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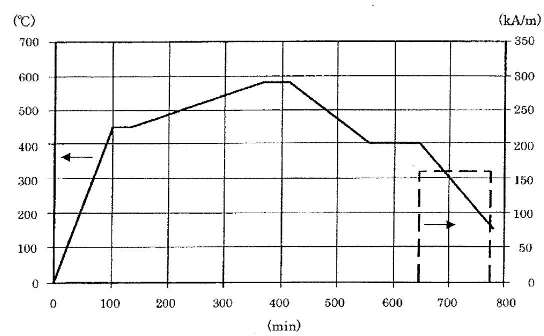
(54) **NANOCRYSTAL ALLOY MAGNETIC CORE, MAGNETIC CORE UNIT, AND METHOD FOR MANUFACTURING NANOCRYSTAL ALLOY MAGNETIC CORE**

(57) A nanocrystalline alloy magnetic core production method for nanocrystallization of a magnetic core formed of a wound or layered amorphous alloy ribbon by a heat treatment, includes a primary heat treatment step of performing a primary heat treatment in the absence of an applied magnetic field to increase a temperature of the magnetic core from a temperature that is lower than a crystallization onset temperature of the magnetic core to a temperature that is higher than or equal to the crystallization onset temperature, and a secondary heat treatment step performed after the primary heat treatment step. The secondary heat treatment step includes a secondary temperature maintaining step of maintaining the temperature constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary temperature decreasing step of, after the secondary temperature maintaining step, decreasing the temperature in the presence of a magnetic field applied in a direction perpendicular to a magnetic path.

FIG.2



EP 3 522 186 A1

Description

TECHNICAL FIELD

[0001] The present application relates to nanocrystalline alloy magnetic cores including a wound or layered nanocrystalline alloy, magnetic core units, and production methods for nanocrystalline alloy magnetic cores.

BACKGROUND ART

[0002] Among magnetic core units in which a conducting wire is wound around a magnetic core are common-mode choke coils and current transformers. A common-mode choke coil is used in, for example, a filter which separates a signal from noise based on their conduction modes. A current transformer, which is a type of transformer for measuring a current, is used in, for example, a current-measuring device and a ground-fault interrupter. These devices have a magnetic core of a soft magnetic material that is used to form a closed magnetic circuit. Such a magnetic core is preferably formed of a thin band (ribbon) of a Fe- or Co-based nanocrystalline alloy, as disclosed in Patent Document No. 1. Nanocrystalline alloys exhibit a higher saturation flux density than those of permalloy and Co-based amorphous alloys, and a higher magnetic permeability than those of Fe-based amorphous alloys.

[0003] A representative composition of nanocrystalline alloys is disclosed in, for example, Patent Document No. 2. A typical example method for producing a magnetic core using a nanocrystalline alloy includes a step of rapidly cooling a molten raw material alloy having a desired composition to produce an amorphous alloy ribbon, a step of winding the amorphous alloy ribbon into a ring-shaped core material, and a step of crystallizing the amorphous alloy ribbon by a heat treatment to obtain a magnetic core having nanocrystalline tissue.

[0004] In addition, the magnetic characteristics, such as a magnetic permeability μ and a squareness ratio, of a nanocrystalline alloy magnetic core can be significantly changed by changing a temperature profile during the heat treatment or applying a magnetic field in a specific direction during the heat treatment. For example, Patent Document No. 3 discloses a magnetic core having a magnetic permeability μ (50 Hz to 1 kHz) of as high as 70,000 or more and a squareness ratio of as low as 30% or less, which is obtained by applying a magnetic field in the height direction or radial direction of the magnetic core. Patent Document No. 3 (paragraph [0018]) discloses a production method including performing a primary heat treatment for nanocrystallization of an alloy magnetic core with the surface temperature of the alloy magnetic core maintained at the crystallization temperature + 100°C or less. As a result, even large-size magnetic cores can have superior soft magnetic characteristics, and even when a large number of magnetic cores are subjected to the heat treatment, variations in characteristics of the magnetic cores are small, resulting in high mass-productivity. Thus, nanocrystalline alloy magnetic cores having superior soft magnetic characteristics can be produced. Patent Document No. 3 also indicates that if the surface temperature is out of the above temperature range, problems arise such as an increase in coercive force.

