

Description

Magnet core and method for its production

The invention relates to a magnet core pressed using an alloy powder and a pressing additive to form a composite. It further relates to a method for producing a magnet core of this type.

The use of powder cores made from iron or alloy powder has been established for many years. Amorphous or nanocrystalline alloys, too, are increasingly used, being superior to crystalline powders, for example in their remagnetisation properties. Compared to amorphous powders, nanocrystalline powders offer the advantage of higher thermal stability, making magnet cores made from nanocrystalline powders suitable for high operating temperatures.

The raw material for nanocrystalline powder cores typically is an amorphous strip or a strip material made nanocrystalline by heat treatment. The strip, which is usually cast in a rapid solidification process, first has to be mechanically pulverised, for example in a grinding process. It is then pressed together with an additive in a hot or cold pressing process to form composite cores. The finished pressings may then be subjected to heat treatment for turning the amorphous material into nanocrystalline material.

EP 0 302 355 B1 discloses a variety of methods for the production of nanocrystalline powders from iron-based alloys. The amorphous strip is pulverised in vibratory or ball mills.

US 6,827,557 discloses a method for the production of amorphous or nanocrystalline powders in an atomising process. This method involves the problem that the cooling rate of the melt depends heavily on particle size and that the cooling rates required for a homogenous amorphous microstructure are often not obtainable, in particular with

larger particles. This results in powder particles with a strongly varying degree of crystallisation.

The level of iron losses is an important characteristic of magnet cores. Two factors contribute to iron losses, these being frequency-dependent eddy-current losses and hysteresis losses. In applications such as storage chokes or filter chokes, for instance, iron losses at a frequency of 100 kHz and a modulation of 0.1 T are relevant. In this typical range, iron losses are dominated by hysteresis losses.

The invention is therefore based on the problem of specifying a magnet core made from an alloy powder with minimal hysteresis losses and therefore low iron losses.

In addition, the present invention is based on the problem of specifying a method suitable for the production of a magnet core of this type.

According to the invention, this problem is solved by the subject matter of the independent patent claims. Advantageous further developments of the invention form the subject matter of the dependent patent claims.

In a composite magnet core according to the invention made from a powder of nanocrystalline or amorphous particles and a pressing additive, the particles have first surfaces represented by the original surfaces of a nanocrystalline or amorphous strip and second surfaces represented by surfaces produced in a pulverisation process. The overwhelming majority of these second surfaces are essentially smooth cut or fracture surfaces without any plastic deformation, the proportion T of areas of plastic deformation of the second surfaces being $0 \leq T \leq 0.5$.

The invention is based on the perception that the characteristics of the individual powder particles, in particular their fracture or surface characteristics, significantly affect the properties of the finished magnet core. It has been found that the surfaces of particles produced by pulverisation, for example of strip material, include areas of major plastic deformation. Mechanical stresses developing in these deformed areas

result in undesirably high hysteresis losses. In addition, a high energy input in the pulverisation process leads to structural damage and the formation of nuclei for crystallite.

In the pressing process, too, mechanical stresses are introduced into the magnet core, and mechanical distortion due to different coefficients of thermal expansion for the powder and the pressing additive is possible. These stresses can, however, be reduced to an insignificant level by subsequent heat treatment.

Structural damage caused by deformation at the particle surface, however, cannot be repaired. For this reason, it has to be avoided largely in advance to reduce iron losses.

The proportion T of areas of plastic deformation of the particle surfaces is expediently limited to $0 \leq T \leq 0.2$.

By reducing mechanical stresses, in particular by reducing plastic deformation at the particle surfaces, cycle losses P of $P \leq 5 \mu\text{Ws}/\text{cm}^3$, preferably $P \leq 3 \mu\text{Ws}/\text{cm}^3$, are obtainable.

The nanocrystalline particles expediently have the alloy composition $(\text{Fe}_{1-a}\text{M}_a)_{100-x-y-z-\alpha-\beta-\gamma}\text{Cu}_x\text{Si}_y\text{B}_z\text{M}'_\alpha\text{M}''_\beta\text{X}_\gamma$, wherein M is Co and/or Ni, wherein M' is at least one element from the group consisting of Nb, W, Ta, Zr, Hf, Ti and Mo, wherein M'' is at least one element from the group consisting of V, Cr, Mn, Al, elements of the platinum group, Sc, Y, rare earths, Au, Zn, Sn and Re, wherein X is at least one element from the group consisting of C, Ge, P, Ga, Sb, In, Be und As, and wherein a, x, y, z, α , β and γ are specified in atomic percent and meet the following conditions: $0 \leq a \leq 0.5$; $0.1 \leq x \leq 3$; $0 \leq y \leq 30$; $0 \leq z \leq 25$; $0 \leq y+z \leq 35$; $0.1 \leq \alpha \leq 30$; $0 \leq \beta \leq 10$; $0 \leq \gamma \leq 10$.

