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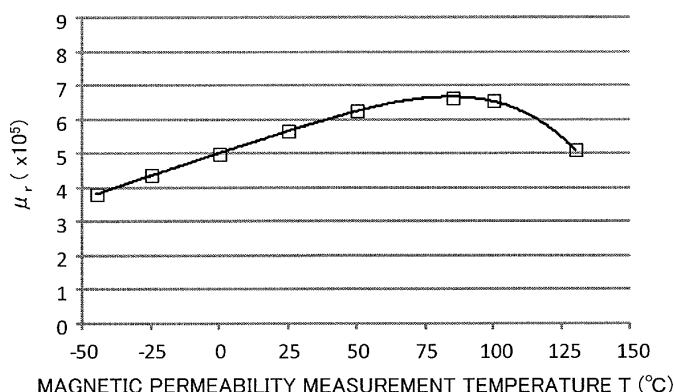
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(54) **CURRENT TRANSFORMER CORE, METHOD FOR MANUFACTURING SAME, AND DEVICE EQUIPPED WITH SAID CORE**

(57) A manufacturing method of a current transformer core includes: the step of providing a core element formed by winding or layering a Fe-based amorphous alloy ribbon whose thickness is not more than 15 μm and which can be converted into nanocrystals; a longitudinal-field heat treatment step which includes performing a heat treatment on the core element in the presence of a magnetic field of not less than 100 A/m applied in a magnetic path direction of the core element, thereby forming a core; and a transverse-field heat treatment step which includes, after the longitudinal-field heat treatment

step, performing a heat treatment on the core in the presence of a magnetic field applied in a direction perpendicular to the magnetic path direction of the core, thereby forming a core. $\mu_r(25)$ is adjusted by the transverse-field heat treatment step to a value between $0.4 \times \mu_r(\text{max})(25)$ and $0.9 \times \mu_r(\text{max})(25)$ where $\mu_r(\text{max})(T)$ is $\mu_r(T)$ achieved by the longitudinal-field heat treatment step, and $\mu_r(T)$ is an amplitude magnetic permeability of the core measured at a temperature T ($^{\circ}\text{C}$) in the presence of an AC magnetic field of frequency $f=50$ Hz and amplitude $H=1.0$ A/m.

FIG. 8



Description**TECHNICAL FIELD**

5 **[0001]** The present disclosure relates to a current transformer core and a manufacturing method thereof. The present disclosure also relates to a device which includes the current transformer core.

BACKGROUND ART

10 **[0002]** Current transformers (CT) are current transforming devices for use in measurement and are used in, for example, current meters and earth leakage circuit breakers. The current transformers have a soft magnetic material core (magnetic core) which is used for a closed magnetic circuit. Patent Document 1 discloses that, as this current transformer core, a core formed of a ribbon of a Fe-based nanocrystalline alloy is preferred. The Fe-based nanocrystalline alloy exhibits a higher saturation magnetic flux density than Permalloy and Co-based amorphous alloys and has a higher magnetic permeability than Fe-based amorphous alloys.

15 **[0003]** Typical compositions of the Fe-based nanocrystalline alloy are disclosed in, for example, Patent Document 2 and Patent Document 3. A typical example of the manufacturing method of a core with the use of a Fe-based nanocrystalline alloy includes the steps of: quenching a melt of material alloy which has a desired composition, thereby producing an amorphous alloy ribbon; winding this amorphous alloy ribbon into a ring-shaped core element; and performing a heat treatment so as to crystallize the amorphous alloy ribbon, thereby obtaining a core which has a nanocrystalline organization.

20 **[0004]** Patent Document 4 discloses a magnetic core which is formed by winding a steel ribbon of a Fe-based nanocrystalline alloy, whose magnetic permeability is greater than 12,000 and smaller than 350,000, of which the ratio of the saturation magnetic flux density B_s and the residual magnetic flux density B_r (B_r/B_s) is small, and of which the temperature dependence of the magnetic permeability is small.

25 **[0005]** In this specification, a ring-shaped structure formed of a Fe-based alloy ribbon on which a heat treatment in a longitudinal magnetic field is not yet finished is referred to as "core element". This is sometimes strictly distinguished from the "core" that is formed of a Fe-based nanocrystalline alloy ribbon on which the heat treatment has been finished.

CITATION LIST**PATENT LITERATURE****[0006]**

35 Patent Document 1: Japanese Patent No. 2501860

Patent Document 2: Japanese Examined Patent Publication No. 4-4393

Patent Document 3: Japanese Examined Patent Publication No. 7-74419

40 Patent Document 4: Japanese PCT National Phase Laid-Open Publication No. 2002-530854

SUMMARY OF INVENTION**TECHNICAL PROBLEM**

45 **[0007]** As for the above-described current transformer, further improvement in magnetic permeability of the core has been demanded for the purpose of size reduction and cost reduction in a device such as a current meter. This is because improvement in magnetic permeability of the core not only leads to higher sensitivity to an electric current to be measured but also enables core size reduction and reduction in the number of turns of a coil around the core.

50 **[0008]** A conventional solution for improvement in magnetic permeability of the Fe-based nanocrystalline alloy is to apply a magnetic field in a magnetic path direction of the core element in the step of crystallization by a heat treatment. However, the core produced in such a way has such a problem that a magnetic deviation is likely to occur due to a large residual magnetic flux density B_r . If the core has a magnetic deviation, the magnetic permeability at the point of operation decreases so that characteristics demanded of the current transformer cannot be obtained.

55 **[0009]** To adapt itself to variations in the device environment such as the use temperature, the current transformer also needs to have such an excellent temperature characteristic that the high magnetic permeability of the core exhibits a small variation within the use temperature range.

[0010] Embodiments of the present disclosure provide a current transformer core which realizes the characteristics that are necessary in, for example, uses for sensing of electrical leakage, a manufacturing method of the core, and a

device which includes the core.

SOLUTION TO PROBLEM

[0011] A current transformer core of the present disclosure is a current transformer core formed by winding or layering a soft magnetic material layer, wherein the soft magnetic material layer is formed of a Fe-based nanocrystalline alloy ribbon whose thickness is not more than 15 μm ,

[0012] $\Delta\mu_r(100-0)$ is not more than 0.5 where $\Delta\mu_r(100-0)$ is $|\mu_r(100)-\mu_r(0)|/\mu_r(0)$, and $\mu_r(T)$ is an amplitude magnetic permeability of the core measured at a temperature T ($^{\circ}\text{C}$) in the presence of an applied AC magnetic field of frequency $f=50$ Hz and amplitude $H=1.0$ A/m, and

the ratio of a residual magnetic flux density B_r and a saturation magnetic flux density B_m , B_r/B_m , is less than 0.9 where a magnetic flux density $B(80)$ with magnetic field $H=80$ A/m is defined as the saturation magnetic flux density B_m .

[0013] In one embodiment, $\mu_r(25)$ has a value between $0.4 \times \mu_r(\text{max})(25)$ and $0.9 \times \mu_r(\text{max})(25)$ where $\mu_r(\text{max})(T)$ is $\mu_r(T)$ achieved by heating a core element to not less than a crystallizing temperature in the presence of a magnetic field of not less than 100 A/m applied in a magnetic path direction (longitudinal-field heat treatment), the core element being formed by shaping a Fe-based amorphous alloy ribbon which has a substantially identical composition and shape to those of the Fe-based nanocrystalline alloy ribbon so as to have a substantially identical shape to that of the core.

[0014] In one embodiment, $\mu_r(25) \geq 4 \times 10^5$ holds true.

[0015] In one embodiment, $\mu_r(100)-\mu_r(0)$ has a positive value.

[0016] A manufacturing method of a current transformer core according to the present disclosure includes:

the step of providing a core element formed by winding or layering a Fe-based amorphous alloy ribbon whose thickness is not more than 15 μm and which can be converted into nanocrystals;

a longitudinal-field heat treatment step which includes heating the core element to not less than a crystallizing temperature in the presence of a magnetic field of not less than 100 A/m applied in a magnetic path direction of the core element, thereby forming a core; and

a transverse-field heat treatment step which includes, after the longitudinal-field heat treatment step, heating the core to a temperature less than the crystallizing temperature in the presence of a magnetic field applied in a direction perpendicular to the magnetic path direction of the core, thereby forming a current transformer core, wherein $\mu_r(25)$ is adjusted by the transverse-field heat treatment step to a value between $0.4 \times \mu_r(\text{max})(25)$ and $0.9 \times \mu_r(\text{max})(25)$ where $\mu_r(\text{max})(T)$ is $\mu_r(T)$ achieved by the longitudinal-field heat treatment step, and $\mu_r(T)$ is an amplitude magnetic permeability of the core measured at a temperature T ($^{\circ}\text{C}$) in the presence of an AC magnetic field of frequency $f=50$ Hz and amplitude $H=1.0$ A/m.

[0017] In one embodiment, $\Delta\mu_r(100-0)$ is not more than 0.5 where $\Delta\mu_r(100-0)$ is $|\mu_r(100)-\mu_r(0)|/\mu_r(0)$ of a manufactured current transformer core.

[0018] A device according to the present disclosure includes: the current transformer core as set forth in any of the foregoing paragraphs; a coil provided around the current transformer core; and a sensing circuit coupled with the coil.

ADVANTAGEOUS EFFECTS OF INVENTION

[0019] According to the present disclosure, it is possible to provide a current transformer core which is formed of a Fe-based nanocrystalline alloy layer that has high magnetic permeability but is unlikely to undergo a magnetic deviation, and has an excellent temperature characteristic.

BRIEF DESCRIPTION OF DRAWINGS

[0020]

FIG. 1 is a diagram showing the configuration of a measurement system used in measurement of the magnetic permeability.

FIG. 2A is a graph illustrating the relationship between the temperature of a longitudinal-field heat treatment and the magnetic permeability $\mu_r(25)$ of the core in the case where a core element was formed by winding a Fe-based amorphous alloy ribbon (thickness: 18 μm) which had the composition of $\text{Fe}_{74}\text{Cu}_1\text{Nb}_3\text{Si}_{15.5}\text{B}_{6.5}$.

FIG. 2B is a graph illustrating the relationship between the temperature of a longitudinal-field heat treatment and the magnetic permeability $\mu_r(25)$ of the core in the case where a core element was formed by winding a Fe-based amorphous alloy ribbon (thickness: 13 μm) which had the composition of $\text{Fe}_{74}\text{Cu}_1\text{Nb}_3\text{Si}_{15.5}\text{B}_{6.5}$.

FIG. 3 is a graph illustrating the relationship between a longitudinal magnetic field during the process of a longitudinal-field heat treatment and the magnetic permeability $\mu_r(25)$ of the core in the case where a core element was formed by winding a Fe-based amorphous alloy (thickness: 13 μm) which had the composition of $\text{Fe}_{74}\text{Cu}_1\text{Nb}_3\text{Si}_{15.5}\text{B}_{6.5}$.

FIG. 4 is a graph illustrating the temperature characteristic of the magnetic permeability $\mu_r(T)$ of the core for Sample A where the longitudinal magnetic field illustrated in FIG. 3 was 19 A/m and Sample B where the longitudinal magnetic field was 230 A/m.

