(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 571 796 A1

(12) **EUROPEAN PATENT APPLICATION**
published in accordance with Art. 153(4) EPC

(43) Date of publication:
18.06.2025 Bulletin 2025/25

(21) Application number: **23895823.5**

(22) Date of filing: **23.04.2023**

(51) International Patent Classification (IPC):
H01F 1/053 $^{(2006.01)}$ ***H01F 41/02*** $^{(2006.01)}$
H01F 1/06 $^{(2006.01)}$ ***H01F 1/08*** $^{(2006.01)}$

(52) Cooperative Patent Classification (CPC):
H01F 1/053; H01F 1/06; H01F 1/08; H01F 41/02

(86) International application number:
PCT/CN2023/090162

(87) International publication number:
WO 2024/113657 (06.06.2024 Gazette 2024/23)

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
KH MA MD TN

(30) Priority: **30.11.2022 CN 202211543719**

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(54) MAGNETIC STEEL CONTAINING HIGH-ABUNDANCE RARE EARTH ELEMENTS, PREPARATION METHOD THEREFOR, AND USE THEREOF

(57) The invention discloses a magnetic steel containing high-abundance rare earth elements, the preparation method therefor and use thereof. The preparation method for a magnetic steel containing high-abundance rare earth elements comprises the following steps of: (1) subjecting a powder of a main alloy and a powder of an auxiliary alloy to mixing, pulverizing, shaping and sintering, wherein the main alloy has a composition of $(RE_aPr_bNd_c)dFe_eAl_fCu_gGa_hZr_iTi_jB_k$; RE is a high-abundance rare earth element comprising one or more of La, Ce, Y, Er, Yb, Gd, Tm and Sm; the auxiliary alloy has a composition of $R_mFe_nCu_oAl_p$; R is a rare earth element; (2) subjecting a sintered body obtained in step (1) and a diffusion source raw material composition to grain boundary diffusion treatment. The present invention improves the magnetic properties of a magnet containing high-abundance rare earth by constructing a composite magnetic hardening shell layer.

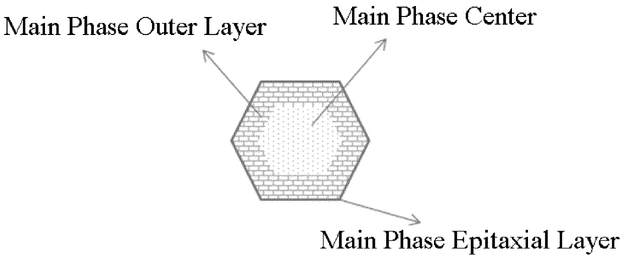

Fig. 1

Processed by Luminess, 75001 PARIS (FR)

Description

FIELD OF THE INVENTION

[0001] The invention relates to a magnetic steel containing high-abundance rare earth elements, the preparation method therefor and use thereof.

BACKGROUND OF THE INVENTION

[0002] Neodymium-iron-boron permanent magnet materials are widely used in electronic products, automobiles, wind power, home appliances, elevators and industrial robots due to their excellent magnetic properties. For example, they provide magnetic fields in permanent magnet motors such as focusing motors, drive motors, wind turbines, elevator traction machines, and positioning motors. The demand for neodymium-iron-boron permanent magnet materials is increasing, among which the demand for Pr/Nd/Dy/Tb is increasing significantly. At the same time, high-abundance rare earths and other rare earths are largely shelved, resulting in waste.

[0003] However, adding high-abundance rare earth elements such as La, Ce, Y, Er, Yb, Gd, Tm or Sm to neodymium-iron-boron permanent magnet materials will reduce the magnetic properties of the permanent magnet materials, which limits the application of high-abundance rare earth elements such as La, Ce, Y, Er, Yb, Gd, Tm or Sm in permanent magnet materials.

SUMMARY OF THE INVENTION

[0004] Mainly to overcome the defect in the prior art that the use of high-abundance rare earth elements cannot effectively improve the coercive force and maintain the remanence, the present invention provides a magnetic steel containing high-abundance rare earth elements, the preparation method therefor and use thereof. The present invention makes full use of the HA of Y/Er/Yb/Gd/Tm/Sm, Pr/Nd/Ho/Dy, and Dy/Tb by constructing a composite magnetic hardening shell layer, thereby improving the magnetic properties of magnets containing high -abundance rare earths.

[0005] The present invention solves the above technical problems mainly through the following technical solutions.

[0006] A first technical solution of the invention provides a preparation method for a magnetic steel containing high-abundance rare earth elements, comprising following steps of:

(1) subjecting a powder of a main alloy and a powder of an auxiliary alloy to mixing, pulverizing, shaping and sintering,

wherein the main alloy has a composition of $(RE_aPr_bNd_c)_dFe_eAltCu_gGa_hZr_iTi_jB_k$;
RE is a high-abundance rare earth element; RE comprises one or more of La, Ce, Y, Er, Yb, Gd, Tm and Sm;
in terms of atomic percentage, a is 0.05-0.3; b is 0.1-1.2; c is 0.5-0.9; d is 13-15; e is 78-80; f is 0.2-0.4; g is 0.1-0.3; h is 0.2-0.5; i is 0.2-0.4; j is 0.2-0.4; k is 5-6;
wherein the auxiliary alloy has a composition of $R_mFe_nCu_oAl_p$;
R is a rare earth element;
in terms of atomic percentage, m is 45-55; n is 35-45; o is 4-8; p is 4-8;

(2) subjecting a sintered body obtained in step (1) and a diffusion source raw material composition to grain boundary diffusion treatment;

wherein, in terms of atomic percentage, the diffusion source raw material composition comprises a heavy rare earth element with a content of more than m.

[0007] In the present invention, in the composition of the main alloy, RE preferably comprises Y

[0008] In the present invention, preferably, in the composition of the main alloy, a is 0.1 in atomic percentage.

[0009] In the present invention, preferably, in the composition of the main alloy, b is 0.18-1 in atomic percentage, more preferably 0.22-0.9.

[0010] In the present invention, preferably, in the composition of the main alloy, c is 0.55-0.8 in atomic percentage, more preferably 0.57-0.68.

[0011] In the present invention, preferably, in the composition of the main alloy, d is 13-14 in atomic percentage, more preferably 13.64.

[0012] In the present invention, preferably, in the composition of the main alloy, in terms of atomic percentage: e is 78.5-80, more preferably 78.88-79.48, for example 79.26.

[0013] **In** the present invention, preferably, in the composition of the main alloy, in terms of atomic percentage: f is 0.2-0.3, more preferably 0.24.