As an alternative, the particles may have the alloy composition $(\text{Fe}_{1-a-b}\text{Co}_a\text{Ni}_b)_{100-x-y-z}\text{M}_x\text{B}_y\text{T}_z$, wherein M is at least one element from the group consisting of Nb, Ta, Zr, Hf, Ti, V and Mo, wherein T is at least one element from the group consisting of Cr,

W, Ru, Rh, Pd, Os, Ir, Pt, Al, Si, Ge, C and P, and wherein a, b, x, y and z are specified in atomic percent and meet the following conditions: $0 \leq a \leq 0.29$; $0 \leq b \leq 0.43$; $4 \leq x \leq 10$; $3 \leq y \leq 15$; $0 \leq z \leq 5$.

The compositions listed above include alloys such as $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$ and the non-magnetostrictive alloy $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{15.5}\text{B}_7$.

A possible alternative are amorphous particles of the alloy composition $\text{M}_\alpha\text{Y}_\beta\text{Z}_\gamma$, wherein M is at least one element from the group consisting of Fe, Ni and Co, wherein Y is at least one element from the group consisting of B, C and P, wherein Z is at least one element from the group consisting of Si, Al and Ge, and wherein α , β and γ are specified in atomic percent and meet the following conditions: $70 \leq \alpha \leq 85$; $5 \leq \beta \leq 20$; $0 \leq \gamma \leq 20$. Up to 10 atomic percent of the M component may be replaced by at least one element from the group consisting of Ti, V, Cr, Mn, Cu, Zr, Nb, Mo, Ta und W and up to 10 atomic percent of the (Y+Z) component may be replaced by at least one element from the group including In, Sn, Sb und Pb. These conditions are for example met by the alloy $\text{Fe}_{76}\text{Si}_{12}\text{B}_{12}$.

One possible pressing additive is glass solder, and ceramic silicates and/or thermo-setting resins such as epoxy resins, phenolic resins, silicone resins or polyimides may also be used.

The magnet core according to the invention offers the advantage of significantly reduced iron losses compared to conventional powder composite cores, which can be ascribed to a reduction of the frequency-independent proportion of the losses, i.e. the hysteresis losses. The magnet core according to the invention can be used in inductive components such as chokes for correcting the power factor (PFC chokes), in storage chokes, filter chokes or smoothing chokes.

According to the invention, a method for the production of a magnet core comprises the following steps: first, a strip or foil of a typically amorphous, soft magnetic alloy is made available. The strip or foil may, however, alternatively be nanocrystalline.

The term “strip” in this context includes fragments of strip or a roughly – i.e. without a particularly high energy input – crushed strip, for example flakes. The strip or foil is pulverised using a technique which causes a minimum of structural damage. This process is usually based on cutting and/or breaking. The aim is a pulverisation process with minimum energy input. For this purpose, the powder particles are removed from the pulverising chamber on reaching their final grain size, the dwell time t in the pulverising chamber preferably being $t < 60$ s. The powder produced in this way is then mixed with at least one pressing additive and pressed to form a magnet core.

As a result of the short pulverisation process, the energy input into the powder particles produced, which would cause their plastic deformation, is kept to a minimum. As the strip is not pulverised by crushing or grinding, but mainly by cutting, those surfaces of the powder particles which represent new particle surfaces following pulverisation are largely smooth cut or fracture surfaces without any plastic deformation. Mechanical distortion, which would result in undesirably high hysteresis losses which cannot be reversed by heat treatment to the required degree, are in this production method avoided from the start.

Before pulverisation, the strip or foil is expediently made brittle by heat treatment, so that it can be pulverised even more easily and with a lower energy input. The amorphous strip can be converted into coarse-grained powder fractions at a temperature T_{mill} of $-195^{\circ}\text{C} \leq T_{\text{mill}} \leq 20^{\circ}\text{C}$, because such low temperatures improve grindability, thus further reducing the energy input of the process.

After pressing, the magnet core is expediently subjected to a heat treatment process, whereby distortions caused by the different coefficients of thermal expansion of powder and additive or pressing stresses can be eliminated. The heat treatment of the pressed magnet core also enables its magnetic properties to be adjusted as required.