[0005] Patent Document No. 4 discloses a magnetic core for a pulse transformer which is formed of a nanocrystalline alloy, and has an initial relative permeability of 50,000 or more at -20°C and 50°C. Patent Document No. 4 also discloses a specific production method for such a magnetic core in which a primary heat treatment is performed for 2 hours or less at 500-580°C for crystallization, and thereafter, a secondary heat treatment is performed at a temperature that is higher than or equal to 300°C and is lower than the temperature of the heat treatment for crystallization and the Curie temperature of a bcc phase formed by the crystallization. Patent Document No. 4 also indicates that a field heat treatment can be performed in combination with the above treatments. Patent Document No. 4 (examples and figures 1 and 2) also discloses the profile of a field heat treatment in which a magnetic field is applied from the start of maintaining the temperature in the secondary heat treatment.

[0006] Patent Document No. 5 discloses an example in which a nanocrystalline alloy magnetic core is subjected to a primary heat treatment and a secondary heat treatment as in Patent Document No. 4. Patent Document No. 5 discloses temperature and applied magnetic field profiles according to which a magnetic field is applied from the start of maintaining the temperature (figures. 4, 5(a), 5(b), and 6), and a temperature and applied magnetic field profile according to which the temperature is decreased without being maintained, and at the same time, a magnetic field is applied (figure 5(c)). Note that the characteristic feature of Patent Document No. 5 is a specific cooling rate (20°C/min or more until 400°C) after the primary heat treatment.

CITATION LIST

PATENT LITERATURE

[0007]

Patent Document No. 1: Japanese Patent No. 2501860
Patent Document No. 2: Japanese Publication for Opposition No. H04-4393
Patent Document No. 3: Japanese Laid-Open Patent Publication No. H07-278764
Patent Document No. 4: Japanese Laid-Open Patent Publication No. H07-94314
Patent Document No. 5: Japanese Laid-Open Patent Publication No. H08-85821

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0008] Nanocrystalline alloy magnetic cores are required to have further improved characteristics, i.e. a higher magnetic permeability and impedance relative magnetic permeability at 1 MHz or less, and a smaller temperature-dependent change in magnetic permeability. The present disclosure provides a nanocrystalline alloy magnetic core, magnetic core unit, and nanocrystalline alloy magnetic core production method that can have a further improvement in at least one of the two types of characteristics.

SOLUTION TO PROBLEM

[0009] A first nanocrystalline alloy magnetic core production method according to the present disclosure for nanocrystallization of a magnetic core formed of a wound or layered amorphous alloy ribbon by a heat treatment, includes: a primary heat treatment step of performing a primary heat treatment in the absence of an applied magnetic field to increase a temperature of the magnetic core from a temperature that is lower than a crystallization onset temperature of the magnetic core to a temperature that is higher than or equal to the crystallization onset temperature; and a secondary heat treatment step performed after the primary heat treatment step. The secondary heat treatment step includes a secondary temperature maintaining step of maintaining the temperature constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary temperature decreasing step of, after the secondary temperature maintaining step, decreasing the temperature in the presence of a magnetic field applied in a direction perpendicular to a magnetic path.

[0010] In the secondary temperature maintaining step, after the temperature of the magnetic core is in the range of $\pm$5°C with respect to the temperature at the time when the application of the magnetic field is started, the temperature may be maintained in the range of $\pm$5°C for 1 min or more.

[0011] The applied magnetic field may have a strength of 60 kA/m or more.

[0012] The maintenance temperature in the secondary heat treatment may be 200-500°C.

[0013] The maintenance temperature in the primary heat treatment may be 550-600°C.

[0014] The amorphous alloy ribbon may have a thickness of 7-15 μm.