FIG. 5 is a graph illustrating an example of the profiles of the temperature and the magnetic field intensity of a transverse-field heat treatment in the present embodiment.

FIG. 6 is a graph illustrating B-H curves of respective samples obtained when the duration for which the heat treatment temperature was retained at 400°C (retention time) was set to 60 minutes, 90 minutes and 120 minutes among the profiles illustrated in FIG. 5, and B-H curves of a sample before a transverse-field heat treatment.

FIG. 7 is a graph illustrating the magnetic permeability of respective samples obtained when the duration for which the heat treatment temperature was retained at 400°C (retention time) was set to 60 minutes, 90 minutes and 120 minutes among the profiles illustrated in FIG. 5.

FIG. 8 is a graph illustrating the measurement temperature dependence of the magnetic permeability for one of the samples illustrated in FIG. 7 where the duration for which the heat treatment temperature was retained at 400°C (retention time) was set to 90 minutes.

FIG. 9 is a graph illustrating the relationship between the magnetic field intensity in a transverse-field heat treatment and the magnetic permeability $\mu_r(25)$.

FIG. 10 is a flowchart illustrating an example of the manufacturing method of a current transformer core according to the present disclosure.

FIG. 11A is a perspective view showing an example of the basic structure of a current transformer 100 to which the present disclosure is applicable.

FIG. 11B is a perspective view showing an example where the current transformer 100 is applied to a zero-phase current transformer.

FIG. 12 is a diagram showing a circuit configuration example of an earth leakage circuit breaker 20 which includes the current transformer 100 shown in FIG. 11B.

DESCRIPTION OF EMBODIMENTS

[0021] Hereinafter, an embodiment of the present disclosure is described in detail with reference to the drawings. Note that, however, excessively detailed descriptions are sometimes omitted. For example, well-known matter in the art and descriptions of substantially equal elements are sometimes omitted. This is for the sake of avoiding the following descriptions from being unnecessarily redundant and assisting one skilled in the art to easily understand the descriptions. Note that the present inventor provides the attached drawings and the following descriptions for the purpose of assisting one skilled in the art to sufficiently understand the present disclosure. However, the present inventor does not intend that these drawings and descriptions limit the subject matter recited in the claims.

(Embodiment)

< Current transformer core >

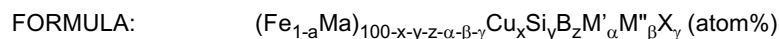
[0022] The current transformer core of the present embodiment is a current transformer core formed by winding or layering a soft magnetic material layer. The current transformer core can be realized by winding a ribbon-like soft magnetic material layer or layering a plurality of rings punched out from the soft magnetic material layer. The soft magnetic material layer which is a part of the current transformer core of the present embodiment is formed of a Fe-based nanocrystalline alloy ribbon whose thickness is in the range of not less than 8 μm and not more than 15 μm (typically about 13 μm). As will be described later, it was found from experiments conducted by the present inventor that the thickness of the Fe-based nanocrystalline alloy ribbon is a significant factor which strongly influences the characteristics of the current transformer core for use in sensing of electrical leakage.

< Fe-based nanocrystalline alloy ribbon >

[0023] A Fe-based nanocrystalline alloy used in the current transformer core of the present embodiment is basically produced by a method which includes the step of quenching a molten alloy, thereby obtaining an amorphous alloy ribbon which has a predetermined composition, and the heat treatment step of heating this amorphous alloy ribbon so as to form nanocrystalline grains. It has been known from the results of analysis by X-ray diffraction and a transmission electron microscope that the nanocrystalline grains are Fe in a body-centered cubic structure in which Si or the like is incorporated

such that a solid solution is formed. At least 80 volume% of the alloy is occupied by nanocrystalline grains whose average grain diameter measured at the maximum dimension is not more than 100 nm. The other part of the alloy than the nanocrystalline grains is mainly amorphous. The proportion of the nanocrystalline grains may be substantially 100 volume%.

[0024] The composition of the Fe-based nanocrystalline alloy used in the embodiment of the present disclosure is represented by the following formula:



[0025] Here, M is Co and/or Ni. M' is at least one element selected from the group consisting of Nb, W, Ta, Zr, Hf, Ti and Mo. M'' is at least one element selected from the group consisting of V, Cr, Mn, Al, platinum-group elements, Sc, Y, rare earth elements, Au, Zn, Sn and Re. X is at least one element selected from the group consisting of C, Ge, P, Ga, Sb, In, As and Be.

[0026] The factors that define the composition, a, x, y, z, α , β and γ , respectively meet the following conditions:

$$0 \leq a < 0.5$$

$$0.1 \leq x \leq 3$$

$$10 \leq y \leq 20$$

$$5 \leq z \leq 10$$

$$0.1 \leq \alpha \leq 5$$

$$0 \leq \beta \leq 10$$

$$0 \leq \gamma \leq 10$$

[0027] The Fe-based nanocrystalline alloy used in the embodiment of the present disclosure contains Cu in a proportion of 0.1 to 3 atom%. If Cu is smaller than 0.1 atom%, the effect of decreasing the core loss and the effect of increasing the magnetic permeability, which are caused by addition of Cu, are rarely achieved. On the other hand, if Cu is greater than 3 atom%, there is a probability that the core loss is rather larger than that which occurs in an alloy to which Cu is not added. Also, the magnetic permeability deteriorates. In the present disclosure, the particularly preferred content x of Cu is 0.5 to 2 atom%. Within this range, the core loss is particularly small.

[0028] The causes of decrease of the core loss and increase of the magnetic permeability by addition of Cu are not elucidated but can be estimated as follows. The interaction parameter between Cu and Fe is positive, so that the solid solubility is low and Cu and Fe have a tendency to separate. Therefore, if an alloy in an amorphous state is heated, Fe atoms or Cu atoms gather together to form a cluster, so that composition fluctuations occur. Therefore, a large number of local regions are produced which are likely to undergo crystallization, and these regions serve as cores for generation of nanocrystalline grains. The major constituent of this crystal is Fe, and Cu is rarely incorporated so that a solid solution is not formed. Therefore, by crystallization, Cu is purged from the nanocrystalline grains so that the concentration of Cu increases in a region surrounding the crystal grains. Thus, it is estimated that the crystal grains are difficult to grow.

[0029] It is estimated that the effect of reducing the size of crystal grains which is achieved by addition of Cu is particularly improved by the presence of Nb, Ta, W, Mo, Zr, Hf, Ti or the like. If Nb, Ta, W, Mo, Zr, Hf, Ti or the like is not present, the size of crystal grains is not reduced so much. The effect of accelerating the size reduction is particularly

large in the cases of Nb, Ta, Zr, Hf, and Mo. Of these elements, particularly when Nb is added, an alloy is obtained whose crystal grain size is likely to be reduced and which also has excellent soft magnetic properties. When Nb is added, a nanocrystalline phase is produced whose major constituent is Fe. Accordingly, magnetostriction is small as compared with Fe-based amorphous alloys, and the magnetic anisotropy that is attributed to the internal stress-strain decreases. These phenomena are estimated to be ones of the reasons that the soft magnetic properties are improved. These elements are contained in the range of 0.1 to 5 atom%, preferably in the range of 2 to 5 atom%. If it is less than 0.1 atom%, there is a probability that the size reduction of the crystal grains is insufficient. If it exceeds 5 atom%, the decrease of the saturation magnetic flux density is large.

[0030] Si and B are elements which are particularly useful in reducing the size of crystal grains of the Fe-based nanocrystalline alloy. The Fe-based nanocrystalline alloy is obtained by, for example, after an amorphous alloy is obtained by the effect of addition of Si and B, performing a heat treatment so as to form nanocrystalline grains. The content of Si is in the range of 10 to 20 atom%. A preferred content of Si is in the range of 14 to 20 atom%. If the content of Si is less than 10 atom%, the amorphous formability of the alloy is low, so that it is difficult to stably produce amorphous matter. Further, decrease of the crystalline magnetic anisotropy of the alloy is insufficient, and therefore, it is difficult to achieve excellent soft magnetic properties (e.g., low coercivity). If the content of Si exceeds 20 atom%, decrease of the saturation magnetic flux density of the alloy is large, and the resultant alloy is likely to embrittle. Note that the content of B is in the range of 5 to 10 atom%. B is an element indispensable for formation of amorphous matter. If the content of B is less than 5 atom%, the amorphous formability is low, so that it is difficult to stably produce amorphous matter. If the content of B exceeds 10 atom%, decrease of the saturation magnetic flux density is large. A still preferred content of B is not more than 7 atom%. If the contents of Si and B are excessively large, the saturation magnetic flux density of the alloy markedly decreases.

[0031] The Fe-based nanocrystalline alloy may contain at least one element selected from the group consisting of C, Ge, P, Ga, Sb, In, Be and As in a proportion of not more than 10 atom%. These elements are useful in conversion to amorphous matter in formation of an amorphous alloy ribbon. When added together with Si and B, these elements assist the conversion to amorphous matter and provide the effect of adjusting the magnetostriction and the Curie temperature.

[0032] Elements such as V, Cr, Mn, Al, platinum-group elements, Sc, Y, rare earth elements, Au, Zn, Sn, Re and the like have the effect of improving the anticorrosiveness, the effect of improving the magnetic properties, and the effect of adjusting the magnetostriction. The content of such elements is not more than 10 atom% at the highest. If the content exceeds 10 atom%, the saturation magnetic flux density markedly decreases. A particularly preferred content of these elements is not more than 8 atom%. Of these elements, when at least one element selected from the group consisting of Ru, Rh, Pd, Os, Ir, Pt, Au, Cr and V is added, the resultant core has particularly excellent anticorrosiveness.

[0033] The major constituent of the remaining part, exclusive of impurities, is substantially Fe. Part of Fe can be substituted with Co and/or Ni. The content of M (Co and/or Ni) in the above formula, a, is $0 \leq a < 0.5$. If a exceeds 0.3, there is a probability that the core loss increases. Therefore, preferably $0 \leq a \leq 0.3$. Here, to achieve high magnetic permeability, $a=0$ is preferred.

[0034] Next, an embodiment of the manufacturing method of the current transformer core according to the present disclosure is described.

[0035] First, an amorphous alloy ribbon, which is to be a soft magnetic material layer, is formed from a molten alloy which has the above-described composition by a known liquid quenching method (rapid quenching method) such as single-roll method, double-roll method, and the like. In the present disclosure, the thickness of the amorphous alloy ribbon is not more than 15 μm . The lower limit of the thickness can be set to, for example, 8 μm from the viewpoint of mass production. The peripheral velocity of a cooling roll can be set to, for example, about 15 to 50 m/sec. The cooling roll can be made of pure copper that has excellent thermal conductivity or a copper alloy such as Cu-Be, Cu-Cr, Cu-Zr and Cu-Zr-Cr. In the case of mass production, the cooling roll can be water-cooled. In formation of the amorphous alloy ribbon, the temperature variation of the roll is kept small because formation of the amorphous organization of the alloy can sometimes differ depending on the cooling rate. Note that the thickness of the amorphous alloy ribbon, t, is a value obtained by a weight conversion method. For example, the weight M of a sample of 2 m (longitudinal direction) $\times$ 50 mm (width direction) is measured from a long amorphous alloy ribbon, and the density d [kg/m^3] is determined by dry density measurement (e.g., measurement with an AccuPyc II 1340 series product manufactured by SHIMADZU CORPORATION) according to a constant volume expansion method. With the weight M and the density d, thickness t[m] = $M/((2 \times 50^{-3}) \times d)$ can be calculated.