[0014] **In** the present invention, preferably, in the composition of the main alloy, in terms of atomic percentage: g is 0.2.

[0015] **In** the present invention, preferably, in the composition of the main alloy, in terms of atomic percentage: h is 0.3-0.4, more preferably 0.36.

[0016] **In** the present invention, preferably, in the composition of the main alloy, in terms of atomic percentage: i is 0.2-0.3, more preferably 0.26.

[0017] **In** the present invention, preferably, in the composition of the main alloy, in terms of atomic percentage: j is 0.2-0.3, more preferably 0.27.

[0018] **In** the present invention, preferably, in the composition of the main alloy, in terms of atomic percentage: k is 5.5-6, more preferably 5.75.

[0019] **In** the present invention, preferably, the main alloy has a composition of:

$(Y_{0.1}PrNd_{0.9})_{13.64}Fe_{79.26}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
$(Y_{0.05}Pr_{0.18}Nd_{0.57})_{13.64}Fe_{78.88}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
$(La_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
$(Ce_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
$(Yb_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
$(Tm_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
$(Gd_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
$(Sm_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$.

[0020] In the present invention, the main alloy can be used to form the main phase center and the main phase outer layer.

[0021] In the present invention, preferably, in the composition of the auxiliary alloy, R is Dy or Pr.

[0022] In the present invention, preferably, in the composition of the auxiliary alloy, in atomic percentage: m is 50; n is 40; o is 5; p is 5.

[0023] In the present invention, preferably, the composition of the auxiliary alloy is $Dy_{50}Fe_{40}Cu_5Al_5$ or $Pr_{50}Fe_{40}Cu_5Al_5$.

[0024] In the present invention, in step (1), the mass ratio of the powder of the main alloy to the powder of the auxiliary alloy is preferably (90-99): (10-1), more preferably 98:2.

[0025] In the present invention, in step (1), preferably, the pulverization process comprises hydrogen decrepitation pulverization and micro-pulverization.

[0026] Here, the hydrogen decrepitation pulverization preferably comprises hydrogen absorption, dehydrogenation, and cooling treatment.

[0027] Here, the micro-pulverization is preferably jet-milling pulverization.

[0028] The jet-milling pulverization is preferably carried out in anitrogen atmosphere having an oxidizing gas with a content of 150 ppm or less.

[0029] The pulverization chamber pressure of thejet-milling pulverization is preferably 0.38 MPa.

[0030] The jet-milling pulverization time of the jet-milling pulverization is preferably 3 hours.

[0031] In the present invention, in step (1), preferably, the shaping process is a magnetic field shaping method or a hot pressing and hot deforming method.

[0032] Here, the magnetic field strength of the magnetic field shaping method is preferably 1.5T or more, for example, 1.6T.

[0033] In the present invention, in step (1), preferably, the sintering process comprises preheating, sintering, and cooling under vacuum conditions.

[0034] Here, the preheating temperature is preferably 300-600°C. The preheating time is preferably 1-2h. More preferably, the preheating is performed at 300°C and 600°C for 1h respectively.

[0035] Here, the sintering temperature is preferably 1080-1090°C.

[0036] Here, the sintering time is preferably 4h.

[0037] In the present invention, in step (2), preferably, the diffusion source raw material composition is an alloy powder containing a heavy rare earth element; it can be used to form a main phase epitaxial layer.

[0038] Here, the heavy rare earth element preferably comprises Dy and/or Tb.

[0039] The atomic percentage of the heavy rare earth element is preferably 50-80 at%; more preferably 60-70 at%.

[0040] In the present invention, in step (2), preferably, the diffusion source raw material composition further comprises M; the M preferably comprises one or more of Al, Cu and Ga; more preferably Al and Cu.

[0041] Here, the atomic percentage of M is preferably 20-50 at%; more preferably 30-40 at%;

When the M comprises Cu, the atomic percentage of Cu is preferably 10-25 at%; more preferably 15-20 at%.

[0042] When the M comprises Al, the atomic percentage of Al is preferably 10-25 at%; more preferably 15-20 at%.

[0043] In the present invention, in step (2), preferably, the diffusion source raw material composition is $Dy_{70}Cu_{15}Al_{15}$.

[0044] In the present invention, the mass ratio of the sintered body obtained in step (1) to the diffusion source raw material composition is (98-99.5): (0.5-2), preferably 99.2:0.8.

[0045] In the present invention, in step (2), preferably, the grain boundary diffusion is carried out in a high-purity Ar gas atmosphere. The pressure of the high-purity Ar gas atmosphere is preferably 8×10^{-3}Pa-2×10^{5}Pa.

[0046] In the present invention, in step (2), preferably, the temperature of the grain boundary diffusion is 800-980°C, for example, 900°C.

[0047] In the present invention, in step (2), preferably, in the grain boundary diffusion, the time of the grain boundary diffusion is 12-30h, preferably 15-28h; for example, 24h.

[0048] In the present invention, in step (2), preferably, after the grain boundary diffusion, diffusion heat treatment and/or aging heat treatment are also comprised.

[0049] Here, the temperature of the diffusion heat treatment is preferably 850-950°C, for example, 900°C. The time of the aging heat treatment is preferably 20-40h, for example, 24h.

[0050] Here, the temperature of the aging heat treatment is preferably 440-580°C, for example, 500°C. The time of the aging heat treatment is preferably 2-4h, for example, 4h.

[0051] In the present invention, the powder of the main alloy is preferably prepared by the following method: the RE, the Pr, the Nd, the Fe, the Al, the Cu, the Ga, the Zr, the Ti and the B are mixed in proportion, and then smelted and cast.

[0052] Here, the smelting is preferably carried out in a high-frequency vacuum induction smelting furnace. The vacuum degree of the smelting is preferably 5×10^{-2}Pa. The smelting temperature is preferably 1500°C or less.

[0053] Here, the casting is preferably carried out in an Ar gas atmosphere, and cooled at a rate of 10^{2}°C/sec-10^{4}°C/sec.

[0054] In the present invention, the powder of the auxiliary alloy is preferably prepared by the following method: the R, the Fe, the Cu and the Al are mixed in proportion, and heated and smelted in a vacuum induction smelting furnace under argon protection at a rate of 10^{2}°C/sec-10^{4}°C/sec.

[0055] A second technical solution of the invention provides a magnetic steel containing high-abundance rare earth elements, which is prepared by the preparation method for the magnetic steel containing high-abundance rare earth elements as described above.