In order to produce a magnet core of maximum homogeneity with defined properties, the powder is expediently subjected to a separation or grading process following

pulverisation. Different size fractions of powder particles are then processes separately.

Example 1

In one embodiment of the method according to the invention, strip was produced from an $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$ alloy in a quick solidification process, followed by thermal embrittlement and pulverisation with minimum energy input, largely by cutting action. For comparison, strip produced in the same way was pulverised by conventional methods. The fracture surfaces or particle surfaces of the powder particles produced according to the invention showed virtually no plastic deformation, while the conventionally produced powder particles exhibited major deformation. Booth powders were graded, and identical fractions were mixed with 5 percent by weight of glass solder as pressing additive. In a uniaxial hot pressing process, the mixtures were pressed to form powder cores at a temperature of 500°C and a pressure of 500 MPa. The cycle losses of the magnet cores produced by these processes were then determined. The cycle losses correspond to the hysteresis losses during a complete magnetisation cycle. Cycle losses are determined by dividing the losses through frequency and by forming limit values for vanishing frequencies. Cycle losses depend on maximum modulation, but no longer on remagnetisation frequency.

Cycle losses following the pressing process were approximately $16 \mu\text{Ws}/\text{cm}^3$ for conventionally produced magnet cores and approximately $15.8 \mu\text{Ws}/\text{cm}^3$ for magnet cores produced according to the invention.

After pressing, the magnet cores were subjected to one hour's heat treatment at 520°C to effect a nanocrystallisation of the powder particles. Following this, the cycle losses were once again determined. They were approximately $5.5 \mu\text{Ws}/\text{cm}^3$ for conventionally produced magnet cores and approximately $2 \mu\text{Ws}/\text{cm}^3$ for magnet cores produced according to the invention. During the heat treatment process, the stresses induced by pressing into the magnet core are therefore largely eliminated, and at the same time, the heat treatment effects the nanocrystallisation of originally amorphous structures and thus the adjustment of good magnetic properties. Following this, the

hysteresis losses of the finished nanocrystalline powder cores are virtually exclusively determined by the characteristics of the fracture or particle surfaces.

Example 2

In a further embodiment of the method according to the invention, strip was likewise produced from an $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$ alloy in a quick solidification process, followed by thermal embrittlement and pulverisation with minimum energy input, largely by cutting action, in less than 60 s. For comparison, strip produced in the same way was pulverised with high energy input and a duration of more than 600 s. Once again, the fracture surfaces or particle surfaces of the powder particles produced according to the invention showed virtually no plastic deformation, while the conventionally produced powder particles exhibited major deformation.

As in the first example, the powders were graded and pressed together with glass solder to form magnet cores. After a heat treatment process as described above, the cycle losses of the magnet cores were determined. Magnet cores produced from different size fractions of powder particles were investigated separately in order to take account of the effect of particle size. For particles with a diameter of 200-300 μm , the cycle losses of the magnet cores according to the invention amounted to 2.3 $\mu\text{Ws}/\text{cm}^3$ and for comparable cores produced by conventional means to 4.3 $\mu\text{Ws}/\text{cm}^3$. For particles with a diameter of 300-500 μm , the cycle losses of the magnet cores according to the invention amounted to 2.0 $\mu\text{Ws}/\text{cm}^3$ and for comparable cores produced by conventional means to 3.2 $\mu\text{Ws}/\text{cm}^3$. For particles with a diameter of 500-710 μm , the cycle losses of the magnet cores according to the invention amounted to 1.7 $\mu\text{Ws}/\text{cm}^3$ and for comparable cores produced by conventional means to 2.3 $\mu\text{Ws}/\text{cm}^3$.

Example 3

In a further embodiment of the method according to the invention, strip was likewise produced from an $\text{Fe}_{76}\text{Si}_{12}\text{B}_{12}$ alloy in a quick solidification process, followed by

thermal embrittlement and pulverisation with minimum energy input, largely by cutting action, in less than 60 s to produce particles with a diameter of 200-300 μm .

As in the first and second examples, the powders were graded and pressed together with glass solder at a temperature of 420°C to form magnet cores. Cycle losses were determined after a two-hour heat treatment process at 440°C. For particles with a diameter of 200-300 μm , the cycle losses of the magnet cores according to the invention amounted to 4 $\mu\text{Ws}/\text{cm}^3$ at a modulation of 0.1 T.