[0036] The length of an amorphous alloy ribbon industrially manufactured by the liquid quenching method exceeds several kilometers. As such, in a casting process which lasts a long time, it is important to maintain a sufficient cooling capacity immediately after ejection of a molten alloy to the cooling roll. That is, due to the sufficient cooling capacity, an alloy of an amorphous organization can be stably obtained. As for the thickness of the alloy ribbon to be manufactured, it is estimated that, as the thickness decreases, cooling is easier and amorphous matter is stably obtained. However, according to research conducted by the present inventor, it was found that when the alloy ribbon thickness is not more than 15 μm , high magnetic permeability is stably achieved in a manufactured core. The reasons for this are not elucidated

but can be estimated as follows. Due to the reduced thickness of the alloy ribbon, an amorphous organization is obtained extremely stably, and furthermore, in generation of a nanocrystallized organization by a heat treatment, the crystal grain diameter of the organization is generally uniform and very small.

[0037] The process of producing an amorphous alloy by the liquid quenching method can be carried out in air when this alloy does not include an active metal. When the alloy includes an active metal, production of the amorphous alloy may be carried out in an inert gas such as Ar or He or in a reduced pressure atmosphere. Quenching may be carried out in an atmosphere including a nitrogen gas, a carbon monoxide gas or a carbon dioxide gas. It is advantageous that the surface roughness of the amorphous alloy solidified by quenching is small. The surface roughness of the amorphous alloy ribbon (arithmetic average roughness Ra) can be set to, for example, 5 μm or smaller, preferably 2 μm or smaller, more preferably 1 μm or smaller.

[0038] A ring-shaped structure can be produced by winding or layering the amorphous alloy ribbon. The thus-produced ring-shaped structure (core element) has such a configuration that a plurality of amorphous alloy layers are layered. There may be a small gap or any other material between respective ones of the amorphous alloy layers. The volume occupancy of the amorphous alloy layers in the core element is, for example, about 70% to 90%.

[0039] In the present embodiment, a core element formed by winding the amorphous alloy ribbon is provided. However, the present disclosure is not limited to such an example.

[0040] Next, a crystallizing heat treatment is performed as follows. A core element formed by winding or layering the amorphous alloy layer is heated in a nonreactive atmosphere gas. According to research conducted by the present inventor and his coworkers, sufficient magnetic permeability was achieved when the heat treatment was carried out in a nitrogen gas. The nitrogen gas can be used substantially as the nonreactive gas. An inert gas can also be used as the nonreactive gas. The heat treatment may be performed in vacuum.

[0041] The temperature of the above-described crystallizing heat treatment can be set within the range of 510°C to 600°C. The temperature of the crystallizing heat treatment is preferably set to 550°C to 600°C. If the heat treatment temperature is less than 510°C or more than 600°C, the magnetostriction is large. The retention time at the above-described heat treatment temperature (heat treatment duration) can be set within the range of about 5 minutes to 24 hours. If the heat treatment duration is shorter than 5 minutes, it is difficult to maintain the entirety of the alloy that forms the core at a uniform temperature, so that the magnetic properties are likely to vary. On the other hand, if the heat treatment duration is longer than 24 hours, not only deterioration of productivity but also deterioration of the magnetic properties is likely to occur due to excessive growth of crystal grains or generation of crystal grains in uneven forms.

[0042] In the present embodiment, the crystallizing heat treatment is performed in a DC or AC magnetic field. Such a heat treatment performed in a magnetic field causes a magnetic anisotropy in the alloy used in the current transformer core. The magnetic field may be applied during the entire period of the heat treatment or may be applied during a portion of the period of the heat treatment. The magnetic field is applied in the longitudinal direction of the alloy layer in the core element formed by winding the amorphous alloy layer (the circumferential direction of the ring-shaped core element). The intensity of the applied magnetic field is set to, for example, 100 A/m or greater such that the alloy layer reaches magnetic saturation. Such a magnetic field is referred to as "longitudinal magnetic field". A crystallizing heat treatment performed in the presence of an applied longitudinal magnetic field is referred to as "longitudinal-field heat treatment". As the intensity of the longitudinal magnetic field increases, the magnetic permeability $\mu_r(T)$ increases. When the intensity of the longitudinal magnetic field increases to some level, $\mu_r(T)$ saturates (see FIG. 3 which will be described later).

[0043] On the other hand, when a longitudinal magnetic field is applied to the ring-shaped core element to such an extent that the alloy layer reaches magnetic saturation, the residual magnetic flux density Br greatly increases, and the ratio of the residual magnetic flux density Br and the saturation magnetic flux density Bm, Br/Bm, increases. In the present application, the saturation magnetic flux density Bm is defined as the magnetic flux density B(80) with the magnetic field H=80 A/m. Br/Bm is also referred to as "squareness ratio".

[0044] After the longitudinal-field heat treatment, a magnetic field is applied in the vertical direction of the core. For example, the heat treatment temperature is not less than 200°C. The magnetic field is applied for 20 minutes or longer at a temperature less than the crystallizing temperature of the amorphous alloy. The intensity of the applied magnetic field is, for example, not less than 80 kA/m. Such a magnetic field is referred to as "transverse magnetic field". A heat treatment performed in the presence of an applied transverse magnetic field is referred to as "transverse-field heat treatment". The longitudinal magnetic field and the transverse magnetic field may be any of a DC magnetic field, an AC magnetic field and a pulsed magnetic field. Due to the transverse-field heat treatment, the residual magnetic flux density Br decreases although the magnetic permeability decreases and, accordingly, Br/Bm decreases, resulting in a current transformer core in which a magnetic deviation is unlikely to occur. Since high magnetic permeability is achieved due to the longitudinal-field heat treatment, the magnetic permeability of the core after the transverse-field heat treatment is higher than the conventional level, and the high magnetic permeability is maintained within the use temperature range, so that the temperature characteristics are excellent.

< Magnetic permeability >

[0045] In the present application, the term "magnetic permeability" has the same meaning as "relative magnetic permeability". A magnetic permeability measured at temperature T (°C) in the presence of an applied AC magnetic field of frequency f=50 Hz and amplitude H=1.0 ampere/meter (A/m) is referred to as "amplitude magnetic permeability", which is expressed as "magnetic permeability $\mu_r(T)$ " or simply " $\mu_r(T)$ ". When the measurement temperature is not particularly specified, the magnetic permeability means a value measured at 25°C, i.e., $\mu_r(25)$. For the sake of simplicity, $\mu_r(25)$ is sometimes simply expressed as " μ_r " in the drawings.

[0046] The magnetic permeability of a core which is subjected to the longitudinal-field heat treatment with such a magnetic field intensity that the variation (increase) of the magnetic permeability is not found any more even when the applied longitudinal magnetic field is increased is defined as " $\mu_r(\max)(T)$ ". In the embodiment of the present disclosure, when the intensity of the longitudinal magnetic field during the crystallizing heat treatment is 100 A/m, the variation (increase) of the magnetic permeability is not found at a lower magnetic field intensity (e.g., 90 A/m). Therefore, $\mu_r(\max)(T)$ of the present application means the magnetic permeability of a core which is obtained when the longitudinal magnetic field intensity during the crystallizing heat treatment is 100 A/m.

[0047] FIG. 1 is a diagram showing the configuration of a measurement system used in measurement of the magnetic permeability $\mu_r(T)$. In the shown configuration, the primary side conductor 14 of the current transformer is coupled with a function generator 54 configured to generate an AC voltage signal which has an arbitrary frequency and an arbitrary waveform, via a digital multimeter (DMM) 52 which is capable of measuring the DC voltage, direct current, AC voltage and electric resistance over a wide range and a resistance R. Meanwhile, the secondary side conductor 12 of the current transformer is coupled with another digital multimeter (DMM) 56 that is different from the digital multimeter 52 on the primary side conductor 14 side. In the measurement of the present application, the value of the resistance R was set to 47 ohms, and digital multimeter 34401A manufactured by Agilent Technologies was used as the digital multimeters 52 and 56. Multifunction generator WF1973 manufactured by NF CORPORATION was used as the function generator 54 for generation of an AC voltage signal.

[0048] The magnetic permeability $\mu_r(T)$ is determined by the following formula based on the result of a measurement at temperature T:

$$\mu_r(T) = \frac{V_o}{4.44 \times f \times A_e \times H \times \mu_0}$$

where V_o (V) is the voltage value measured by the digital multimeter (DMM) 56, A_e (m²) is the effective cross-sectional area of the core, μ_0 is the magnetic permeability in vacuum, f (Hz) is the frequency, and H (A/m) is the intensity of an AC magnetic field applied by the primary side conductor 14.

[0049] In the present embodiment, the heat treatment is divided into two phases, in which magnetic fields of different directions are applied. By performing such a distinctive heat treatment in magnetic fields, a current transformer core which exhibits excellent magnetic properties can be realized. In the first phase heat treatment in a magnetic field, the magnetic field is formed in the direction of a magnetic path formed in a ring-shaped core element ("longitudinal-field heat treatment"). By this heat treatment, the core element is changed to a core. Then, in the second phase heat treatment in a magnetic field, the magnetic field is formed in a direction perpendicular to the direction of the above-described magnetic path and applied to the core ("transverse-field heat treatment"). By appropriately performing such a two-phase heat treatment in the magnetic fields, a current transformer core of excellent magnetic properties can be obtained. This aspect is described in detail in the following section.

< Effects of longitudinal-field heat treatment on magnetic permeability $\mu_r(25)$ >

[0050] As a result of research conducted by the present inventor, it was found that the magnetic permeability $\mu_r(25)$ after the longitudinal-field heat treatment largely varies depending on the thickness of the Fe-based nanocrystalline alloy ribbon. First, this point is described below.

[0051] FIG. 2A is a graph illustrating the magnetic permeability $\mu_r(25)$ in the case where a core element was formed by winding a Fe-based amorphous alloy ribbon (thickness: 18 μ m, width: 10 mm) which had the composition of Fe₇₄Cu₁Nb₃Si_{15.5}B_{6.5}. In this example, the dimensions of the core were the inside diameter of 20 mm, the outside diameter of 30 mm, and the height of 10 mm. The heat treatment temperature (retention temperature) in the process of the longitudinal-field heat treatment was set to 520°C, 540°C and 560°C. The magnetic permeability $\mu_r(25)$ was evaluated based on four samples for each of the retention temperatures. The retention time at the retention temperature was one hour for each sample. The temperature increase rate up to the retention temperature was 6°C/min. The temperature decrease rate from the retention temperature was 1.5°C/min. The applied magnetic field was 230 A/m. The magnetic

field was applied over the entire temperature range. By this heat treatment process, the Fe-based amorphous alloy ribbon was crystallized and changed into a Fe-based nanocrystalline alloy ribbon.