[0056] A third technical solution of the invention provides a magnetic steel containing high-abundance rare earth elements, wherein a main phase of the magnetic steel containing high-abundance rare earth elements comprises a main phase center, a main phase outer layer and a main phase epitaxial layer; the main phase outer layer is located on an outer side of the main phase center and completely covers the main phase center; the main phase epitaxial layer is located on an outer side of the main phase outer layer and completely covers the main phase outer layer;

wherein a content of a high-abundance rare earth element RE_1 in the main phase center is A_1 at%, wherein at% refers to an atomic percentage of the high-abundance rare earth element in the main phase center in the magnetic steel containing high-abundance rare earth elements;
a content of a high-abundance rare earth element RE_2 in the main phase outer layer is A_2 at%, wherein at% refers to an atomic percentage of the high-abundance rare earth element in the main phase outer layer in the magnetic steel containing high-abundance rare earth elements;

$$A_1 \text{ at\%} > A_2 \text{ at\%};$$

wherein the main phase center has an average diameter of r_1, and the main phase outer layer has an average thickness of r_2, $1 < r_1/r_2 < 5$;
wherein the main phase epitaxial layer comprises a heavy rare earth element RH; and the main phase epitaxial layer has an average thickness of r_3, 2nm<r_3<500nm.

[0057] In the present invention, the main phase center may comprise a light rare earth element RL_1, and the light rare earth element RL_1 comprises a high-abundance rare earth element RE_1.

[0058] In the main phase center, the light rare earth element RL_1 preferably comprises Pr and/or Nd. The atomic percentage of the light rare earth element RL_1 is preferably 9.0 at%-10.0 at%, for example, 9.63 at%.

[0059] In the main phase center, the atomic percentage of the high-abundance rare earth element RE_1 is preferably 0.5 at%-3.0 at%, more preferably 2.0 at%-3.0 at%, for example 2.69 at%.

[0060] In the present invention, the main phase outer layer may comprise a light rare earth element RL_2, and the light rare earth element RL_2 comprises a high-abundance rare earth element RE_2.

[0061] In the main phase outer layer, the light rare earth element RL_2 preferably comprises Pr and/or Nd. The atomic percentage of the light rare earth element RL_2 is preferably 9.0 at%-10.0 at%, such as 9.91 at%.

[0062] In the present invention, the high-abundance rare earth element RE_1 in the main phase center and the high-abundance rare earth element RE_2 in the main phase outer layer can independently comprise one or more of La, Ce, Y, Er, Yb, Gd, Tm and Sm; preferably comprise Y, Yb, Gd, Tm or Sm.

[0063] In the present invention, the atomic percentage of the high-abundance rare earth element RE_2 in the main phase outer layer is preferably 0.5 at%-3.0 at%, more preferably 2.0 at%-3.0 at%, for example 2.28 at%.

[0064] In the present invention, the average diameter of the main phase is R, preferably, 2μm<R<15um.

[0065] In the present invention, the average diameter of the main phase center is r_1, the average thickness of the main phase outer layer is r_2, and r1/r2 is preferably 2-4, for example, 3.

[0066] In the present invention, the average thickness of the main phase epitaxial layer is r_3, and r_3 is preferably 100-400nm, for example, 200-300nm.

[0067] In the main phase epitaxial layer, the heavy rare earth element RH preferably comprises Dy and/or Tb.

[0068] In the main phase epitaxial layer, the content of the heavy rare earth element RH is preferably 2.5 wt%; the percentage refers to the mass percentage of the heavy rare earth element RH in the magnetic steel containing high-abundance rare earth elements.

[0069] In the present invention, the magnetic steel containing high-abundance rare earth elements generally further comprises a grain boundary phase. The grain boundary phase can be conventional in the art. Preferably, the grain boundary phase comprises elements such as Fe, Al, Cu, Ga, Zr, Ti, and B.

[0070] In the present invention, the anisotropy fields of the main phase epitaxial layer, the main phase center and the main phase outer layer decrease in sequence.

[0071] A fourth technical solution of the invention provides use of the magnetic steel containing high-abundance rare earth elements described above as an electronic component in an electric motor.

[0072] On the basis of conforming to the common sense in the art, the above-mentioned preferred conditions can be arbitrarily combined to obtain the preferred embodiments of the present invention.

[0073] The reagents and raw materials used in the present invention are commercially available.

[0074] The positive and progressive effects of the present invention are as follows:
In the magnetic steel containing high-abundance rare earth elements according to the present invention, the content of high-abundance rare earth elements in the main phase center can be higher than that in the main phase outer layer, and the magnetic properties of the magnetic steel are better. In addition, regarding the magnetic steel containing high-abundance rare earth elements according to the present invention, the main phase outer layer and the main phase epitaxial layer in the main phase can form a composite magnetic hardening shell layer, which is beneficial to improving the magnetic properties of the magnetic steel and improving the utilization rate of the heavy rare earth elements.

[0075] According to micromagnetism theory, the impurities or defects on the surface of the grains make the surface of the grains more easily demagnetized, thereby causing the overall demagnetization of the grains. The area closer to the surface of the grains is more easily demagnetized. In order to enhance the anti-demagnetization ability and improve the coercive force of the magnet, the area on the surface of the grain needs to be magnetically strengthened. Regarding the magnetic steel containing high-abundance rare earth elements according to the present invention, the anti-demagnetization ability of the main phase grains gradually weakens from the center to the surface. However, since it has a composite magnetic hardening shell layer with gradually increasing magnetic hardening strength in the main phase grain center, the outer layer, and the epitaxial layer, it can improve the anti-demagnetization ability of the grains while maintaining cost optimization.

BRIEF DESCRIPTION OF THE DRAWINGS

[0076] Fig.1 is a schematic diagram of the main phase structure of the magnetic steel containing high-abundance rare earth elements in Examples 1-10.

DETAILED DESCRIPTION OF THE INVENTION

[0077] The present invention is further described below by way of examples, but the present invention is not limited to the scope of the examples. The experimental methods in the following examples without specifying specific conditions are carried out according to conventional methods and conditions, or selected according to the product specifications.

Example 1

[0078] The preparation method for the Y-containing magnetic steel in Example 1 is as follows:
The general chemical formula of the main phase raw material for the Y-containing permanent magnet is: $(Y_{0.1}PrNd_{0.9})_{13.64}Fe_{79.26}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$.

[0079] The prepared raw materials were placed in a crucible made of alumina, and vacuum smelted in a high-frequency vacuum induction smelting furnace at a temperature of 1500°C or less in a vacuum of 5×10^{-2}Pa. After vacuum melting, Ar gas was introduced into the smelting furnace to make the gas pressure reach 55,000 Pa, and then casting was performed to obtain a rapidly cooled main phase alloy at a cooling rate of 10^2°C/second to 10^4°C/second.