[0015] The amorphous alloy ribbon may have a composition represented by a general formula: $(Fe_{1-a}M_a)_{100-x-y-z-\alpha-\beta-\gamma}Cu_xSi_yB_zM'_{\alpha}M''_{\beta}X_{\gamma}$ (atom%) (where M represents Co and/or Ni, M' represents at least one element selected from the group consisting of Nb, Mo, Ta, Ti, Zr, Hf, V, Cr, Mn, and W, M" represents at least one element selected from the group consisting of Al, platinum-group elements, Sc, rare-earth elements, Zn, Sn, and Re, X represents at least one element selected from the group consisting of C, Ge, P, Ga, Sb, In, Be, and As, and a, x, y, z, α, β, and γ satisfy $0 \leq a \leq 0.5$, $0.1 \leq x \leq 3$, $0 \leq y \leq 30$, $0 \leq z \leq 25$, $5 \leq y + z \leq 30$, $0 \leq \alpha \leq 20$, $0 \leq \beta \leq 20$, and $0 \leq \gamma \leq 20$, respectively).

[0016] The nanocrystalline alloy magnetic core production method may further include a step of, after the secondary heat treatment, performing impregnation with a resin.

[0017] Tn the secondary heat treatment, after the temperature of the magnetic core is maintained constant at the temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field, the temperature may be maintained in the presence of a magnetic field applied in the direction perpendicular to the magnetic path, and thereafter, the temperature may be decreased in the presence of a magnetic field applied in the direction perpendicular to the magnetic path.

[0018] In the secondary temperature maintaining step, after the temperature of the magnetic core is in the range of $\pm$5°C with respect to the temperature at which the temperature decrease is started, the temperature may be maintained in the temperature range of $\pm$5°C for 1 min or more, and thereafter, a magnetic field may be applied in the direction perpendicular to the magnetic path while the temperature is maintained in the temperature range of $\pm$5°C.

[0019] In the secondary heat treatment step, after the temperature of the magnetic core is maintained constant at the temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature, in the absence of an applied magnetic field, the temperature may be decreased in the presence of a magnetic field applied in the direction perpendicular to the magnetic path from the start of the temperature decrease.

[0020] The magnetic core may have a volume of 3000 mm^3 or more.

[0021] In the primary heat treatment step, the rate of the temperature increase may be lower than 1.0°C/min.

[0022] In the primary heat treatment step, a highest value of the temperature may be higher than 550°C and lower than or equal to 585°C.

[0023] In the secondary heat treatment step, a highest value of the temperature during the application of the magnetic field may be higher than or equal to 200°C and lower than 400°C.

[0024] In the secondary heat treatment step, the magnetic field may be applied while the temperature is decreased at an average rate of 4°C/min or less.

[0025] A second nanocrystalline alloy magnetic core production method according to the present disclosure has a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature. In the primary heat treatment step, the rate of the temperature increase is lower than 1.0°C/min.

[0026] A third nanocrystalline alloy magnetic core production method according to the present disclosure has a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature. In the primary heat treatment step, a highest value of the temperature is higher than 550°C and lower than or equal to 585°C.

[0027] A fourth nanocrystalline alloy magnetic core production method according to the present disclosure has a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature. In the secondary heat treatment step, a highest value of the temperature during the application of the magnetic field is higher than or equal to 200°C and lower than 400°C.

[0028] A fifth nanocrystalline alloy magnetic core production method according to the present disclosure has a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature. In the secondary heat treatment step, the magnetic field may be applied while the temperature is decreased at an average rate of 4°C/min or less.

[0029] In the third to fifth nanocrystalline alloy magnetic core production methods, in the primary heat treatment step, the rate of the temperature increase may be lower than 1.0°C/min.

[0030] In the second, fourth, and fifth nanocrystalline alloy magnetic core production methods, in the primary heat treatment step, a highest value of the temperature may be higher than 550°C and lower than or equal to 585°C.

[0031] In the second, third, and fifth nanocrystalline alloy magnetic core production methods, a highest value of the temperature during the application of the magnetic field may be higher than or equal to 200°C and lower than 400°C.