[0052] As seen from FIG. 2A, when the retention temperature of the longitudinal-field heat treatment was decreased from 560°C to 520°C, the average of the magnetic permeability $\mu_r(25)$ increased from about 4×10^5 to about 5.5×10^5 , although there was a large variation. Br/Bm calculated from the saturation magnetic flux density Bm and the residual magnetic flux density Br that were determined from B-H curves was 0.93 in each sample.

[0053] FIG. 2B is a graph illustrating the magnetic permeability $\mu_r(25)$ in the case where a core element was formed by winding a Fe-based amorphous alloy ribbon (thickness: 13 μm , width: 10 mm) which had the composition of $\text{Fe}_{74}\text{Cu}_1\text{Nb}_3\text{Si}_{15.5}\text{B}_{6.5}$ (which was the same as that of the above-described 18 μm thick Fe-based amorphous alloy ribbon). The dimensions of the core and the heat treatment (annealing) conditions were the same as those of the core of FIG. 2A. The heat treatment temperature (retention temperature) in the process of the longitudinal-field heat treatment was set to 520°C, 540°C and 560°C. The magnetic permeability $\mu_r(25)$ was evaluated based on four samples for each of the retention temperatures. By the process of the longitudinal-field heat treatment, the Fe-based amorphous alloy ribbon was crystallized and changed into a Fe-based nanocrystalline alloy ribbon.

[0054] As seen from FIG. 2B, the average of the magnetic permeability $\mu_r(25)$ exhibits a value generally equal to about 9×10^5 irrespective of the temperature of the longitudinal-field heat treatment. Br/Bm calculated from the maximum magnetic flux density Bm and the residual magnetic flux density Br that were determined from B-H curves was 0.93 in each sample. Note that Bm is the magnetic flux density B(80) at the magnetic field H=80 A/m. When a relatively thin, 13 μm thick Fe-based amorphous alloy ribbon was thus used, the magnetic permeability $\mu_r(25)$ greatly increased and, furthermore, the value of the magnetic permeability $\mu_r(25)$ was stabilized. On the other hand, irrespective of the thickness of the ribbon, Br/Bm exceeded 0.9 and was equal to 0.93. High magnetic permeability $\mu_r(25)$ with the thickness of 13 μm was more than expected. Based on this knowledge, the present disclosure defines the thickness of the Fe-based nanocrystalline alloy ribbon as one of the means for improving the magnetic permeability.

[0055] Of the samples shown in FIG. 2B, a sample obtained by the heat treatment at 560°C is hereinafter referred to as "Sample 1". Effects of the intensity of the longitudinal magnetic field on the magnetic properties were examined using Sample 1.

[0056] FIG. 3 is a graph illustrating the variation of the magnetic permeability $\mu_r(25)$ of such a core that the dimensions of the core and the heat treatment conditions were the same as those of Sample 1 except for the intensity of the longitudinal magnetic field. The intensity of the longitudinal magnetic field was adjusted within the range of 6 A/m to 115 A/m by adjusting a longitudinal magnetic field forming current flowing through a conductor wire (conductor wire for formation of a longitudinal magnetic field) which was arranged so as to penetrate through the central opening of a ring-shaped core element in the longitudinal-field heat treatment. The value of $\mu_r(25)$ of the core at a longitudinal magnetic field intensity of not less than 75 A/m as shown in FIG. 3 is about 9.5×10^5 . This value is large as compared with the value of $\mu_r(25)$ of Sample 1 shown in FIG. 2B (about 8.7×10^5). Such a difference in value is probably attributed to the variation of the core samples.

[0057] As seen from FIG. 3, when the intensity of the longitudinal magnetic field is not less than 80 A/m, the magnetic permeability $\mu_r(25)$ saturates.

[0058] FIG. 4 is a graph illustrating the temperature characteristic of the magnetic permeability $\mu_r(T)$ of the core for each of Sample A where the longitudinal magnetic field during the longitudinal-field heat treatment was 19 A/m and Sample B (Sample 1) where the longitudinal magnetic field during the longitudinal-field heat treatment was 230 A/m. In the graph, the horizontal axis represents the measurement temperature T, and the vertical axis represents the magnetic permeability $\mu_r(T)$.

[0059] As seen from FIG. 4, in Sample A for which the longitudinal magnetic field intensity was relatively small, the magnetic permeability $\mu_r(T)$ sharply decreased as the measurement temperature T increased. Where the amplitude magnetic permeability of the core measured at 100°C was represented by $\mu_r(100)$, the amplitude magnetic permeability of the core measured at 0°C was represented by $\mu_r(0)$, and $[\mu_r(100)-\mu_r(0)]/\mu_r(0)$ was represented by $\Delta\mu_r(100-0)$, $\Delta\mu_r(100-0)$ was about 0.55. On the other hand, in Sample B (Sample 1) for which the longitudinal magnetic field intensity was relatively large and the magnetic permeability $\mu_r(25)$ saturated and exhibited the maximum value, the magnetic permeability $\mu_r(T)$ decreased as the measurement temperature T increased. This tendency was the same as that of Sample A. However, $\Delta\mu_r(100-0)$ was a small value, 0.14, and the variation of the magnetic permeability within the use temperature range of 0°C to 100°C was suppressed, resulting in excellent temperature characteristics.

[0060] Sample A also exhibited high squareness as Sample B (Sample 1) did, i.e., Br/Bm was 0.93, according to the direct current B-H curve and had such magnetic properties that a magnetic deviation is likely to occur.

[0061] It was found from the above-described results that Br/Bm cannot be decreased by changing the longitudinal magnetic field intensity.

[0062] As seen from the foregoing, when the thickness of the Fe-based amorphous alloy is not more than 15 μm and the longitudinal magnetic field intensity during the crystallizing heat treatment is set such that the alloy has a sufficient magnetic anisotropy, large magnetic permeability and excellent temperature characteristics can be achieved. However,

the Br/Bm is not decreased, and a magnetic deviation is likely to occur. Further improvements are necessary for uses of the current transformer core.

[0063] The present inventor wholeheartedly carried out extensive researches and, as a result, found that by performing a manufacturing process which will be described below a current transformer core can be realized of which practically sufficiently high magnetic permeability is stably achieved within the use temperature range, and Br/Bm is greatly decreased, although the magnetic permeability is lower than that achieved by the longitudinal-field heat treatment. That is, firstly, the thickness of the Fe-based amorphous alloy is controlled to be not more than 15 μm , and the longitudinal magnetic field intensity during the process of the longitudinal-field heat treatment is set to such an extent that the alloy has a sufficient magnetic anisotropy (e.g., not less than 100 A/m), whereby a core is manufactured in which a relatively high value of the magnetic permeability $\mu_r(25)$ can be realized. Thereafter, an appropriate transverse-field heat treatment is performed on the core, whereby reduction of Br/Bm is realized. In the following section, measurement results are described in detail.

[0064] FIG. 5 is a graph illustrating an example of the profiles of the temperature and the magnetic field intensity of the transverse-field heat treatment in the present embodiment. In the graph, the temperature profile is represented by a solid line, and the magnetic field intensity profile is represented by a dotted line. In this example, a transverse magnetic field of 160 kA/m was applied to the core over a period including the entirety of the period where the temperature of the core increased, the period where the core was retained at a predetermined heat treatment temperature, and the period where the temperature of the core decreased (about 4 hours). In the example of FIG. 5, the heat treatment temperature was 400°C, and the retention time was 1 hour and 30 minutes (90 minutes).

[0065] FIG. 6 is a graph illustrating B-H curves of current transformer cores obtained by further applying a transverse magnetic field according to the profile illustrated in FIG. 5 to Sample 1 of which the dimensions of the core were the inside diameter of 20 mm, the outside diameter of 30 mm, and the height of 10 mm, with the duration for which the core was retained at the heat treatment temperature of 400°C (retention time) being set to 60 minutes, 90 minutes and 120 minutes, and B-H curves of the core of Sample 1 before the transverse-field heat treatment. The samples with the retention time of 60 minutes, 90 minutes and 120 minutes are Example 1, Example 2 and Example 3, respectively. Table 1 presented below shows, for respective samples, the values of the maximum magnetic flux density Bm, the residual magnetic flux density Br, the coercivity Hc, and the squareness ratio Br/Bm, which were determined from the B-H curves of FIG. 6. Bm is the magnetic flux density B(80) at magnetic field H=80 A/m.

[Table 1]

	Before transverse-field heat treatment (Comparative Example)	Retention time 60 minutes (Example 1)	Retention time 90 minutes (Example 2)	Retention time 120 minutes (Example 3)
Bm (T)	1. 150	1. 167	1. 153	1. 150
Br (T)	1. 064	0. 797	0. 759	0. 677
Hc (A/m)	0. 59	0. 67	0. 72	0. 72
Br/Bm	0. 93	0. 68	0. 66	0. 59

[0066] As seen from FIG. 6 and Table 1, by adding the transverse-field heat treatment, the residual magnetic flux density Br decreases as compared with that achieved before the heat treatment. Since the variation of Bm is small, Br/Bm can decrease to be less than 0.9. By elongating the retention time of the heat treatment, the residual magnetic flux density Br and Br/Bm are further decreased.

[0067] FIG. 7 is a graph illustrating the relationship between the retention time of the transverse-field heat treatment (400°C) and $\mu_r(25)$ in Examples 1 to 3. The magnetic permeability $\mu_r(25)$ after the longitudinal-field heat treatment of the measured core (magnetic field intensity: 100 A/m) saturates with respect to the magnetic field intensity and exhibits the maximum value. This maximum value, $\mu_r(\text{max})(25)$, was 9.5×10^5 . For each retention time, $\mu_r(25)$ of two samples were measured. Table 2 shows the relationship between the retention time and the magnetic permeability $\mu_r(25)$, $\mu_r(25)/\mu_r(\text{max})(25)$.

[Table 2]

	Retention time (min)	$\mu_r(25) (\times 10^5)$	$\mu_r(25)/\mu_r(\max) (25)$
Example 1	60	7.18	0.76
		7.87	0.83
Example 2	90	5.76	0.61
		5.93	0.62
Example 3	120	4.57	0.48
		4.36	0.46

[0068] As seen from FIG. 7 and Table 2, the magnetic permeability $\mu_r(25)$ decreased as the retention time of the transverse-field heat treatment increased. The magnetic permeability $\mu_r(25)$ monotonically decreases with respect to the retention time. In this example, the magnetic permeability can be estimated by the formula of $\mu_r(25) = (10.5 - 0.05 \times t) \times 10^5$ where $\mu_r(25)$ is the magnetic permeability and t is the retention time (min). In other words, the magnetic permeability can be adjusted by controlling the retention time of the transverse-field heat treatment.

[0069] FIG. 8 is a graph illustrating the measurement temperature dependence of the magnetic permeability of the sample of Example 2, which is one of the above-described samples, where the duration for which the heat treatment temperature was retained at 400°C (retention time) was set to 90 minutes.