[0080] The composition of the grain boundary auxiliary alloy is $Dy_{50}Fe_{40}Cu_5Al_5$ (at%). According to the composition of the grain boundary alloy, the required raw materials were prepared, heated and smelted in a vacuum medium frequency induction smelting furnace under argon protection, and a rapidly cooled grain boundary auxiliary phase alloy was obtained at a cooling rate of 10^2°C/s to 10^4°C/s.

[0081] The main phase alloy and the grain boundary auxiliary phase alloy were mixed evenly at a mass ratio of 98:2.

[0082] Hydrogen decrepitation pulverization process: The uniformly mixed alloys were plased into a hydrogen decrepitation furnace. Then, hydrogen with a purity of 99.9% was introduced into the hydrogen decrepitation furnace, and the hydrogen pressure was maintained at 0.15MPa. After sufficient hydrogen absorption, the temperature was raised while vacuuming, and the hydrogen was fully dehydrogenated. After cooling, the powder after hydrogen decrepitation pulverization was removed.

[0083] Micro-pulverization process: In a nitrogen atmosphere having an oxidizing gas with a content of 150 ppm or less, the powder after hydrogen decrepitation pulverization was subjected to a jet-milling pulverization for 3 hours under a pulverization chamber pressure of 0.38MPa to obtain a fine powder. Oxidizing gas refers to oxygen or moisture.

[0084] Zinc stearate was added to the powder after the jet-milling pulverization. The amount of zinc stearate added was 0.12% of the weight of the mixed powder. Then a V-type mixer was used for thorough mixing.

[0085] Magnetic field shaping process: By using a right-angle oriented magnetic field shaping machine, the above-mentioned powder with zinc stearate added was subjected to primary shaping to be shaped into a cube with a side length of 25 mm at a forming pressure of 0.35 ton/cm^2 in an orienting magnetic field of 1.6 T. After the primary shaping, demagnetization was performed in a magnetic field of 0.2T. In order to prevent the molded body from contacting the air after the primary shaping, the molded body was sealed and then a secondary forming machine (an isostatic pressing machine) was used for secondary forming at a pressure of 1.3 ton/cm^2.

[0086] Sintering process: Each molded body was moved into a sintering furnace for sintering. Sintering was carried out under a vacuum of 5×10^{-3}Pa, at 300°C and 600°C for 1 hour each. Then, sintering was carried out at a temperature of 1080°C for 4 hours. After that, Ar gas was introduced to make the gas pressure reached 0.1MPa, and then cooled to room temperature.

[0087] After a sintered body was prepared, it was further subjected to grain boundary diffusion. The sintered body was processed into a magnet with a diameter of 20 mm and a sheet thickness of less than 7 mm, wherein the thickness direction is the magnetic field orientation direction. After the surface was cleaned, an alloy powder ($Dy_{70}Cu_{15}Al_{15}$) made of a Dy alloy was fully sprayed on the magnet. The coated magnet was dried. In a high-purity Ar gas atmosphere, the alloy powder with Dy elements attached to the magnet surface was subjected to diffusion heat treatment at 900°C for 24 hours. Then, the temperature was lowered to room temperature. The diffused magnet was subjected to aging heat treatment, wherein the heat treatment temperature was 500°C. and the heat treatment time was 4 hours.

Example 2

[0088] The preparation method for the Y-containing magnetic steel in Example 1 is as follows:
The general chemical formula of the main phase raw material for the Y-containing permanent magnet is: $(Y_{0.1}PrNd_{0.9})_{13.64}Fe_{79.26}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$.

[0089] The prepared raw materials were placed in a crucible made of alumina, and vacuum smelted in a high-frequency vacuum induction smelting furnace at a temperature of 1500°C or less in a vacuum of 5×10^{-2}Pa. After vacuum melting, Ar gas was introduced into the smelting furnace to make the gas pressure reach 55,000 Pa, and then casting was performed to obtain a rapidly cooled main phase alloy at a cooling rate of 10^2°C/second to 10^4°C/second.

[0090] The composition of the grain boundary auxiliary alloy is $Pr_{50}Fe_{40}Cu_5Al_5$ (at%). According to the composition of the grain boundary alloy, the required raw materials were prepared, heated and smelted in a vacuum medium frequency induction smelting furnace under argon protection, and a rapidly cooled grain boundary auxiliary phase alloy was obtained at a cooling rate of 10^2°C/s to 10^4°C/s.

[0091] The main phase alloy and the grain boundary auxiliary phase alloy were mixed evenly at a mass ratio of 98:2.

[0092] Hydrogen decrepitation pulverization process: The uniformly mixed alloys were plased into a hydrogen decrepitation furnace. Then, hydrogen with a purity of 99.9% was introduced into the hydrogen decrepitation furnace, and the hydrogen pressure was maintained at 0.15MPa. After sufficient hydrogen absorption, the temperature was raised while vacuuming, and the hydrogen was fully dehydrogenated. After cooling, the powder after hydrogen decrepitation pulverization was removed.

[0093] Micro-pulverization process: In a nitrogen atmosphere having an oxidizing gas with a content of 150 ppm or less, the powder after hydrogen decrepitation pulverization was subjected to a jet-milling pulverization for 3 hours under a pulverization chamber pressure of 0.38MPa to obtain a fine powder. Oxidizing gas refers to oxygen or moisture.

[0094] Zinc stearate was added to the powder after the jet-milling pulverization. The amount of zinc stearate added was 0.12% of the weight of the mixed powder. Then a V-type mixer was used for thorough mixing.

[0095] Magnetic field shaping process: By using a right-angle oriented magnetic field shaping machine, the above-mentioned powder with zinc stearate added was subjected to primary shaping to be shaped into a cube with a side length of

25 mm at a forming pressure of 0.35 ton/cm^2 in an orienting magnetic field of 1.6 T. After the primary shaping, demagnetization was performed in a magnetic field of 0.2T. In order to prevent the molded body from contacting the air after the primary shaping, the molded body was sealed and then a secondary forming machine (an isostatic pressing machine) was used for secondary forming at a pressure of 1.3 ton/cm^2.

[0096] Sintering process: Each molded body was moved into a sintering furnace for sintering. Sintering was carried out under a vacuum of 5×10^{-3}Pa, at 300°C and 600°C for 1 hour each. Then, sintering was carried out at a temperature of 1080°C for 4 hours. After that, Ar gas was introduced to make the gas pressure reached 0.1MPa, and then cooled to room temperature.