[0032] In the second, third, and fourth nanocrystalline alloy magnetic core production methods, in the secondary heat treatment step, the magnetic field may be applied while the temperature is decreased at an average rate of 4°C/min or less.

[0033] The secondary heat treatment step may include a step of decreasing the temperature to 100°C or lower in the presence of the applied magnetic field.

[0034] The applied magnetic field may have a strength of 50 kA/m or more.

[0035] The amorphous alloy ribbon may have a thickness of 7-15 μm.

[0036] A nanocrystalline alloy magnetic core according to the present disclosure includes a wound or layered nanocrystalline alloy ribbon. As measured at room temperature in the presence of an applied alternating-current magnetic field having a frequency f of 1 kHz and an amplitude H of 0.05 amperes/meter (A/m), the nanocrystalline alloy magnetic core has a magnetic permeability μ (1 kHz) of 70,000 or more, a squareness ratio Br/Bm of 50% or less, and a coercive force of 1.0 A/m or less.

[0037] Another nanocrystalline alloy magnetic core according to the present disclosure includes a wound or layered nanocrystalline alloy ribbon. The nanocrystalline alloy ribbon contains a Fe-based material. The nanocrystalline alloy magnetic core has an impedance relative magnetic permeability μrz of 48,000 or more at a frequency of 100 kHz.

[0038] The impedance relative magnetic permeability μrz may be 90,000 or more at a frequency of 10 kHz, 48,000 or more at a frequency of 100 kHz, and 8,500 or more at a frequency of 1 MHz.

[0039] The amorphous alloy ribbon may have a thickness of 7-15 μm.

[0040] The nanocrystalline alloy magnetic core may be impregnated with a resin.

[0041] The nanocrystalline alloy magnetic core may be for a common-mode choke coil.

[0042] A magnetic unit according to the present disclosure includes: any of the above nanocrystalline alloy magnetic cores; and a conducting wire wound around the nanocrystalline alloy magnetic core.

ADVANTAGEOUS EFFECTS OF INVENTION

[0043] In the nanocrystalline alloy magnetic core, magnetic core unit, and nanocrystalline alloy magnetic core production method of the present disclosure, a temperature-dependent change in the magnetic permeability can be reduced, and/or the magnetic permeability and impedance relative magnetic permeability at 1 MHz or less can be increased.

BRIEF DESCRIPTION OF DRAWINGS

[0044]

