electrical resistivity and improved mechanical strength between the individual particles of the compacted and heat treated ferromagnetic powder composition.

Although Fig. 1 shows the particles of the compound comprising bismuth and oxygen 14 being present in the first coating 12, it is contemplated that the particles of the compound comprising bismuth and oxygen 14 may additionally be dispersed within the second coating 13 or divided between the first and second coatings.

Further, although Fig. 1 shows the first coating 12 and the second coating 13 completely covering the soft magnetic iron-based core particle 11, one or both of these coatings may alternatively cover the soft magnetic iron-based core particle 11 only partially.

Example 10: Addition of alloyed soft-magnetic powder to the ferromagnetic powder composition

Further experiments were made to evaluate the effect of adding a further ferromagnetic powder composition, specifically an iron-silicon powder (6.8wt Si), to a ferromagnetic powder composition comprising core particles consisting of essentially pure iron. The core particles consisting of essentially pure iron were coated according to the procedure described in example 1 (0.1375 wt% silicate and 15 mol% V). The alloyed iron-silicon soft magnetic core particles of the further ferromagnetic powder composition ("FeSi") were separately coated with 0.11wt% silicate (sample 9-3), or treated with phosphoric acid diluted in acetone (sample 9-4).

The compaction of the reference (incl. 0.3% amide wax) was done at 1100 MPa (die temperature 100C) and the heat treatment at maximum 700°C. The mixtures including alloyed powder (sample 9-2 to 9-4, incl. 0.1% amide wax) were instead compacted at 1600MPa using die wall lubrication (DWL; die temperature 60C) and heat treated at maximum 740°C. The results are shown in table 9 below:

Table 9: Addition of alloyed soft-magnetic powder

Sample	Mix	HT	TRS	Res	B10	μ-max	Hc	Total core loss	DC
9-1	Ref	700°C, 3000 ppm O_2	48.4	13846	1.60	488	106	76.4	51.3
9-2	30% FeSi	740°C, 1500 ppm O_2	28.3	1289	1.48	379	103	79.1	52.0
9-3	50% FeSi	740°C, 1500 ppm O_2	11.6	1984	1.34	239	95	77.6	48.0
9-4	50% FeSi	740°C, 1500 ppm O_2	13.9	6229	1.46	343	94	70.4	46.4

The reference sample (9-1) shows excellent density and mechanical strength, however, the coercivity and DC-loss is higher compared to the alloyed mixtures. Sample 9-2, mixed with 30% FeSi-powder, can reduce the coercivity slightly. However, due to the decreased density (and permeability μmax), the DC-loss remains similar as the reference. By introducing 50% coated FeSi-powder, it is shown that the DC-loss can be reduced significantly, see sample 9-3. The sample 9-4, incl. 50% phosphate-coated FeSi-powder and a relatively thicker silicate coating on the essentially pure iron powder (0.165wt%), shows improved total core loss and DC-loss as compared to the reference sample.

Example 11: Increased mechanical strength

Further experiments were made to evaluate factors influencing the mechanical strength of objects and components produced from the ferromagnetic powder composition. Achieving higher mechanical strength, e.g. as measured by transverse rupture strength (TRS), without sacrificing magnetic properties, can allow the components to be used in more tough environments, such as in high-speed motors or for heavy-duty robotics. Briefly, it was found in this example that by modifying the heat treatment parameters, the mechanic and magnetic properties could be tailored to better meet the requirements of different applications.

Below in table 10, examples of different heat treatment protocols are listed. The ferromagnetic powder composition was as generally described above with 0.11 wt% silicate. The lubricant was amide wax (EBS).

The standard treatment (Ref.) is performed in a fixed atmosphere where the internal lubricant is carefully removed (ca 400°C, 20min), directly followed by the curing and stress relaxation treatment (615°C, 20min). The fixed atmosphere is normally between 0.5~1.5% oxygen (5000-15000 ppm) in nitrogen. By instead performing the delubrication in inert atmosphere (e.g. nitrogen), followed by a separate relaxation step at 615°C, 20min in 0.5% oxygen (5000 ppm), the TRS is increased (A). However, by also introducing a pre-oxidation step in ambient air at between 200~250C (i.e. below the vaporization temperature of the lubricant), the resistivity is improved (C, E-I). Increasing the oxygen concentration slightly in the last relaxation step, the TRS is further improved without increasing the coercivity (D vs. E). Sample F and H provide the highest TRS.

It appears that the pre-oxidation helps the lubricant to burn off and/or vaporize in a beneficial way. Table 10 also shows that during the de-lubrication, it is beneficial to avoid oxygen in the furnace atmosphere, otherwise the coercivity increases due to oxidation of

the ferromagnetic powder composition (D). It should also be avoided to delubricate during the relaxation treatment, followed by the oxidation treatment in 1.5% oxygen (15000 ppm)(J).