[0097] After a sintered body was prepared, it was further subjected to grain boundary diffusion. The sintered body was processed into a magnet with a diameter of 20 mm and a sheet thickness of less than 7 mm, wherein the thickness direction is the magnetic field orientation direction. After the surface was cleaned, an alloy powder ($Dy_{70}Cu_{15}Al_{15}$) made of a Dy alloy was fully sprayed on the magnet. The coated magnet was dried. In a high-purity Ar gas atmosphere, the alloy powder with Dy elements attached to the magnet surface was subjected to diffusion heat treatment at 900°C for 24 hours. Then, the temperature was lowered to room temperature. The diffused magnet was subjected to aging heat treatment, wherein the heat treatment temperature was 500°C. and the heat treatment time was 4 hours.

Example 3

[0098] The sintered body raw material composition for the Y-containing magnetic steel in Example 3 is as follows in terms of atomic percentage:

$$(Y_{0.05}Pr_{0.18}Nd_{0.57})_{13.64}Fe_{78.88}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0099] Other details are the same as those in Example 1.

Example 4

[0100] The sintered body raw material composition for the La-containing magnetic steel in Example 4 is as follows in terms of atomic percentage:

$$(La_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0101] Other details are the same as those in Example 1.

Example 5

[0102] The sintered body raw material composition for the Ce-containing magnetic steel in Example 5 is as follows in terms of atomic percentage:

$$(Ce_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0103] Other details are the same as those in Example 1.

Example 6

[0104] The sintered body raw material composition for the Yb-containing magnetic steel in Example 6 is as follows in terms of atomic percentage:

$$(Yb_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0105] Other details are the same as those in Example 1.

Example 7

[0106] The sintered body raw material composition for the Tm-containing magnetic steel in Example 7 is as follows in terms of atomic percentage:

$$(Tm_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0107] Other details are the same as those in Example 1.

Example 8

[0108] The sintered body raw material composition for the Gd-containing magnetic steel in Example 8 is as follows in terms of atomic percentage:

$$(Gd_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0109] Other details are the same as those in Example 1.

Example 9

[0110] The sintered body raw material composition for the Sm-containing magnetic steel in Example 9 is as follows in terms of atomic percentage:

$$(Sm_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0111] Other details are the same as those in Example 1.

Example 10

[0112] The sintered body raw material composition for the Er-containing magnetic steel in Example 10 is as follows in terms of atomic percentage:

$$(Er_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75};$$

[0113] Other details are the same as those in Example 1.

Comparative Example 1

[0114] In Comparative Example 1, the sintered body raw material composition of the Y-containing magnetic steel is: $(Y_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$, and the diffusion source raw material composition used was $Dy_{30}Fe_{40}Cu_{15}Al_{15}$ in atomic percentage;

[0115] Other details are the same as those in Example 1.

Comparative Example 2

[0116] In Comparative Example 2, the sintered body raw material composition of the Y-containing magnetic steel is: $(Y_{0.4}Pr_{0.18}Nd_{0.57})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$ in atomic percentage;

[0117] Other details are the same as those in Example 1.

Comparative Example 3

[0118] In Comparative Example 3, the sintered body raw material composition of the Y-containing magnetic steel is: $(Y_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}$ $Ti_{0.27}B_{5.75}$ in atomic percentage; and the temperature of the diffusion heat treatment was 800°C.

[0119] Other details are the same as those in Example 1.

Effect Example 1

1. Characterization of microstructure

[0120]

(1) The structural schematic diagram of the main phase in the magnetic steels containing high abundance rare earth elements of Examples 1-10 is shown in Fig. 1.

(2) The magnetic steels containing high-abundance rare earth elements in Example 1-2 was tested by using a field emission electron probe microanalyzer EPMA surface distribution test.

[0121] According to the results of the EPMA surface distribution test, the average diameter R of the main phase, the diameter r_1 of the main phase center, the average thickness r_2 of the main phase outer layer and the main phase epitaxial layer were measured. The specific method is as follows:
By combining the system scale in the EPMA surface distribution test results and the "Particle Size Distribution Calculation Version 1.2" software, the average diameter R of the main phase and the average diameter r_1 of the main phase center are measured. The numbers for measurements were 20. Since the grains had irregular shapes, the sizes of the larger and smaller directions of a single grain were measured respectively, and by calculating their average value, the average diameter R of the main phase and the average diameter r_1 of the main phase center can be obtained. The results are shown in Table 1 below.

[0122] The average thickness r_2 of the main phase outer layer can be calculated by the average diameter R of the main phase and the average diameter r_1 of the main phase center, specifically: the average thickness r_2 of the main phase outer layer = (the average diameter R of the main phase - the average diameter r_1 of the main phase center) / 2. The results of r_2 are shown in Table 1.

[0123] According to the EPMA surface distribution test results, the shell thickness of Dy in the Dy surface distribution can be obtained, and the average thickness r_3 of the main phase epitaxial layer can be calculated from it, specifically: The average thickness r_3 of the main phase epitaxial layer = the shell thickness of Dy in the Dy surface distribution/2. The results of r_3 are shown in Table 1.

Table 1

	Average Diameter R of Main Phase (μm)	Average Diameter r_1 of Main Phase Center (nm)	Average Thickness r_2 of Main Phase Outer Layer (nm)	r_1/r_2	Average Thickness r3 of Main Phase Epitaxial Layer (nm)
Example 1	4.7	2.9	0.8	3.62	290
Example 2	4.5	2.0	1.2	1.67	230
Example 3	4.6	2.2	1.2	1.83	240
Example 4	5.2	2.5	1.4	1.78	270
Example 5	4.5	2.5	1	2.5	230
Example 6	4.7	2	1.3	1.54	210
Example 7	5.0	2.9	1.1	2.63	240
Example 8	5.7	3.1	1.3	2.38	220
Example 9	4.8	2.3	1.2	1.91	210
Example 10	5.4	3	1.2	2.5	240
Comparative Example 1	4.2	3.4	0.4	8.5	230
Comparative Example 2	5.4	4.2	0.6	7	250
Comparative Example 3	4.6	3.6	0.5	7.2	200

2. Characterization of magnetic properties

[0124] The magnetic properties of the magnetic steels containing high-abundance rare earth elements before and after diffusion in Examples 1-2 were tested by using a permanent magnet material testing system NIM-62000. The test results are shown in Table 3 below.