[0070] As seen from this graph, over a wide range from about -50°C to about 100°C, the magnetic permeability increases generally monotonically as the measurement temperature increases, and $\mu_r(100) - \mu_r(0)$ has a positive value. $\Delta\mu_r(100-0)$ of the current transformer core measured at temperature T (°C) in the presence of an applied AC magnetic field which had frequency $f=50$ Hz and amplitude $H=1.0$ A/m was about 0.25. Likewise, also in the samples of Example 1 and Example 3, $\Delta\mu_r(100-0)$ was not more than 0.5.

[0071] FIG. 9 is a graph illustrating the relationship between the magnetic field intensity in the transverse-field heat treatment and the magnetic permeability $\mu_r(25)$. A Fe-based amorphous alloy ribbon (thickness: 13 μm , width: 10 mm) was produced which had the same alloy composition of $\text{Fe}_{74}\text{Cu}_1\text{Nb}_3\text{Si}_{15.5}\text{B}_{6.5}$ as Sample 1 but which was from a different production lot. The alloy ribbon was wound to form a core element. The core element was subjected to a longitudinal-field heat treatment under the same conditions as those of Sample 1. Further, a transverse-field heat treatment was performed on the core which had been subjected to the longitudinal-field heat treatment. In the heat treatment, the retention temperature was 380°C, and the retention time was 90 minutes. $\mu_r(25)$ of the respective samples in the cases where the transverse magnetic field intensity was 80 kA/m (Example 4), 160 kA/m (Example 5), and 320 kA/m (Example 6) are shown in the graph. As the magnetic field intensity increases, $\mu_r(25)$ monotonically decreases. It is understood that the magnetic permeability of the core can be adjusted by controlling the transverse magnetic field intensity in the heat treatment. In each of Examples 4 to 6, the evaluated Br/Bm was less than 0.9. Br/Bm had a tendency to decrease as the magnetic field intensity increases. In each of Examples 4 to 6, $\Delta\mu_r(100-0)$ was not more than 0.5. In Examples 4 to 6, $\mu_r(25)/\mu_r(\max)$ was 0.5 to 0.7. Here, the magnetic permeability $\mu_r(25)$ of the core after the longitudinal-field heat treatment (magnetic field intensity: 100 A/m) saturated with respect to the magnetic field intensity and exhibited the maximum value. $\mu_r(\max)(25)$ was 8×10^5 .

[0072] As understood from the foregoing description, a manufacturing method of a current transformer core according to the present disclosure includes: the step of providing a core element formed by winding or layering a Fe-based amorphous alloy ribbon whose thickness is not more than 15 μm and which can be converted into nanocrystals; a longitudinal-field heat treatment step which includes performing a heat treatment on the core element in the presence of a magnetic field applied in a magnetic path direction of the core element so as to crystallize the amorphous alloy, thereby obtaining a core; and a transverse-field heat treatment step which includes performing a heat treatment on the core obtained after the longitudinal-field heat treatment step in the presence of a magnetic field applied in a direction perpendicular to the magnetic path direction of the core, thereby forming a current transformer core. By the transverse-field heat treatment step, $\mu_r(25)$ is adjusted to a value between $0.4 \times \mu_r(\max)(25)$ and $0.9 \times \mu_r(\max)(25)$ where $\mu_r(T)$ is the amplitude magnetic permeability measured at temperature T (°C) in the presence of an applied AC magnetic field of frequency $f=50$ Hz and amplitude $H=1.0$ A/m, and $\mu_r(\max)(T)$ is $\mu_r(T)$ after the longitudinal-field heat treatment step (before the transverse-field heat treatment). As a result, a current transformer core is obtained which has such excellent temperature characteristics that $\Delta\mu_r(100-0)$ is not more than 0.5 and Br/Bm is less than 0.9 where $\Delta\mu_r(100-0)$ is $|\mu_r(100) - \mu_r(0)|/\mu_r(0)$ measured after manufacture.

[0073] FIG. 10 is a flowchart illustrating an example of the manufacturing method of a current transformer core according to the present disclosure. As described above, at step S120, a core element is provided which is formed by winding or layering a Fe-based amorphous alloy ribbon whose thickness is not more than 15 μm .

[0074] Then, at step S140, a longitudinal-field heat treatment is performed. The treatment temperature of the longitudinal-field heat treatment can be set to a temperature not less than the crystallizing temperature, e.g., within the range of 510 to 600°C. The retention time of the treatment temperature can be set within the range of 5 minutes to 24 hours. If it is shorter than 5 minutes, it is difficult to obtain magnetic properties with small variations among respective cores. If it is longer than 24 hours, the productivity greatly deteriorates. The intensity of an applied longitudinal magnetic field can be set within the range of not less than 100 A/m. If the longitudinal magnetic field intensity is less than 100 A/m, there is a probability that provision of a magnetic anisotropy is insufficient. If the longitudinal magnetic field intensity exceeds 300 A/m, it is difficult stably carry out the treatment.

[0075] Then, at step S160, a transverse-field heat treatment is performed. The treatment temperature of the transverse-field heat treatment can be set to a temperature less than the crystallizing temperature, e.g., within the range of not less than 200°C and less than the longitudinal-field heat treatment temperature. If it is less than 200°C, there is a probability that the effects of the magnetic field treatment are insufficient. If it is not less than the longitudinal-field heat treatment temperature, there is a probability that the effects of the longitudinal magnetic field treatment greatly decrease, and the effects brought about by a different magnetic field treatment, i.e., a transverse magnetic field treatment performed after the longitudinal magnetic field treatment in the present disclosure, cannot be achieved. The retention time of the treatment temperature can be set within the range of 20 minutes to 120 minutes. If the retention time is less than 20 minutes, there is a probability that the magnetic field application effect (provision of a magnetic anisotropy) is insufficient. If the retention time exceeds 120 minutes, the productivity decreases. The intensity of the applied transverse magnetic field can be set within the range of 80-320 kA/m. If the transverse magnetic field intensity is less than 80 kA/m, there is a probability that provision of a magnetic anisotropy is insufficient. If the transverse magnetic field intensity exceeds 320 kA/m, a stable magnetic field intensity is unlikely to be obtained, and the treatment becomes difficult.

[0076] Between step S140 and step S160, the core can be cooled to about the room temperature. Desirably, application of the transverse magnetic field is continued till the core is sufficiently cooled to a temperature not more than 200°C.

[0077] Typically, when used, the current transformer core can be housed in a case which is made of a resin, or the like, for the purpose of protection of the current transformer core itself and insulation of a coil from the other circuit elements. A core element formed by winding an alloy ribbon is formed of an elongated ribbon-shaped continuous alloy layer and is therefore advantageous in terms of handleability. After the current transformer core of the present embodiment is housed in a case which is made of a resin or the like, a coil is formed around the core for sensing, whereby a current transformer can be manufactured.

< Current Transformer >

(Example 7)

[0078] FIG. 11A shows an example of the basic structure of a current transformer **100** to which the present disclosure is applicable. The current transformer **100** typically includes a ring-shaped (cylindrical) core **10** and a secondary side conductor (secondary side coil) **12** coiled around the core **10** such as shown in FIG. 11A. The primary side conductor **14**, which is the object of the current measurement, can typically be inserted so as to extend through the center opening of the core **10**. The primary side conductor **14** may be wound around the core **10** so as to make two or more turns as is the secondary side conductor **12**. The primary side conductor **14** and the secondary side conductor **12** can be an arbitrary known wire whose surface is covered for insulation.

[0079] In the example of FIG. 11A, only part of each of the primary side conductor **14** and the secondary side conductor **12** is schematically shown. The shown primary side conductor **14** has the shape of a linear stick, although the actual shape of the primary side conductor **14** is not limited to such a shape. Both ends of the primary side conductor **14** are electrically coupled with an unshown wire, circuit, voltage source or current source.

[0080] When an electric current flows through the primary side conductor **14** shown in FIG. 11A, a magnetic field is produced around the primary side conductor **14**, and a closed magnetic path is formed in the ring-shaped core **10** that has high magnetic permeability. When an alternating current is flowing through the primary side conductor **14**, the magnetic flux density in the core **10** periodically varies so that an AC voltage is produced in the secondary side conductor **12**. As a result, an electric current flows through an unshown circuit coupled with the secondary side conductor **12**. The electric current flowing through the primary side conductor **14** can be measured based on the voltage or current output to the secondary side conductor **12**.

[0081] FIG. 11B shows an example where the current transformer **100** is applied to a zero-phase current transformer (ZCT). In the example of FIG. 11B, the electric currents flowing through the primary side conductors **14** of a single-phase, two-line system are the object of measurement. In the case of a single-phase, three-line system, three primary side conductors are arranged so as to extend through the opening of the core **10** although not shown. The zero-phase current transformer is capable of sensing a leakage current when an abnormal current resulting from electrical leakage flows through the primary side conductors **14**. The configuration of the current transformer **100** can be designed such

that, when a leakage current of 30 milliamperes (mA) flows at the frequency of, for example, 50 Hz through the primary side conductors **14**, a voltage of 4 millivolts (mV) is produced in the secondary side conductor **12**.

< Earth leakage circuit breaker >

(Example 8)

[0082] FIG. **12** shows a circuit configuration example of an earth leakage circuit breaker **20** which includes the current transformer **100** such as shown in FIG. **11B**. This earth leakage circuit breaker **20** includes a current transformer core **10**, a secondary side conductor **12** coiled around the core **10**, a sensing circuit **16** coupled with the secondary side conductor **12**, and a trip device **18** coupled with the sensing circuit **16**.

[0083] In the example of FIG. **12**, an alternating current from a transformer **30** is supplied to the earth leakage circuit breaker **20** via wires of a single-phase, two-line system. The transformer **30** is coupled with, for example, an electric power system for business purposes or any other AC power supply. The earth leakage circuit breaker **20** is placed on an electrical path coupled with a load **40**. The load **40** can be an electronic device or electric machine which is configured to receive an AC power for operation. The earth leakage circuit breaker **20** is placed in, for example, a distribution board.

[0084] In a normal state, the sum of electric currents flowing through a pair of primary side conductors **14** is zero. In this case, the trip device **18** of the earth leakage circuit breaker **20** maintains the electrical path in a conducting state, and the load **40** receives an AC power from the transformer **30**. When electrical leakage occurs due to, for example, deteriorated insulation of the load **40**, an ground fault current flows from the load **40**. Accordingly, the total of the electric currents flowing through the pair of primary side conductors **14** exhibits a significant value exceeding zero, and as a result, a voltage is produced in the secondary side conductor **12**. Describing based on the above-described example, the configuration of the current transformer **100** is designed such that when an alternating current of 30 mA flows at the frequency of, for example, 50 Hz as a leakage current, a voltage of 4 mV is produced in the secondary side conductor **12**. In this case, the leakage current of 30 mA refers to the difference between the currents flowing through the pair of primary side conductors **14**, rather than each of the currents flowing through the pair of primary side conductors **14**.