Table 10: Heat treatments

Sample	Heat treatment	TRS	Res	B10	μ-max	Hc	Total core loss
Ref	400°C, 20min, 1% O_2 615°C, 20 min, 1% O_2	62	14562	1.58	528	135	82.1
A	450°C, 30 min, 100% N_2 615°C, 20 min, 0.5% O_2	103	3903	1.58	481	137	84.4
B	220°C, 18h, Air 615°C, 20 min, 0% O_2	70	1874	1.59	482	138	83.0
C	250°C, 1h, Air 450°C, 30 min, 100% N_2 615°C, 20 min, 0.5% O_2	91	8705	1.58	491	137	83.4
D	250°C, 1h, Air 450°C, 20 min, 1% O_2 625°C, 20 min, 0.5% O_2	100	13894	1.54	423	147	87.2
E	220°C, 18h, Air 450°C, 30 min, 100% N_2 615°C, 20 min, 0.5% O_2	110	10671	1.58	477	141	84.6
F	220°C, 18h, Air 450°C, 30 min, 100% N_2 615°C, 20 min, 1.5% O_2	124	6602	1.58	475	141	84.9
G	220°C, 2h, Air 450°C, 30 min, 100% N_2 615°C, 20 min, 1.5% O_2	111	4840	1.58	476	152	88.8
H	210°C, 30h, Air 450°C, 30 min, 100% N_2 615°C, 20 min, 1.5% O_2	128	5803	1.58	465	152	89.0

I	220°C, 18h, Air 450°C, 30 min, 100% N_2 600°C, 40 min, 1.5% O_2	117	7414	1.57	458	145	87.1
J	220°C, 18h, Air 615°C, 20 min, 100% N_2 400°C, 1h, 1.5% O_2	93	320	1.58	468	152	95.5

Feasible modifications of the technology proposed herein

The technology proposed herein is not limited to the embodiments described above and shown in the drawings, which primarily have an illustrative and exemplifying purpose. This patent application is intended to cover all adjustments and variants of the preferred embodiments described herein, thus the present invention is defined by the wording of the appended claims and the equivalents thereof.

Throughout this specification and the claims which follows, unless the context requires otherwise, the word “comprise”, and variations such as “comprises” or “comprising”, will be understood to imply the inclusion of a stated integer or steps or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

Claims

1. A ferromagnetic powder composition comprising:

(i) soft magnetic iron-based core particles, and

(ii) a first coating at least partially covering and being in direct contact with the surface of the core particles, the first coating comprising:

a. a silicate of the general formula $(K_2O)\alpha(SiO_2)\beta$, wherein α is moles of K_2O, β is moles of SiO_2, and the β/α molar ratio is in the interval from 0.5 to 4.1,

i. wherein the silicate is present in an amount of 0.02 to 1.0 wt% calculated based on the total weight of the ferromagnetic powder composition,

b. optionally, particles of a compound comprising bismuth and oxygen having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm, and,

c. a dopant dissolved as an oxo- or hydroxy-anion in the silicate (a).

2. The ferromagnetic powder composition according to claim 1, wherein the first coating further comprises nanoparticles having a D_{50} measured according to ISO 13320-1 of 10-200 nm, or alternatively having a specific surface area (SSA) of 6-120 m^2/g as determined according to ISO 9277:2022.

3. The ferromagnetic powder composition according to claim 2, wherein the nanoparticles are selected from the group consisting of Y_2O_3 nanoparticles, ZrO_2 nanoparticles, ZnO nanoparticles, $Mg(OH)_2$ nanoparticles, MgO nanoparticles, $CaCO_3$ nanoparticles, Al_2O_3 nanoparticles, SiO_2 nanoparticles, and TiO_2 nanoparticles, and wherein the nanoparticles preferably comprise or consist of Y_2O_3 nanoparticles.

4. The ferromagnetic powder composition according to any of the claims 2-3, wherein the content of nanoparticles in the first coating is 1-30 mol%, preferably 1-20 mol% based on the molar content of K (Potassium) in the first coating.

5. The ferromagnetic powder composition according to any of the claims 2-4, wherein the nanoparticles comprise or consist of Y_2O_3 nanoparticles and wherein the content of nanoparticles in the first coating is 10-20 mol% based on the molar content of K (Potassium) in the first coating.

6. The ferromagnetic powder composition according to any preceding claim, wherein the dopant comprises at least one element from group 5, such as V (Vanadium) or Nb (Niobium), or comprises at least one element from group 6, such as Cr (Chromium), W (tungsten), or Mo (Molybdenum), or comprises Al (Aluminium) or P (Phosphorus).