Table 2

		Remanence Br(kGs)	Coercive Force Hcj(kOe)	Maximum Magnetic Energy Product Bhmax (MGoe)	Squareness Hk/Hcj (%)
Example 1	Before Diffusion	13.52	15.61	44.78	98.6
Example 1	After Diffusion	13.38	24.85	43.56	96.2
Example 2	Before Diffusion	13.76	13.82	45.87	98.4
Example 2	After Diffusion	13.53	22.45	44.46	96.5
Example 3	Before Diffusion	13.55	16.39	44.87	97.2
Example 3	After Diffusion	13.39	24.85	43.56	96.3
Example 4	Before Diffusion	13.46	12.57	43.32	92.4
Example 4	After Diffusion	13.26	18.62	41.76	90.8
Example 5	Before Diffusion	13.18	15.43	40.38	93.5
Example 5	After Diffusion	12.94	22.76	38.93	92.7
Example 6	Before Diffusion	13.2	11.34	41.38	95.6
Example 6	After Diffusion	13.04	18.79	39.89	93.7
Example 7	Before Diffusion	13.39	15.45	42.55	97.8
Example 7	After Diffusion	13.25	23.81	41.69	95.4
Example 8	Before Diffusion	13.22	15.94	41.5	96.6
Example 8	After Diffusion	13.07	24.26	42.71	95.7
Example 9	Before Diffusion	13.67	9.74	29.64	84.6
Example 9	After Diffusion	13.42	16.36	38.27	85.1
Example 10	Before Diffusion	13.36	15.45	42.55	97.8
Example 10	After Diffusion	13.21	23.81	41.59	95.4
Comparative Example 1	Before Diffusion	13.52	15.61	44.78	98.6
Comparative Example 1	After Diffusion	13.29	23.46	42.36	95.3
Comparative Example 2	Before Diffusion	13.49	6.3	39.12	86.7
Comparative Example 2	After Diffusion	13.23	14.6	37.19	85.4
Comparative Example 3	Before Diffusion	13.52	15.61	44.78	98.6
Comparative Example 3	After Diffusion	13.31	19.37	40.25	80.3

[0125] As can be seen from the above tables, the remanence, coercive force, maximum magnetic energy product and squareness of the magnetic steels containing high-abundance rare earth elements obtained in Examples 1-10 are relatively excellent.

[0126] In the sintered body raw material composition for the Y-containing magnetic steel in Comparative Example 1, the atomic percentage of Pr (0.22 at%) and the atomic percentage of Nd (0.68 at%) are not within the protection scope of this application. Accordingly, in the microstructure of the magnetic steel obtained in Comparative Example 1, r1/r2 is significantly greater than 5, and the coercive force, maximum magnetic energy product and squareness effect of the magnetic steel are significantly worse than those in Example 1.

[0127] In the sintered body raw material composition for the Y-containing magnetic steel in Comparative Example 2, the atomic percentage of Y (0.4 at%), the atomic percentage of Pr (0.18 at%) and the atomic percentage of Nd (0.57 at%) are not within the protection scope of this application. Accordingly, in the microstructure of the magnetic steel obtained in Comparative Example 2, r1/r2 is significantly greater than 5, and the coercive force, maximum magnetic energy product and squareness effect of the magnetic steel are significantly worse than those in Example 1.

[0128] In the sintered body raw material composition for the Y-containing magnetic steel in Comparative Example 3, the atomic percentage of Pr (0.22 at%) and the atomic percentage of Nd (0.68 at%) are not within the protection scope of this application. Accordingly, in the microstructure of the magnetic steel obtained in Comparative Example 3, r1/r2 is significantly greater than 5, and the coercive force, maximum magnetic energy product and squareness effect of the magnetic steel are significantly worse than those in Example 1.

Claims

1. A preparation method for a magnetic steel containing high-abundance rare earth elements, **characterized by** comprising following steps of:

    (1) subjecting a powder of a main alloy and a powder of an auxiliary alloy to mixing, pulverizing, shaping and sintering,

        wherein the main alloy has a composition of $(RE_aPr_bNd_c)_dFe_eAl_fCu_gGa_hZr_iTi_jB_k$;
        RE is a high-abundance rare earth element; RE comprises one or more of La, Ce, Y, Er, Yb, Gd, Tm and Sm;
        in terms of atomic percentage, a is 0.05-0.3; b is 0.1-1.2; c is 0.5-0.9; d is 13-15; e is 78-80; f is 0.2-0.4; g is 0.1-0.3; h is 0.2-0.5; i is 0.2-0.4; j is 0.2-0.4; k is 5-6;
        wherein the auxiliary alloy has a composition of $R_mFe_nCu_oAl_p$;
        R is a rare earth element;
        in terms of atomic percentage, m is 45-55; n is 35-45; o is 4-8; p is 4-8;

    (2) subjecting a sintered body obtained in step (1) and a diffusion source raw material composition to grain boundary diffusion treatment;

    wherein, in terms of atomic percentage, the diffusion source raw material composition comprises a heavy rare earth element with a content of more than m.

2. The preparation method for a magnetic steel containing high-abundance rare earth elements according to claim 1, **characterized in that** the preparation method for the magnetic steel containing high-abundance rare earth elements satisfies one or more of the following conditions (i)-(vi):

    (i) in the composition of the main alloy, RE comprises Y;
    (ii) in the composition of the main alloy, in terms of atomic percentage:

        a is 0.1;
        b is preferably 0.18-1, more preferably 0.22-0.9;
        c is preferably 0.55-0.8, more preferably 0.57-0.68;
        d is preferably 13-14, more preferably 13.64;
        e is preferably 78.5-80, more preferably 78.88-79.48, further preferably 79.26;
        f is preferably 0.2-0.3, more preferably 0.24;
        g is preferably 0.2;
        h is preferably 0.3-0.4, more preferably 0.36;
        i is preferably 0.2-0.3, more preferably 0.26;
        j is preferably 0.2-0.3, more preferably 0.27;
        k is preferably 5.5-6, more preferably 5.75;

    (iii) the composition of the main alloy is:

        $(Y_{0.1}PrNd_{0.9})_{13.64}Fe_{79.26}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
        $(Y_{0.05}Pr_{0.18}Nd_{0.57})_{13.64}Fe_{78.88}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
        $(La_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
        $(Ce_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
        $(Yb_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
        $(Tm_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
        $(Gd_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$; or
        $(Sm_{0.1}Pr_{0.22}Nd_{0.68})_{13.64}Fe_{79.48}Al_{0.24}Cu_{0.2}Ga_{0.36}Zr_{0.26}Ti_{0.27}B_{5.75}$;

(iv) in the composition of the auxiliary alloy, R is Dy or Pr;
(v) in the composition of the auxiliary alloy, in terms of atomic percentage: m is 50; n is 40; o is 5; p is 5;
(vi) the auxiliary alloy has a composition of $Dy_{50}Fe_{40}Cu_5Al_5$ or $Pr_{50}Fe_{40}Cu_5Al_5$;

preferably, the preparation method for the magnetic steel containing high-abundance rare earth elements satisfies conditions (i) to (vi) at the same time.