[0085] The sensing circuit **16** activates the trip device **18** based on the voltage or current produced in the secondary side conductor **12**. When the voltage or current produced in the secondary side conductor **12** exceeds a predetermined threshold, the sensing circuit **16** activates the trip device **18** in order to shut off the current flowing from the transformer **30** to the load **40**. The earth leakage circuit breaker **20** is configured such that, when an abnormal current which is equal to or greater than a predetermined value flows through the primary side conductor **14** due to electrical leakage, the earth leakage circuit breaker **20** automatically shuts off the current for a short time period, e.g., not more than 0.1 second.

[0086] The current transformer **100** used in such an earth leakage circuit breaker **20** is required to appropriately sense occurrence of a feeble leakage current. The largeness of the leakage current to be sensed is defined by the standards of respective countries. If the magnetic permeability of the core **10** is low, a voltage which is produced in the secondary side conductor **12** when a feeble leakage current is produced is low, so that occurrence of the electrical leakage cannot be sensed appropriately. The upper limit of the magnetic permeability of the core **10** can be appropriately set based on the lower limit of the leakage current to be sensed. For example, when B_r/B_m is less than 0.9, the core **10** has high magnetic permeability, and therefore, the earth leakage circuit breaker **20** can have an excellent leakage shut-off function. Further, since the variation of the magnetic permeability is small within the temperature range of 0°C to 100°C as previously described, the earth leakage circuit breaker **20** can have an excellent leakage shut-off function, which is stable against variation in temperature.

[0087] In the foregoing, the embodiment has been described as an example of the technology disclosed in the present application. However, the technology in the present disclosure is not limited to the example but is applicable to embodiments to which changes, substitutions, additions, omissions, or the like, are occasionally made. Alternatively, combining some of the components described in the above embodiment into a new embodiment is also possible. The components disclosed in the attached drawings and detailed descriptions can include not only those which are indispensable in solving the problems but also those which are simply for the sake of exemplification of the above-described technology and are not indispensable in solving the problems.

[0088] Thus, it should not be acknowledged that the disclosure of those dispensable components in the attached drawings and detailed descriptions immediately means that those dispensable components are indispensable.

INDUSTRIAL APPLICABILITY

[0089] The present disclosure is applicable to a current transformer which can be used in an earth leakage circuit breaker and to a core which is suitable to the current transformer.

REFERENCE SIGNS LIST**[0090]**

- 5 **10** current transformer core
- 12** secondary side conductor (secondary side coil)
- 14** primary side conductor
- 16** sensing circuit
- 18** trip device
- 10 **20** earth leakage circuit breaker
- 30** transformer
- 40** load
- 100** current transformer

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Claims

1. A current transformer core formed by winding or layering a soft magnetic material layer, wherein

20 the soft magnetic material layer is formed of a Fe-based nanocrystalline alloy ribbon whose thickness is not more than 15 μm ,
 $\Delta\mu_r(100-0)$ is not more than 0.5 where $\Delta\mu_r(100-0)$ is $|\mu_r(100)-\mu_r(0)|/\mu_r(0)$, and $\mu_r(T)$ is an amplitude magnetic permeability of the core measured at a temperature T ($^{\circ}\text{C}$) in the presence of an applied AC magnetic field of frequency $f=50$ Hz and amplitude $H=1.0$ A/m, and
 25 the ratio of a residual magnetic flux density B_r and a saturation magnetic flux density B_m , B_r/B_m , is less than 0.9 where a magnetic flux density $B(80)$ with magnetic field $H=80$ A/m is defined as the saturation magnetic flux density B_m .
2. The current transformer core of claim 1, wherein $\mu_r(25)$ has a value between $0.4 \times \mu_r(\text{max})(25)$ and $0.9 \times \mu_r(\text{max})(25)$ where $\mu_r(\text{max})(T)$ is $\mu_r(T)$ achieved by heating a core element to not less than a crystallizing temperature in the presence of a magnetic field of not less than 100 A/m applied in a magnetic path direction (longitudinal-field heat treatment), the core element being formed by shaping a Fe-based amorphous alloy ribbon which has a substantially identical composition and shape to those of the Fe-based nanocrystalline alloy ribbon so as to have a substantially identical shape to that of the core.

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3. The current transformer core of claim 1 or 2, wherein $\mu_r(25) \geq 4 \times 10^5$ holds true.

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4. The current transformer core of any of claims 1 to 3, wherein $\mu_r(100)-\mu_r(0)$ has a positive value.
5. A manufacturing method of a current transformer core, comprising:

40 the step of providing a core element formed by winding or layering a Fe-based amorphous alloy ribbon whose thickness is not more than 15 μm and which can be converted into nanocrystals;
 a longitudinal-field heat treatment step which includes heating the core element to not less than a crystallizing temperature in the presence of a magnetic field of not less than 100 A/m applied in a magnetic path direction of the core element, thereby forming a core; and
 a transverse-field heat treatment step which includes, after the longitudinal-field heat treatment step, heating the core to a temperature less than the crystallizing temperature in the presence of a magnetic field applied in a direction perpendicular to the magnetic path direction of the core, thereby forming a current transformer core, wherein $\mu_r(25)$ is adjusted by the transverse-field heat treatment step to a value between $0.4 \times \mu_r(\text{max})(25)$ and $0.9 \times \mu_r(\text{max})(25)$ where $\mu_r(\text{max})(T)$ is $\mu_r(T)$ achieved by the longitudinal-field heat treatment step, and $\mu_r(T)$ is an amplitude magnetic permeability of the core measured at a temperature T ($^{\circ}\text{C}$) in the presence of an AC magnetic field of frequency $f=50$ Hz and amplitude $H=1.0$ A/m.
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6. The method of claim 5, wherein $\Delta\mu_r(100-0)$ is not more than 0.5 where $\Delta\mu_r(100-0)$ is $|\mu_r(100)-\mu_r(0)|/\mu_r(0)$ of a manufactured current transformer core.

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7. A device comprising:

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the current transformer core as set forth in any of claims 1 to 4;
a coil provided around the current transformer core; and
a sensing circuit coupled with the coil.

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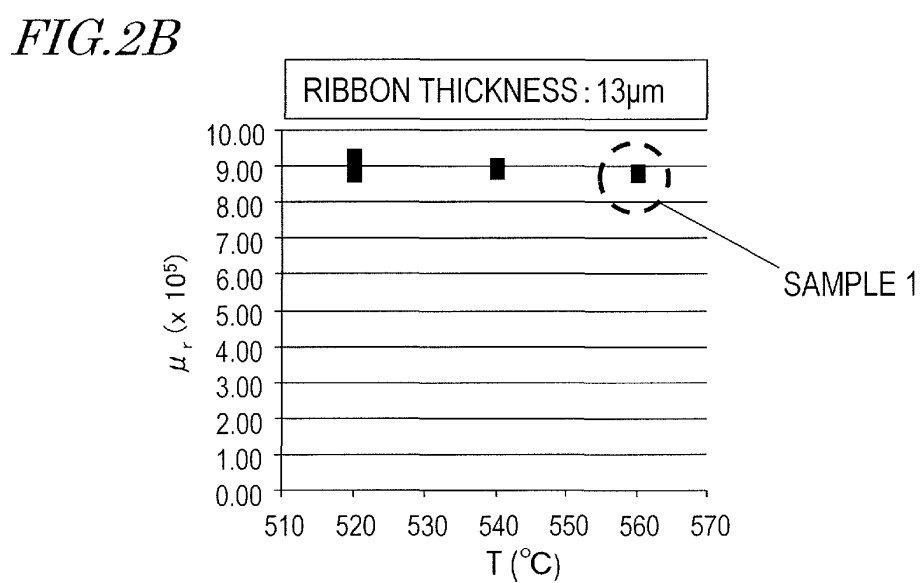
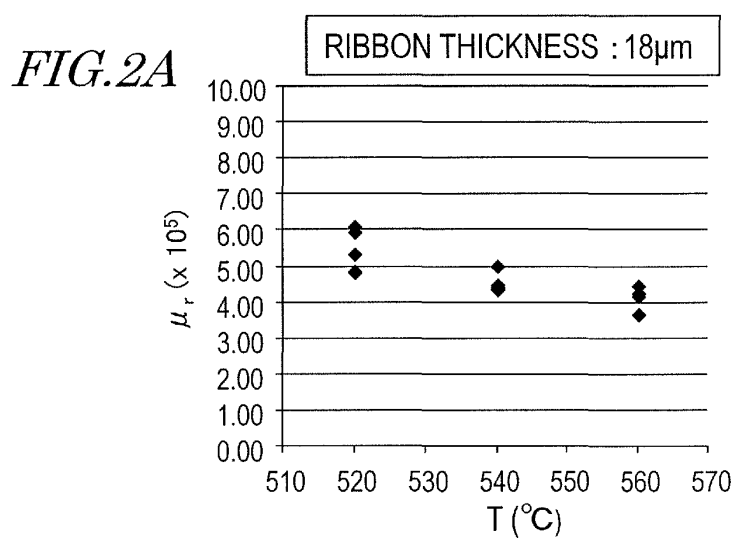
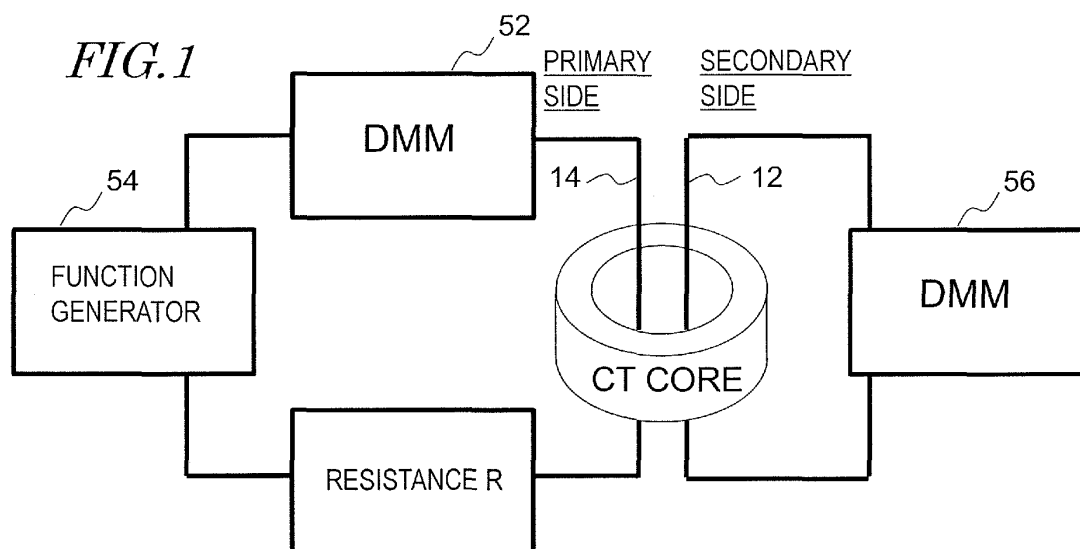