FIG. **1** is a diagram showing a relationship between the coercive force and the temperature-dependent-change ratio of the magnetic permeability (25°C and 100°C) of a nanocrystalline alloy magnetic core according to a first embodiment.
FIG. **2** is a graph showing an example temperature and magnetic field strength profile for a primary heat treatment and a secondary heat treatment in Example 1.
FIG. **3** is a diagram showing the B-H curve of a nanocrystalline alloy magnetic core of Example 1.
FIG. **4** is a diagram showing the B-H curve of a nanocrystalline alloy magnetic core of Comparative Example 1.
FIG. **5** is a diagram schematically showing magnetic cores placed in a heat treatment furnace.
FIG. **6** is a graph showing an example temperature and magnetic field strength profile for a primary heat treatment and a secondary heat treatment in Examples 2-1 and 2-2.
FIG. **7** is an enlarged view of a portion of FIG. **6**.
FIG. **8** is a diagram showing the B-H curves of nanocrystalline alloy magnetic cores obtained in Examples 2-1, 2-2, and 2-3.
FIG. **9** is a graph showing an example temperature and magnetic field strength profile for a primary heat treatment and a secondary heat treatment in Example 2-3.
FIG. **10** is an enlarged view of a portion of FIG. **9**.
FIG. **11** is a graph showing an example temperature and magnetic field strength profile for a primary heat treatment and a secondary heat treatment in Example 3-1.
FIG. **12** is a diagram showing the B-H curves of nanocrystalline alloy magnetic cores obtained in Examples 3-1 and 3-2.
FIG. **13** is a graph showing an example temperature and magnetic field strength profile for a primary heat treatment and a secondary heat treatment in Example 3-2.
FIG. **14** is a graph showing an example temperature and magnetic field strength profile for a primary heat treatment and a secondary heat treatment in this embodiment of Example 4.
FIG. **15** is a diagram showing the B-H curve of a nanocrystalline alloy magnetic core obtained in Example 4.
FIG. **16** is a diagram showing the impedance relative magnetic permeability μrz of the nanocrystalline alloy magnetic core of Example 4.
FIG. **17** is a diagram showing the initial magnetic permeability-vs-frequency characteristics (the real part μ' of the complex relative magnetic permeability) of the nanocrystalline alloy magnetic core of Example 4.
FIG. **18** is a diagram showing the initial magnetic permeability-vs-frequency characteristics (the imaginary part μ" of the complex relative magnetic permeability) of the nanocrystalline alloy magnetic core of Example 4.
FIG. **19** is a diagram showing the B-H curves of a nanocrystalline alloy magnetic core of Example 5 before and after impregnation with a resin.
FIG. **20** is a diagram showing the initial magnetic permeability-vs-frequency characteristics (the real part μ' of the complex relative magnetic permeability) of the nanocrystalline alloy magnetic core of Example 5 before and after impregnation with a resin.
FIG. **21** is a diagram showing the initial magnetic permeability-vs-frequency characteristics (the imaginary part μ" of the complex relative magnetic permeability) of the nanocrystalline alloy magnetic core of Example 5 before and after impregnation with a resin.
FIG. **22** is a diagram showing a relationship between frequency and impedance relative magnetic permeability μrz for different field heat treatments.
FIG. **23** is a graph showing an example temperature and magnetic field strength profile for a primary heat treatment

and a secondary heat treatment in this embodiment.

FIG. **24** is a diagram showing a relationship between temperature increase rate and impedance relative magnetic permeability μrz for several frequencies.

FIG. **25** is a diagram showing a relationship between frequency and real part μ' of complex relative magnetic permeability.

FIG. **26** is a diagram showing a relationship between frequency and imaginary part μ" of complex relative magnetic permeability.

FIG. **27** is a diagram showing a relationship between highest temperature in a primary heat treatment and impedance relative magnetic permeability μrz as measured at several measurement frequencies.

FIG. **28** is a diagram showing a relationship between frequency and real part μ' of complex relative magnetic permeability.

FIG. **29** is a diagram showing a relationship between frequency and imaginary part μ" of complex relative magnetic permeability.

FIG. **30** is a diagram showing a relationship between frequency and impedance relative magnetic permeability μrz for several highest temperatures at which a magnetic field is applied.

FIG. **31** is a diagram showing a relationship between frequency and real part μ' of complex relative magnetic permeability.

FIG. **32** is a diagram showing a relationship between frequency and imaginary part μ" of complex relative magnetic permeability.

FIG. **33** is a diagram showing a relationship between frequency and impedance relative magnetic permeability μrz for several temperature decrease rates.

FIG. **34** is a diagram showing a relationship between frequency and real part μ' of complex relative magnetic permeability.

FIG. **35** is a diagram showing a relationship between frequency and imaginary part μ" of complex relative magnetic permeability.

FIG. **36** is a diagram showing a relationship between frequency and impedance relative magnetic permeability μrz for several lowest temperatures at which a magnetic field is applied.

FIG. **37** is a diagram showing a relationship between frequency and real part μ' of complex relative magnetic permeability.

FIG. **38** is a diagram showing a relationship between frequency and imaginary part μ" of complex relative magnetic permeability.

FIG. **39** is a diagram showing a relationship between magnetic field strength in a secondary heat treatment and impedance relative magnetic permeability μrz as measured at several frequencies.

FIG. **40** is a diagram showing a relationship between frequency and real part μ' of complex relative magnetic permeability.

FIG. **41** is a diagram showing a relationship between frequency and imaginary part μ" of complex relative magnetic permeability.