3. The preparation method for a magnetic steel containing high-abundance rare earth elements according to claim 1, **characterized in that** the preparation method for a magnetic steel containing high-abundance rare earth elements satisfies one or more of the following conditions I-VIII:

I. in step (1), a mass ratio of the powder of the main alloy to the powder of the auxiliary alloy is (90-99): (10-1), preferably 98:2;
II. in step (1), the pulverizing comprises hydrogen decrepitation pulverization and micro-pulverization;

wherein, the hydrogen decrepitation pulverization preferably comprises hydrogen absorption, dehydrogenation and cooling;
wherein, the micro-pulverization is preferably jet-milling pulverization;
the jet-milling pulverization is preferably carried out in a nitrogen atmosphere having an oxidizing gas with a content of 150 ppm or less;
the jet-milling pulverization is performed at a pulverization chamber pressure of preferably 0.38 MPa;
the jet-milling pulverization is performed for a time of preferably 3 hours;

III. in step (1), the shaping is preferably performed by a magnetic field shaping method or a hot pressing and hot deforming method;
wherein, the magnetic field shaping method is performed at a magnetic field strength of preferably 1.5T or more, for example, 1.6T;
IV. in step (1), the process of the sintering comprises preheating, sintering and cooling under vacuum conditions;

wherein the preheating is performed at a temperature of preferably 300-600°C; the preheating is performed for a time of preferably 1-2h; more preferably, the preheating is performed at a temperature of 300°C and 600°C for 1h respectively;
wherein, the sintering is performed at a temperature of preferably 1080-1090°C;
wherein the sintering is performed for a time of preferably 4h;

V. in step (2), the diffusion source raw material composition is an alloy powder comprising a heavy rare earth element;

wherein, the heavy rare earth element preferably comprises Dy and/or Tb;
the heavy rare earth element has an atomic percentage of preferably 50-80 at%, more preferably 60-70 at%;

VI. in step (2), the diffusion source raw material composition further comprises M; the M preferably comprises one or more of Al, Cu and Ga, more preferably Al and Cu;

wherein, the M has an atomic percentage of preferably 20-50 at%, more preferably 30-40 at%;
when the M comprises Cu, the Cu has an atomic percentage of preferably 10-25 at%, more preferably 15-20 at%;
when the M comprise Al, the Al has an atomic percentage of preferably 10-25 at%, more preferably 15-20 at%;

VII. in step (2), the diffusion source raw material composition is $Dy_{70}Cu_{15}Al_{15}$;
VIII. a mass ratio of the sintered body obtained in step (1) to the diffusion source raw material composition is (98-99.5): (0.5-2), preferably 99.2: 0.8;

preferably, the preparation method for a magnetic steel containing high-abundance rare earth elements satisfies conditions I-VIII at the same time.

4. The preparation method for a magnetic steel containing high-abundance rare earth elements according to claim 1,

characterized in that the preparation method for a magnetic steel containing high-abundance rare earth elements satisfies one or more of the following conditions IX-XII:

IX. in step (2), the grain boundary diffusion is carried out in a high-purity Ar gas atmosphere; the high-purity Ar gas atmosphere has a pressure of preferably 8×10^{-3}Pa-2×10^{5}Pa;
X. in step (2), the grain boundary diffusion is performed at a temperature of preferably 800-980°C, for example, 900°C;
XI. in the grain boundary diffusion, the grain boundary diffusion is performed for a time of 12-30h, preferably 15-28h; for example 24h;
XII. in step (2), after the grain boundary diffusion, the preparation method further comprises a diffusion heat treatment and/or an aging heat treatment;
wherein, the diffusion heat treatment is performed at a temperature of preferably 850-950°C, for example, 900°C; the aging heat treatment is performed for a time of preferably 20-40h, for example, 24h;
wherein, the aging heat treatment is performed at a temperature of preferably 440-580°C, such as 500°C; the aging heat treatment is performed for a time of preferably 2-4h, such as 4h;
preferably, the preparation method for a magnetic steel containing high-abundance rare earth elements satisfies conditions IX-XII at the same time.

5. The preparation method for a magnetic steel containing high-abundance rare earth elements according to claim 1, **characterized in that** the powder of the main alloy is prepared by the following method: subjecting the RE, Pr, Nd, Fe, Al, Cu, Ga, Zr, Ti, and B according to the percentages to mixing, smelting and casting;

wherein the smelting is preferably performed by using a high-frequency vacuum induction smelting furnace; the smelting is performed at a vacuum degree of preferably 5×10^{-2}Pa; the smelting is performed at a temperature of preferably 1500°C or less;
wherein the casting preferably comprises cooling at a rate of 10^{2}°C/sec-10^{4}°C/sec in an Ar gas atmosphere.

6. The preparation method for a magnetic steel containing high-abundance rare earth elements according to claim 1, **characterized in that** the powder of the auxiliary alloy is prepared by the following method: subjecting the R, Fe, Cu and Al according to the percentages to mixing, and heating and smelting by using a vacuum induction smelting furnace under the protection of argon at a speed of 10^{2}°C/sec to 10^{4}°C/sec.

7. A magnetic steel containing high-abundance rare earth elements, **characterized in that** the magnetic steel containing high-abundance rare earth elements is prepared by the preparation method for a magnetic steel containing high-abundance rare earth elements according to any one of claims 1-6.

8. A magnetic steel containing high-abundance rare earth elements, **characterized in that** a main phase of the magnetic steel containing high-abundance rare earth elements comprises a main phase center, a main phase outer layer and a main phase epitaxial layer; the main phase outer layer is located on an outer side of the main phase center and completely covers the main phase center; the main phase epitaxial layer is located on an outer side of the main phase outer layer and completely covers the main phase outer layer;

wherein a content of a high-abundance rare earth element RE_1 in the main phase center is A_1 at%, wherein at% refers to an atomic percentage of the high-abundance rare earth element in the main phase center in the magnetic steel containing high-abundance rare earth elements;
a content of a high-abundance rare earth element RE_2 in the main phase outer layer is A_2 at%, wherein at% refers to an atomic percentage of the high-abundance rare earth element in the main phase outer layer in the magnetic steel containing high-abundance rare earth elements;

$$A_1\ \mathrm{at\%} > A_2\ \mathrm{at\%};$$

wherein the main phase center has an average diameter of r_1, and the main phase outer layer has an average thickness of r_2, $1 < r_1/r_2 < 5$;
wherein the main phase epitaxial layer comprises a heavy rare earth element RH; and the main phase epitaxial layer has an average thickness of r_3, $2\text{nm} < r_3 < 500\text{nm}$.