7. The ferromagnetic powder composition according to any preceding claim, wherein:

- the dopant comprises V and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K (Potassium) in the first coating,

- the dopant comprises Nb and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises Cr and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises Mo and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises W and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating,

- the dopant comprises Al and the content of dopant in the first coating is 0.5-5 mol%, preferably 1-3 mol%, more preferably 1.71-2.58 mol% based on the molar content of K in the first coating, and/or,

- the dopant comprises P and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 5-15 mol%, based on the molar content of K in the first coating.

8. The ferromagnetic powder composition according to any preceding claim, wherein the dopant comprises V and the content of dopant in the first coating is 1-30 mol%, preferably 5-20 mol%, more preferably 10-15 mol%, based on the molar content of K in the first coating.

9. The ferromagnetic powder composition according to any preceding claim, wherein the β/α molar ratio is in the interval from 2.0 to 4.1.

10. The ferromagnetic powder composition according to any preceding claim, wherein the first coating comprises particles of a compound comprising bismuth and oxygen having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm.

11. The ferromagnetic powder composition according to any preceding claim, wherein the oxo- or hydroxy-anion of the dopant is a mono anion.

12. The ferromagnetic powder composition according to any preceding claim, further comprising:

(iii) a second coating at least partially covering the surface of the core particles and/or the first coating, the second coating comprising:

a. at least one metal-organic compound having the general formula

$$R_1[(R_1)_x(R_2)_y(M)]_nO_{n-1}R_1 \qquad (I)$$

or

$$R_2[M(OH)_{2(n+1)}]_{(n+1)}O_{(n)}R_2 \qquad (II)$$

wherein M is selected from the group consisting of Si, Ti, Al, and Zr; O is oxygen; R_1 is a hydrolysable group; R_2 is an organic moiety and wherein at least one R_2 contains at least one nitrogen containing group, preferably an amino group; wherein n is the number of repeating units being an integer between 1 and 20; wherein x is 0 or 1; and wherein y is 1 or 2, and x+y is 2,

wherein the content of the at least one metal-organic compound is 0.05 to 0.40 wt%, preferably 0.10 to 0.30 wt%, based on the total weight of the ferromagnetic powder composition.

13. A ferromagnetic powder mixture comprising:

- the ferromagnetic powder composition according to any preceding claim, and

- a further ferromagnetic powder composition,

wherein the further ferromagnetic powder composition comprises soft magnetic iron-based core particles that are different from the soft magnetic iron-based core particles of the ferromagnetic powder composition, and

wherein preferably the soft magnetic iron-based core particles of the further ferromagnetic powder composition comprise or consist of an iron alloy having a higher electrical resistivity and/or hardness than the soft magnetic iron-based core particles of the ferromagnetic powder composition.

14. The ferromagnetic powder mixture according to claim 13, wherein the soft magnetic iron-based core particles of the further ferromagnetic powder composition comprise or consist of an iron alloy selected from the group consisting of FeSi, FeAl, FeSiAl, FeNi, FeCo, and FeNiCo, or combinations or mixtures of such alloys.

15. The ferromagnetic powder mixture according to claim 14, wherein the iron alloy is selected from the group consisting of FeSi, preferably with 3-6.8 wt% Si, and FeSiAl, preferably with 9 wt% Si and 6 wt% Al or 3.5wt% Si and 3wt% Al.

16. The ferromagnetic powder mixture according to any of the claims 13-15, wherein the content of the further ferromagnetic powder composition is up to 90 wt%, such as 30-60 wt% or 10-50 wt%, preferably 20-40 wt%, such as 20-30 wt%, or alternatively 40-60 wt%, such as 45-55 wt%, based on the weight of the ferromagnetic powder mixture.

17. A method of producing a ferromagnetic powder composition comprising the steps of:

(i) providing soft magnetic iron-based core particles,

(ii) contacting the soft magnetic iron-based core particles with a first aqueous solution comprising:

a. a silicate of the general formula $(K_2O)\alpha(SiO_2)\beta$, wherein α is moles of K_2O, β is moles of SiO_2, and the β/α molar ratio is in the interval from 0.5 to 4.1,

i. wherein the silicate is present in an amount of 0.02 to 1.0 wt% calculated based on the total weight of the ferromagnetic powder composition,

b. optionally, particles of a compound comprising bismuth and oxygen having a D_{50} measured according to ISO 13320-1 in the interval of 0.1 to 10 µm,
c. a dopant dissolved as an oxo- or hydroxy-anion in the silicate (a), and
d. optionally, nanoparticles having a D_{50} measured according to ISO 13320-1 of 10-200 nm, or alternatively having a specific surface area (SSA) of 6-120 m^2/g as determined according to ISO 9277:2022.