DESCRIPTION OF EMBODIMENTS

[0045] In order to further improve the characteristics of a nanocrystalline alloy magnetic core, the present inventors have extensively studied the heat treatment profile during the production of a nanocrystalline alloy magnetic core. As a result, it was found that the temperature-dependent change of the magnetic permeability is effectively reduced by decreasing the coercive force. It was also found that a decrease in the coercive force has a relationship with the uniformity of temperature distribution in the magnetic core during a heat treatment in the presence of an applied magnetic field. It was also found that the temperature of the amorphous alloy during a nanocrystallization process should be appropriately controlled in order to obtain a high magnetic permeability and a high impedance relative magnetic permeability. Based on these two findings, the present inventors have conceived of a nanocrystalline alloy magnetic core production method capable of reducing a temperature-dependent change in the magnetic permeability, and/or obtaining a high magnetic permeability and a high impedance relative magnetic permeability.

(First embodiment)

[0046] A first embodiment of the present disclosure will now be described. This embodiment relates to a nanocrystalline alloy magnetic core having a reduced temperature-dependent change in magnetic permeability, a magnetic core unit, and a production method for the nanocrystalline alloy magnetic core. According to the first embodiment, provided is a method for producing a nanocrystalline alloy magnetic core having a high magnetic permeability and a low squareness ratio, and having a stably reduced coercive force Hc. This production method can be used to obtain a nanocrystalline alloy magnetic core having a magnetic permeability μ (1 kHz) of 70,000 or more, a squareness ratio Br/Bm of 50% or less, and having a coercive force Hc of 1 A/m or less.

[0047] A nanocrystalline alloy magnetic core used in a current transformer or a common-mode choke coil has conventionally been required to have a high magnetic permeability μ and a low squareness ratio. Note that, in addition to these characteristics, such a nanocrystalline alloy magnetic core may be required to not significantly change its magnetic permeability with respect to a change in temperature so that the magnetic core is not significantly affected by a change in an environment around a device, such as the temperature at which the device is used.

[0048] As described above, the present inventors have extensively studied in order to find a production method for a magnetic core having a magnetic permeability μ (1 kHz) of as high as 70,000 or more and a squareness ratio of as low as 50% or less, and having a temperature-dependent-change ratio of the magnetic permeabilities μ (1 kHz) at 25°C and 100°C of 15% or less. As a result, as shown in FIG. **1**, it was found that the temperature-dependent-change ratio of the magnetic permeability μ (1 kHz) and the coercive force Hc correlate with each other, and the temperature-dependent-change ratio of the magnetic permeability μ (1 kHz) is reduced by decreasing the coercive force.

[0049] Concerning the decrease of the coercive force, Patent Document No. 3 discloses an alloy magnetic core having similar characteristics, i.e. a magnetic permeability μ (1 kHz) of 70,000 or more and a squareness ratio of 30% or less. As described above, Patent Document No. 3 (paragraph [0018]) suggests that an increase in the coercive force can be reduced by performing a primary heat treatment for nanocrystallization with the surface temperature of an alloy magnetic core maintained at a crystallization temperature + 100°C or less. Note that the field heat treatment disclosed in Patent Document No. 3 is basically performed by applying a magnetic field during the primary heat treatment for nanocrystallization.

[0050] However, when the present inventors produced a magnetic core using a similar method, the present inventors could not verify the effect of reducing an increase in the coercive force. This may be because nanocrystalline alloys self-generate heat during nanocrystallization, and therefore, it is difficult to control their temperature in a furnace.

[0051] With this in mind, the present inventors tried a production method in which a magnetic field is applied in the second heat treatment following the primary heat treatment, instead of the primary heat treatment for nanocrystallization, as in Patent Document Nos. 4 and 5. It was still difficult to reduce the coercive force.