These examples show clearly that the cycle or hysteresis losses of powder cores are strongly affected by the characteristics of the fracture or particle surfaces and that the plastic deformation of these surfaces causes higher hysteresis losses.

Patent Claims

1. Magnet core produced from a composite of a powder of amorphous or nano-crystalline particles and from at least one pressing additive, wherein the particles have first surfaces represented by original strip surfaces and second surfaces represented by surfaces produced in a pulverisation process, characterised in that
the overwhelming majority of these second particle surfaces are essentially smooth cut or fracture surfaces without any plastic deformation, the proportion T of areas of plastic deformation of the second particle surfaces being $0 \leq T \leq 0.5$.
2. Magnet core according to claim 1, characterised in that
the proportion T of areas of plastic deformation of the particle surfaces is $0 \leq T \leq 0.2$.
3. Magnet core according to claim 1 or 2, characterised in that
its cycle losses P are $P \leq 5 \mu\text{Ws}/\text{cm}^3$.
4. Magnet core according to any of claims 1 to 3, characterised in that
its cycle losses P are $P \leq 3 \mu\text{Ws}/\text{cm}^3$.
5. Magnet core according to any of claims 1 to 4, characterised in that
the particles have the alloy composition $(\text{Fe}_{1-a}\text{M}_a)_{100-x-y-z-\alpha-\beta-\gamma}\text{Cu}_x\text{Si}_y\text{B}_z\text{M}'_\alpha\text{M}''_\beta\text{X}_\gamma$, wherein
M is Co and/or Ni, wherein M' is at least one element from the group consisting of Nb, W, Ta, Zr, Hf, Ti and Mo, wherein M'' is at least one element from the

group consisting of V, Cr, Mn, Al, elements of the platinum group, Sc, Y, rare earths, Au, Zn, Sn and Re, wherein X is at least one element from the group consisting of C, Ge, P, Ga, Sb, In, Be und As, and wherein a, x, y, z, α , β and γ are specified in atomic percent and meet the following conditions: $0 \leq a \leq 0.5$; $0.1 \leq x \leq 3$; $0 \leq y \leq 30$; $0 \leq z \leq 25$; $0 \leq y+z \leq 35$; $0.1 \leq \alpha \leq 30$; $0 \leq \beta \leq 10$; $0 \leq \gamma \leq 10$.

6. Magnet core according to any of claims 1 to 4, characterised in that the particles have the alloy composition $(\text{Fe}_{1-a-b}\text{Co}_a\text{Ni}_b)_{100-x-y-z} \text{M}_x\text{B}_y\text{T}_z$, wherein M is at least one element from the group consisting of Nb, Ta, Zr, Hf, Ti, V and Mo, wherein T is at least one element from the group consisting of Cr, W, Ru, Rh, Pd, Os, Ir, Pt, Al, Si, Ge, C and P, and wherein a, b, x, y and z are specified in atomic percent and meet the following conditions: $0 \leq a \leq 0.29$; $0 \leq b \leq 0.43$; $4 \leq x \leq 10$; $3 \leq y \leq 15$; $0 \leq z \leq 5$.
7. Magnet core according to any of claims 1 to 4, characterised in that the particles have the alloy composition $\text{M}_\alpha\text{Y}_\beta\text{Z}_\gamma$, wherein M is at least one element from the group consisting of Fe, Ni and Co, wherein Y is at least one element from the group consisting of B, C and P, wherein Z is at least one element from the group consisting of Si, Al and Ge, and wherein α , β and γ are specified in atomic percent and meet the following conditions: $70 \leq \alpha \leq 85$; $5 \leq \beta \leq 20$; $0 \leq \gamma \leq 20$, wherein up to 10 atomic percent of the M component may be replaced by at least one element from the group consisting of Ti, V, Cr, Mn, Cu, Zr, Nb, Mo, Ta und W and up to 10 atomic percent of the (Y+Z) component may be replaced by at least one element from the group consisting of In, Sn, Sb und Pb.

8. Magnet core according to any of claims 1 to 7,
characterised in that
glass solder is provided as a pressing additive.
9. Magnet core according to any of claims 1 to 7,
characterised in that
ceramic silicates are provided as a pressing additive.
10. Magnet core according to any of claims 1 to 7,
characterised in that
thermosetting resins such as epoxy resin, phenolic resin, silicone resin or
polyimides are provided as a pressing additive.
11. Inductive component with a magnet core according to any of claims 1 to 10.
12. Inductive component according to claim 11,
characterised in that
the inductive component is a choke for correcting the power factor.
13. Inductive component according to claim 11,
characterised in that
the inductive component is a storage choke.
14. Inductive component according to claim 11,
characterised in that
the inductive component is a filter choke.
15. Inductive component according to claim 11,
characterised in that
the inductive component is a smoothing choke.