18. The method according to claim 17, further comprising one or more of the steps of:

(iii) drying the soft magnetic iron-based core particles, and/or
(iv) contacting the soft magnetic iron-based core particles with at least one metal-organic compound having the general formula

$$R_1[(R_1)_x(R_2)_y(M)]_nO_{n-1}R_1 \qquad (I)$$

or

$$R_2[M(OH)_{2(n+1)}]_{(n+1)}O_{(n)}R_2 \qquad (II)$$

wherein M is selected from the group consisting of Si, Ti, Al, and Zr; O is oxygen; R_1 is a hydrolysable group; R_2 is an organic moiety and wherein at least one R_2 contains at least one nitrogen containing group, preferably an amino group; wherein n is the number of repeating units being an integer between 1 and 20; wherein x is 0 or 1; and wherein y is 1 or 2, and x+y is 2,
wherein the content of the at least one metal-organic compound is 0.05 to 0.40 wt%, preferably 0.10 to 0.30 wt%, based on the total weight of the ferromagnetic powder composition, and/or
(v) mixing the soft magnetic iron-based core particles with a lubricant, preferably a particulate lubricant.

19. A method of manufacturing an object from the ferromagnetic powder composition according to any of the claims 1-12 or the ferromagnetic powder mixture according to any of the claims 13-16, comprising the steps of:

(i) compacting the ferromagnetic powder composition according to any of the claims 1-12 or the ferromagnetic powder mixture according to any of the claims 13-16 in

a die at a compaction pressure in the range of 300-2000 MPa, preferably 400-1200 MPa, to obtain a compacted part, and

(ii) heat treating the compacted part in a nonreducing atmosphere, preferably comprising 0-22 wt%, more preferably 0.5 to 2 wt% oxygen (O_2) at a temperature in the range of 300-800 °C, preferably 400-750 °C, more preferably 600-700 °C, to obtain the object.

20. The method according to claim 19, wherein step (ii) comprises heat treating the compacted part at a temperature of 670-700 °C, preferably 680-700 °C.

21. An object comprising a compacted ferromagnetic powder composition according to any of the claims 1-12 or a compacted ferromagnetic powder mixture according to any of the claims 13-16.

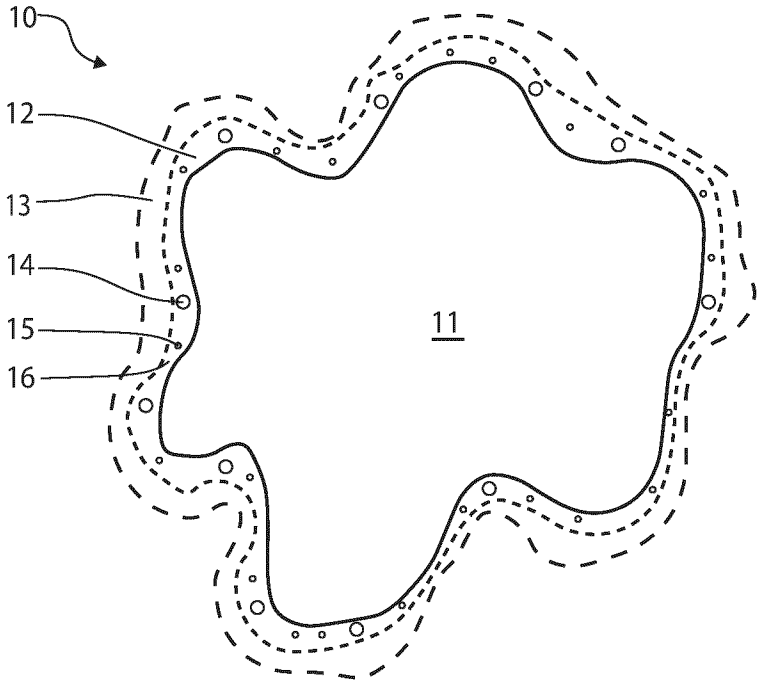


Fig. 1

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/080274

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01F1/33 H01F1/24 H01F3/08 H01F41/02 B22F1/052
B22F1/142 B22F1/16 B22F3/10
ADD. H01F1/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BE 440 486 A (BELL) 31 March 1941 (1941-03-31)	1,17,
A	page 3, lines 12-22 page 4, lines 1-3 page 8, lines 6-8 claims 2, 4-14	19-21 2-16,18

A	US 2014/319406 A1 (SUETSUNA ET AL) 30 October 2014 (2014-10-30) paragraph [0067]	1-21

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 December 2024	19/12/2024

Name and mailing address of the ISA/	Authorized officer
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1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2024/080274

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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