[0052] Based on these results of the study, the present inventors have conceived of a novel nanocrystalline alloy magnetic core production method. A nanocrystalline alloy magnetic core production method according to the first embodiment of the present disclosure is provided for nanocrystallization of a magnetic core formed of a wound or layered amorphous alloy ribbon by a heat treatment, including a primary heat treatment step of performing a primary heat treatment in the absence of an applied magnetic field to increase a temperature of the magnetic core from a temperature that is lower than a crystallization onset temperature of the magnetic core to a temperature that is higher than or equal to the crystallization onset temperature, and a secondary heat treatment step performed after the primary heat treatment step. The secondary heat treatment step includes a secondary temperature maintaining step of maintaining the temperature constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary temperature decreasing step of, after the secondary temperature maintaining step, decreasing the temperature in the presence of a magnetic field applied in a direction perpendicular to a magnetic path.

[0053] Note that the term "maintaining the temperature constant" in the secondary temperature maintaining step of the present application refers to a situation in which the temperature is maintained constant by a temperature control means capable of controlling the temperature of a heat treatment furnace, and the temperature of the heat treatment furnace is controlled to a set temperature. Note that the temperature control means may control either the temperature of the internal wall of the heat treatment furnace or the temperature of the magnetic core, which is a target to be heated. The temperature control means may be one that is known.

[0054] This production method can be employed to obtain a nanocrystalline alloy magnetic core having a reduced coercive force. The nanocrystalline alloy magnetic core thus obtained may, for example, be a wound or layered nanocrystalline alloy ribbon and have a magnetic permeability μ (1 kHz) of 70,000 or more and a squareness ratio Br/Bm of 50% or less, and have a coercive force of 1.0 A/m or less. In addition, in the case where the temperature of the magnetic core is decreased in the presence of an applied magnetic field, a B-H curve (hysteresis loop) having superior linearity is obtained.

[0055] In addition, if, in the secondary temperature maintaining step, the temperature continues to be maintained constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature after the start of the application of a magnetic field, the coercive force can be further reduced. Specifically, the resultant magnetic core has a coercive force of 0.9 A/m or less. In contrast, if the temperature is decreased without being maintained constant after the start of the application of a magnetic field, the impedance relative magnetic permeability μrz can be increased. A magnetic core having a high impedance relative magnetic permeability μrz has characteristics suitable for a common-mode choke coil. Note that maintaining the temperature constant is equivalent to maintaining the temperature with a temperature gradient of, for example, about ±0.2°C/min. The details are described below.

[0056] The reason why the coercive force is reduced by the above production method may be that magnetic anisotropy is temporarily imparted in a direction perpendicular to the magnetic path, so that magnetic domains are formed. Specifically, a magnetization process of a magnetic material includes the rotation component and magnetic domain wall displacement component of a magnetic moment. The rotation component of a magnetic moment is oriented in a certain direction depending on the magnetic anisotropy when an external magnetic field is removed, and therefore, in an ideal case, a magnetic material does not have residual magnetization or coercive force. In contrast to this, as to the magnetic domain wall displacement component, the displacement of magnetic domain walls is blocked by defects, an impurity layer, surface roughness, etc., of a magnetic material, and therefore, a magnetic material has finite residual magnetization and coercive force even when an external magnetic field is removed. In the case where magnetic domains are perpendicular to the magnetic path, the rotation component of a magnetic moment in each magnetic domain is dominant, and the magnetic domain wall displacement component is relatively small, in a magnetization process in which an operating magnetic field is applied to the magnetic path. Therefore, it is considered that when magnetic anisotropy is imparted in a direction perpendicular to the magnetic path, the coercive force is decreased. Furthermore, it is considered that, if the secondary heat treatment is performed when the temperature distribution in the magnetic core is small, the problem can be solved that different parts of the magnetic core have different magnetic characteristics, and therefore, the linearity of the B-H curve is reduced, so that the coercive force increases.

[0057] Note that in the present application, the crystallization onset temperature is defined as a temperature at which an exothermic reaction due to the onset of nanocrystallization is detected as measured by differential scanning calorimetry (DSC) at a temperature increase rate of 10°C/min.