FIG. 3

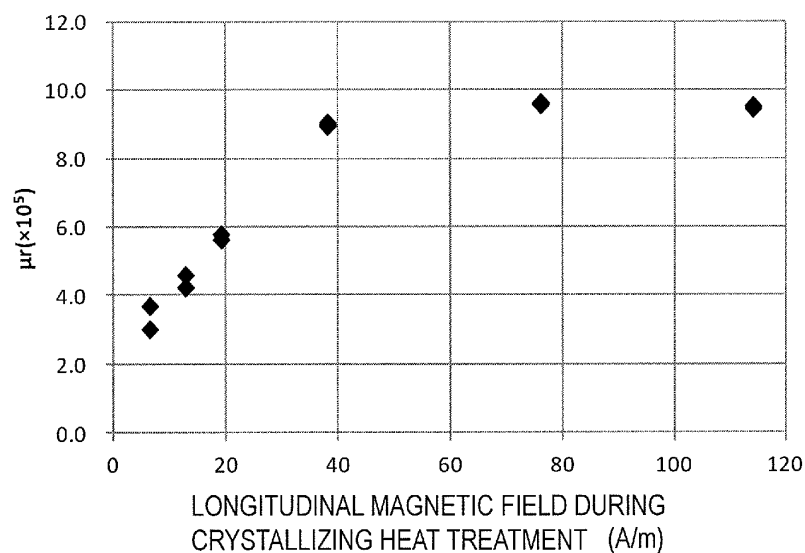


FIG. 4

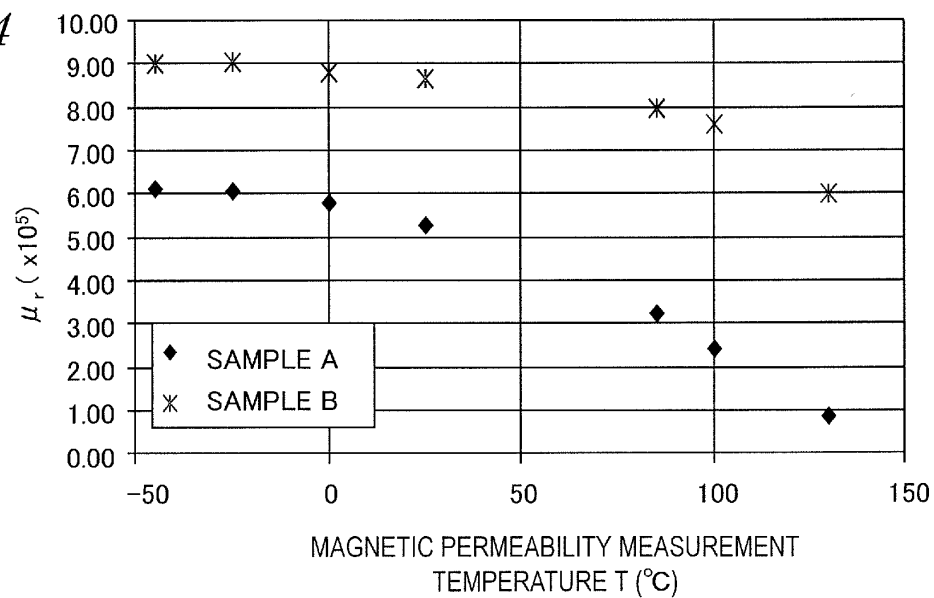


FIG. 5

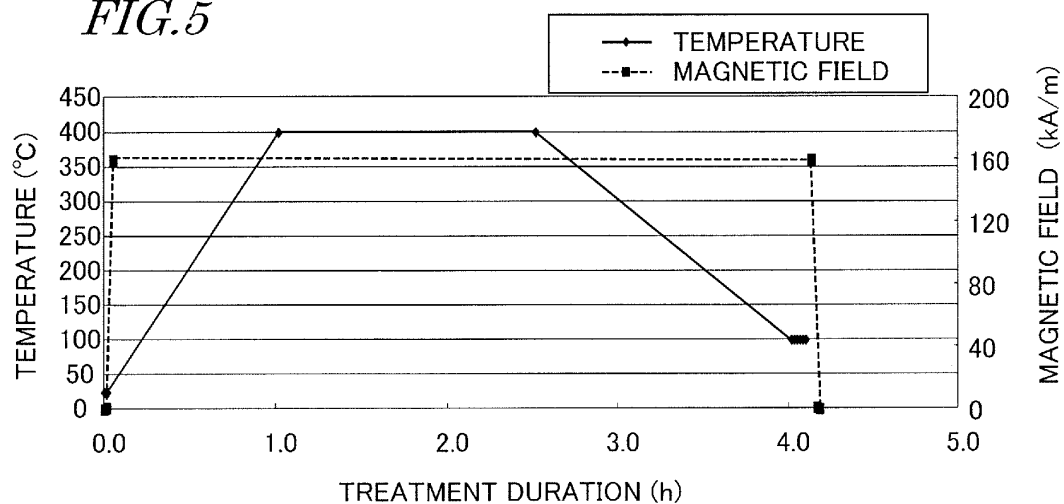


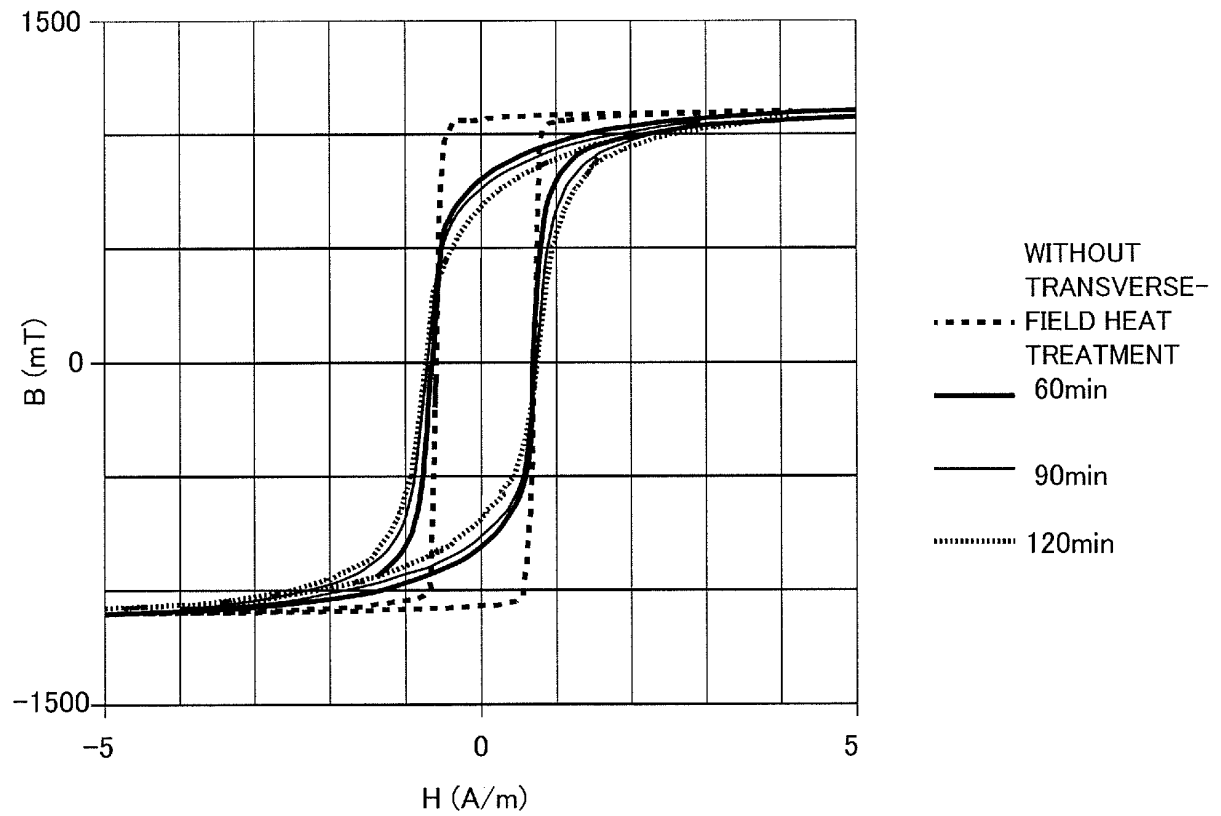
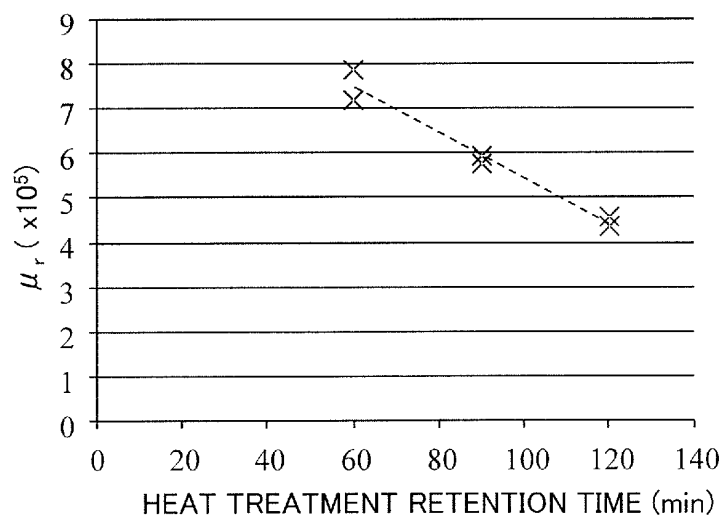
FIG. 6*FIG. 7*