9. The magnetic steel containing high-abundance rare earth elements according to claim 8, **characterized in that** the magnetic steel containing high-abundance rare earth elements satisfies one or more of the following conditions ①-⑩:

① the main phase center comprises a light rare earth element RL_1, and the light rare earth element RL_1 comprises the high-abundance rare earth element RE_1;
in the main phase center, the light rare earth element RL_1 preferably comprises Pr and/or Nd; the light rare earth element RL_1 has an atomic percentage of preferably 9.0 at%-10.0 at%, such as 9.63 at%;
② in the main phase center, the high-abundance rare earth element RE_1 has an atomic percentage of of 0.5 at%-3.0 at%, preferably 2.0 at%-3.0 at%, such as 2.69 at%;
③ the main phase outer layer comprises a light rare earth element RL_2, and the light rare earth element RL_2 comprises the high-abundance rare earth element RE_2;
in the main phase outer layer, the light rare earth element RL_2 preferably comprises Pr and/or Nd; the light rare earth element RL_2 has an atomic percentage of preferably 9.0 at%-10.0 at%, such as 9.91 at%;
④ the high-abundance rare earth element RE_1 in the main phase center and the high-abundance rare earth element RE_2 in the main phase outer layer independently comprise one or more of La, Ce, Y, Er, Yb, Gd, Tm and Sm, preferably comprise Y, Yb, Gd, Tm or Sm;
⑤ in the main phase outer layer, the high-abundance rare earth element RE_2 has an atomic percentage of 0.5 at%-3.0 at%, preferably 2.0 at%-3.0 at%, for example 2.28 at%;
⑥ the main phase has an average diameter of R, $2\mu m<R<15\mu m$;
preferably, the main phase center has an average diameter of r_1, and the main phase outer layer has an average thickness of r_2, and r_1/r_2 is 2-4, for example, 3;
⑦ the main phase epitaxial layer has an average thickness of r_3, and r_3 is 100-400nm, for example, 200-300nm;
⑧ in the main phase epitaxial layer, the heavy rare earth element RH comprises Dy and/or Tb;
in the main phase epitaxial layer, the heavy rare earth element RH has a content of preferably 2.5 wt%, wherein the wt% refers to a mass percentage of the heavy rare earth element RH in the magnetic steel containing high-abundance rare earth elements;
⑨ the magnetic steel containing high-abundance rare earth elements further comprises a grain boundary phase;
the grain boundary phase preferably comprises Fe, Al, Cu, Ga, Zr, Ti and B;
⑩ the anisotropy fields of the main phase epitaxial layer, the main phase center and the main phase outer layer decrease in sequence;
preferably, the magnetic steel containing high-abundance rare earth elements satisfies conditions ①-⑩ at the same time.

10. Use of a magnetic steel containing high-abundance rare earth elements as an electronic component in an electric motor, **characterized in that** the magnetic steel containing high-abundance rare earth elements is as defined in any one of claims 6-9.

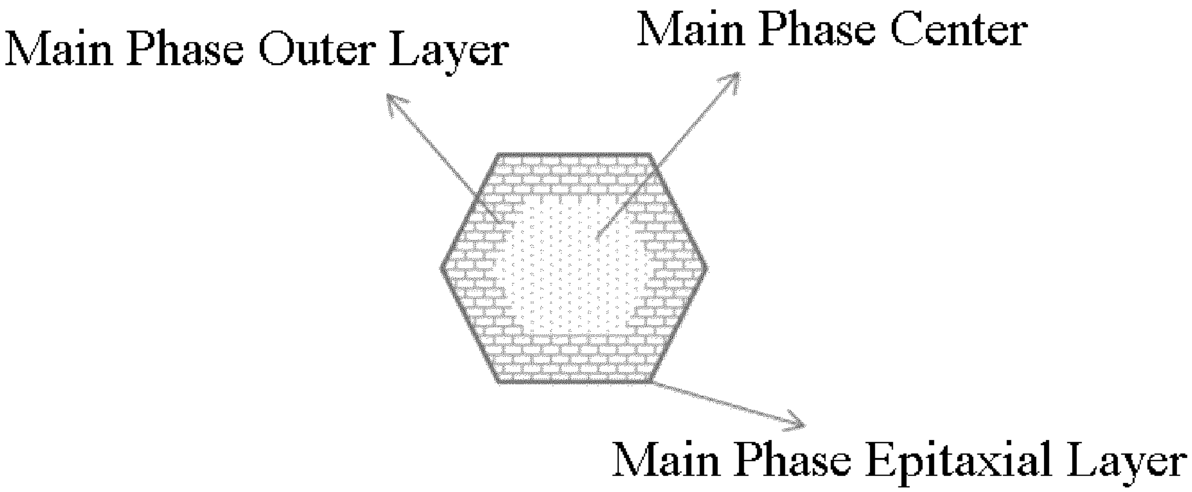
Main Phase Outer Layer
Main Phase Center
Main Phase Epitaxial Layer

Fig. 1

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2023/090162

A. CLASSIFICATION OF SUBJECT MATTER

H01F1/053(2006.01)i; H01F41/02(2006.01)i; H01F1/06(2006.01)i; H01F1/08(2006.01)i

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)

IPC 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)

CNTXT; ENTXT; ENTXTC; DWPI; CNKI: 辅合金, 晶界扩散, 主合金, 稀土, 铁硼, alloy, grain, boundary, diffusion, rare, earth, iron, Fe, B

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
PX	CN 115798850 A (FUJIAN CHANGTING GOLDEN DRAGON RARE-EARTH CO., LTD.) 14 March 2023 (2023-03-14) claims 1-10	1-10
Y	CN 107958760 A (NINGBO INSTITUTE OF MATERIAL TECHNOLOGY AND ENGINEERING, CHINESE ACADEMY OF SCIENCES) 24 April 2018 (2018-04-24) description, paragraphs 6-22	1-10
Y	CN 105170976 A (UNIVERSITY OF SCIENCE AND TECHNOLOGY BEIJING) 23 December 2015 (2015-12-23) description, paragraphs 8-14	1-10
A	CN 107578870 A (INNER MONGOLIA UNIVERSITY OF SCIENCE & TECHNOLOGY) 12 January 2018 (2018-01-12) entire document	1-10

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

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"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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Date of the actual completion of the international search **10 August 2023**	Date of mailing of the international search report **11 August 2023**
Name and mailing address of the ISA/CN **China National Intellectual Property Administration (ISA/CN)** **China No. 6, Xitucheng Road, Jimenqiao, Haidian District, Beijing 100088**	Authorized officer Telephone No.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2023/090162

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