16. Method for the production of a magnet core, comprising the following steps:
 - provision of a strip or foil of an amorphous or nanocrystalline soft magnetic alloy;
 - pulverisation of the strip or foil, wherein the material in the pulverising chamber is largely pulverised by cutting and/or breaking, and wherein the powder particles are removed from the pulverising chamber on reaching their final grain size;
 - mixing of the powder with one or more pressing additives;
 - pressing of the mixture to form a magnet core.
17. Method according to claim 16 characterised in that the dwell time t in the pulverising chamber is $t < 60$ s.
18. Method according to claim 16 or 17, characterised in that the magnet core is subjected to a heat treatment process after pressing.
19. Method according to any of claims 16 to 18, characterised in that the strip or foil is embrittled by heat treatment prior to pulverisation.
20. Method according to any of claims 16 to 19, characterised in that the powder is subjected to a separation process after pulverisation, and in that different powder fractions are processed separately.
21. Method according to any of claims 16 to 20, characterised in that a strip or foil with the alloy composition $(\text{Fe}_{1-a}\text{M}_a)_{100-x-y-z-\alpha-\beta-\gamma}\text{Cu}_x\text{Si}_y\text{B}_z\text{M}'_\alpha\text{M}''_\beta\text{X}_\gamma$ is used, wherein M is Co and/or Ni, wherein M' is at least one element from the group consisting of Nb, W, Ta, Zr, Hf, Ti and Mo, wherein

M'' is at least one element from the group consisting of V, Cr, Mn, Al, elements of the platinum group, Sc, Y, rare earths, Au, Zn, Sn and Re, wherein X is at least one element from the group consisting of C, Ge, P, Ga, Sb, In, Be und As, and wherein a, x, y, z, α , β and γ are specified in atomic percent and meet the following conditions: $0 \leq a \leq 0.5$; $0.1 \leq x \leq 3$; $0 \leq y \leq 30$; $0 \leq z \leq 25$; $0 \leq y+z \leq 35$; $0.1 \leq \alpha \leq 30$; $0 \leq \beta \leq 10$; $0 \leq \gamma \leq 10$.

22. Method according to any of claims 16 to 20, characterised in that a strip or foil with the alloy composition $(\text{Fe}_{1-a-b}\text{Co}_a\text{Ni}_b)_{100-x-y-z} \text{M}_x\text{B}_y\text{T}_z$ is used, wherein M is at least one element from the group consisting of Nb, Ta, Zr, Hf, Ti, V and Mo, wherein T is at least one element from the group consisting of Cr, W, Ru, Rh, Pd, Os, Ir, Pt, Al, Si, Ge, C and P, and wherein a, b, x, y and z are specified in atomic percent and meet the following conditions: $0 \leq a \leq 0.29$; $0 \leq b \leq 0.43$; $4 \leq x \leq 10$; $3 \leq y \leq 15$; $0 \leq z \leq 5$.
23. Method according to any of claims 16 to 20, characterised in that a strip or foil with the alloy composition $\text{M}_\alpha\text{Y}_\beta\text{Z}_\gamma$ is used, wherein M is at least one element from the group consisting of Fe, Ni and Co, wherein Y is at least one element from the group consisting of B, C and P, wherein Z is at least one element from the group consisting of Si, Al and Ge, and wherein α , β and γ are specified in atomic percent and meet the following conditions: $70 \leq \alpha \leq 85$; $5 \leq \beta \leq 20$; $0 \leq \gamma \leq 20$, wherein up to 10 atomic percent of the M component may be replaced by at least one element from the group consisting of Ti, V, Cr, Mn, Cu, Zr, Nb, Mo, Ta und W and up to 10 atomic percent of the (Y+Z) component may be replaced by at least one element from the group consisting of In, Sn, Sb and Pb.

24. Method according to any of claims 16 to 23,
characterised in that
glass solder is used as a pressing additive.
25. Method according to any of claims 16 to 20,
characterised in that
ceramic silicates are used as a pressing additive.
26. Method according to any of claims 16 to 20,
characterised in that
thermosetting resins such as epoxy resin, phenolic resin, silicone resin or
polyimides are used as a pressing additive.