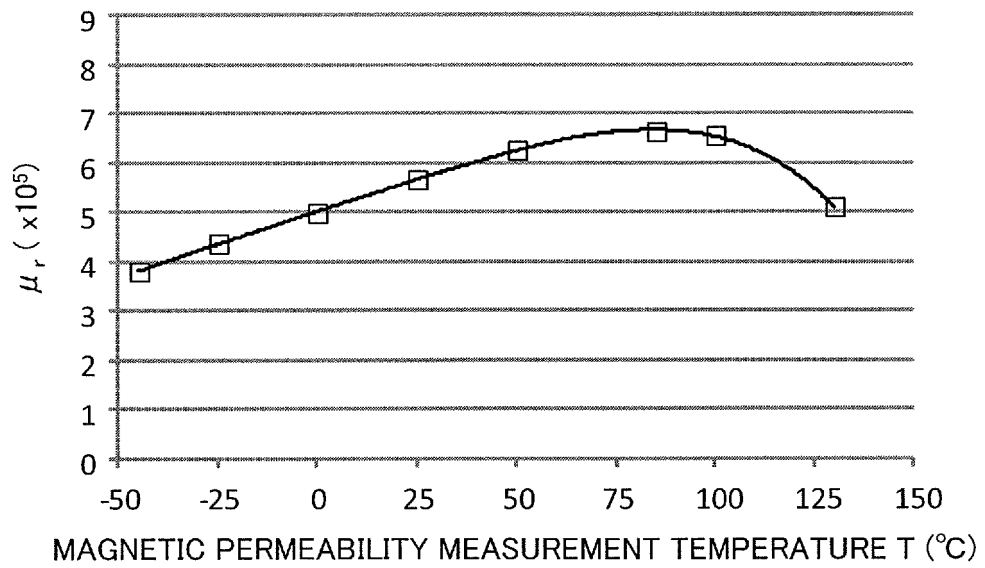
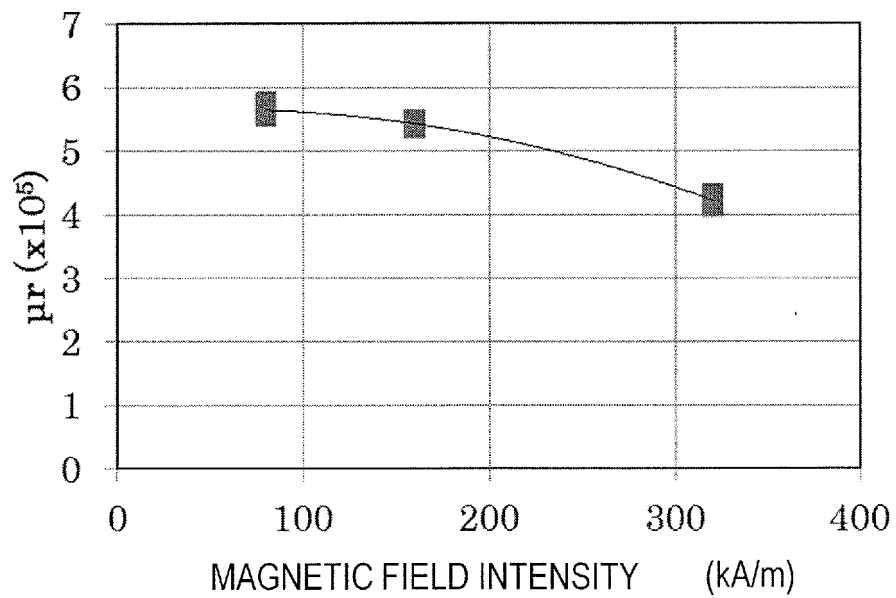
FIG.8*FIG.9*

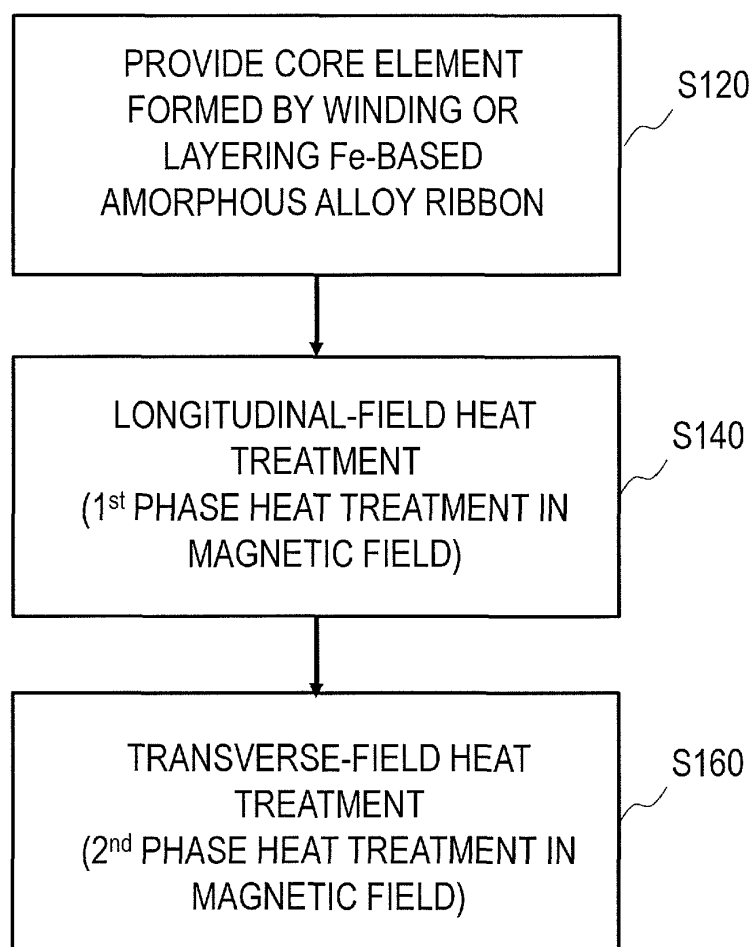
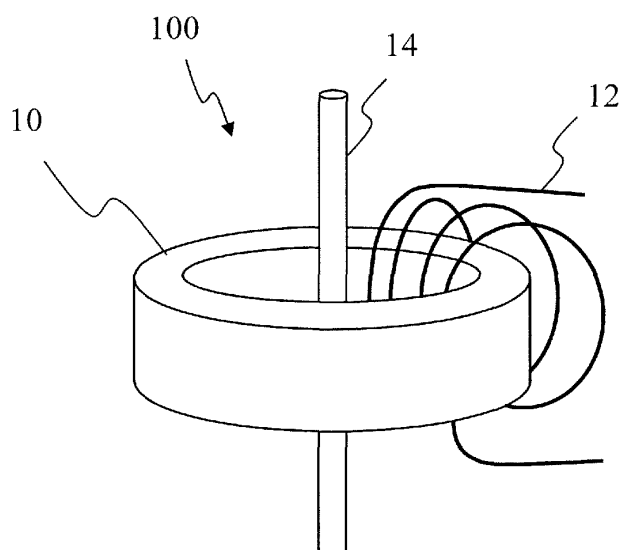
FIG. 10*FIG. 11A*

FIG. 11B

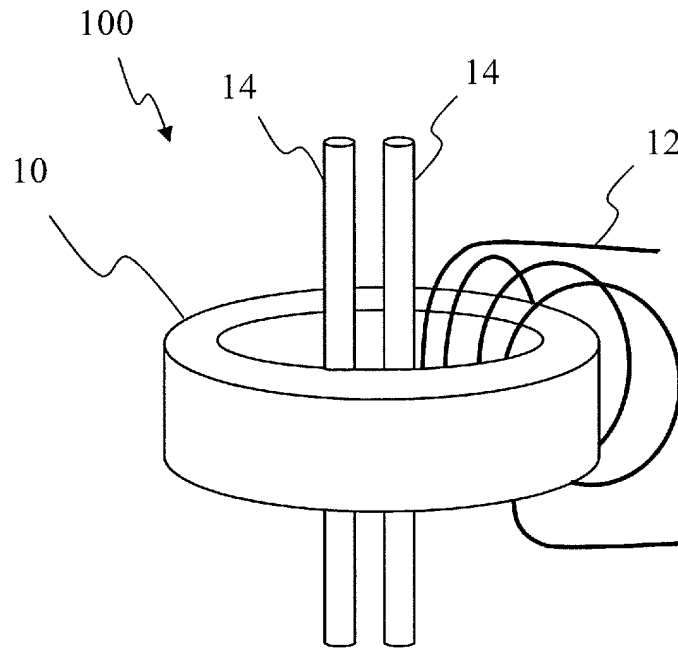
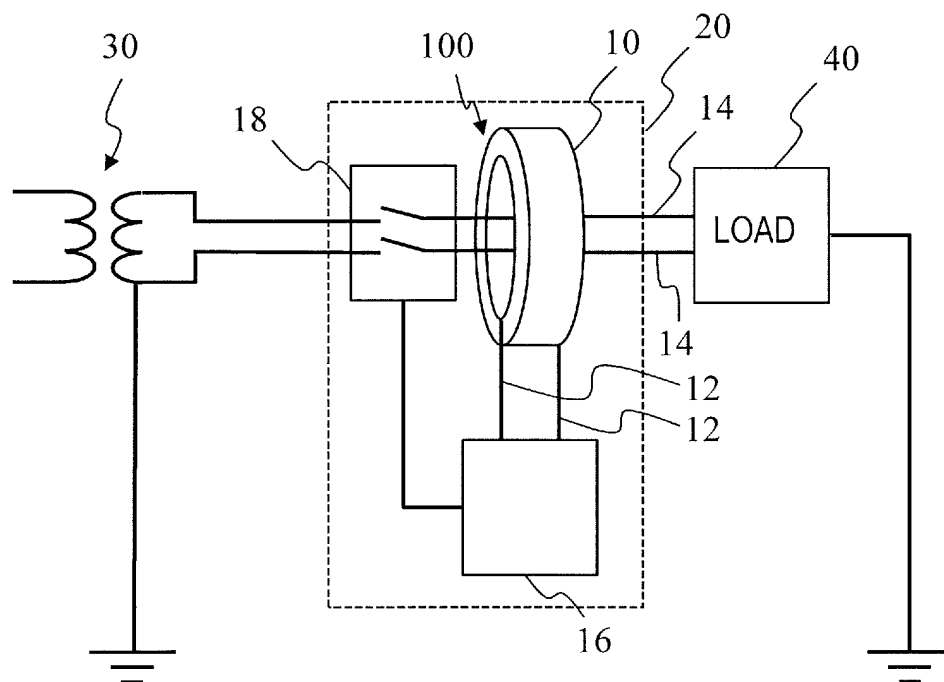


FIG. 12



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2015/071243

A. CLASSIFICATION OF SUBJECT MATTER

H01F38/28(2006.01)i, H01F1/16(2006.01)i, H01F41/02(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)

H01F38/28, H01F1/16, H01F41/02, H01F27/24-27/255, C21D6/00

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

Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2015

Kokai Jitsuyo Shinan Koho 1971-2015 Toroku Jitsuyo Shinan Koho 1994-2015

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2006-525655 A (Vacuumschmelze GmbH & Co. KG), 09 November 2006 (09.11.2006), claims 6, 19; paragraphs [0001], [0030] to [0033], [0048] to [0055]; table 5 & US 2006/0077030 A1 paragraphs [0002], [0041] to [0044], [0063] to [0074]; table 5; claims 6, 19 & WO 2004/088681 A2 & KR 10-2005-0115944 A & CN 1757079 A	1-7
A	JP 8-85821 A (Hitachi Metals, Ltd.), 02 April 1996 (02.04.1996), paragraphs [0008], [0015] to [0026] & US 5611871 A column 2, lines 11 to 16; column 4, line 62 to column 7, line 7	1-7

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

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Date of the actual completion of the international search
02 October 2015 (02.10.15)Date of mailing of the international search report
13 October 2015 (13.10.15)Name and mailing address of the ISA/
Japan Patent Office
3-4-3, Kasumigaseki, Chiyoda-ku,
Tokyo 100-8915, Japan

Authorized officer

Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2015/071243

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2859286 B2 (Hitachi Metals, Ltd.), 17 February 1999 (17.02.1999), claims 1 to 4; column 4, lines 35 to 37; column 6, line 23 to column 7, line 15; fig. 1 to 4 (Family: none)	1-7
A	JP 2710949 B2 (Hitachi Metals, Ltd.), 10 February 1998 (10.02.1998), column 5, lines 28 to 34; column 6, line 42 to column 7, line 20; fig. 1 to 2 (Family: none)	1-7

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REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2501860 B [0006]
- JP 4004393 A [0006]
- JP 7074419 A [0006]
- JP 2002530854 PCT [0006]