(Primary heat treatment)

[0058] The primary heat treatment includes a step of increasing the heat treatment temperature from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature. The heat treatment temperature may be increased in the range of 510-600°C. If the heat treatment temperature is lower than 510°C or higher than 600°C, magnetostriction increases. If the heat treatment temperature is higher than or equal to 550°C, the magnetostriction can be further reduced. Specifically, the magnetostriction can be reduced to 3 ppm or less, 2 ppm or less, and 1 ppm or less. If the heat treatment is performed at a temperature of 550-600°C, the coercive force is likely to increase, In this embodiment, a field heat treatment, which can reduce the coercive force, is applied in the secondary heat treatment, and therefore, the magnetostriction and the coercive force can both be reduced. As a result, even in the case where the nanocrystalline alloy magnetic core is impregnated with a resin, the nanocrystalline alloy magnetic core can have a smaller change in characteristics.

[0059] In the primary heat treatment, the temperature may not be maintained at the highest reachable temperature. Nanocrystallization can be achieved even in the case where the temperature is maintained at the highest temperature for 0 min (no maintenance time). However, the maintenance time is preferably set in the range of 5 min to 24 h. If the maintenance time is 5 min or more, the entire alloy forming the core can be easily caused to have a uniform temperature, likely leading to uniform magnetic characteristics. Meanwhile, if the maintenance time is longer than 24 h, not only the productivity is likely to decrease, but also the magnetic characteristics are likely to decrease due to the excessive growth of crystal grains or the generation of crystal grains having non-uniform morphologies.

[0060] Note that, in the primary heat treatment, the heat treatment temperature is increased from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature. In this case, if the temperature increase rate is as gradual as 0.2-1.2°C/min at the crystallization onset temperature, the generation of a coarse crystal grain size due to self-heat generation occurring during nanocrystallization can be reduced, resulting in stable nanocrystallization. In addition, the magnetostriction can be reduced, and therefore, even in the case where the nanocrystalline alloy magnetic core is impregnated with a resin, the nanocrystalline alloy magnetic core can have a smaller change in characteristics. Note that the temperature may be increased to a temperature that is 20°C lower than the crystallization onset temperature relatively quickly, e.g. at a temperature increase rate of 3-5°C/min.

[0061] In addition, the temperature is preferably decreased from the highest reachable temperature to the maintenance temperature of the secondary heat treatment at a cooling rate of 1-5°C/min. Note that, after the secondary heat treatment, the magnetic core can typically be removed into the atmosphere when the temperature becomes 100°C or less.

[0062] Note that the temperature increase rate at the crystallization onset temperature refers to an average temperature increase rate at which the temperature is increased from a temperature that is 5°C lower than the crystallization onset temperature to a temperature that is 5°C higher than the crystallization onset temperature, i.e. an average temperature increase rate at which the temperature is increased in the primary heat treatment step.

(Secondary heat treatment)

[0063] Of the steps of the secondary heat treatment, in the secondary temperature maintaining step, the temperature maintained in the absence of an applied magnetic field is higher than or equal to 200°C and lower than the crystallization onset temperature, and is preferably 200-500°C. As the maintenance temperature is increased, the magnetic permeability decreases. Therefore, by changing the maintenance temperature of the secondary heat treatment, the magnetic permeability can be controlled. Note that if the temperature is lower than 200°C, the effect of changing the magnetic permeability is not likely to be sufficient. Meanwhile, if the temperature is higher than 500°C, the crystal grain growth of the nanocrystal phase is accelerated, so that the coercive force is likely to increase. Thus, if a magnetic field is applied in the range of 200-500°C, magnetic characteristics that the coercive force is 1.0 A/m are highly likely to be obtained.

[0064] A period of time for which the temperature is maintained constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field is preferably 1 min or more. The period of time for which the temperature is maintained constant is also referred to as an "actual maintenance time." As used herein, the term "actual maintenance time" refers to a period of time between when the temperature of the magnetic core reaches the set maintenance temperature and when the application of a magnetic field is started. More specifically, the term "actual maintenance time" refers to a period of time between when the temperature of the magnetic core reaches a temperature range of ±5°C with respect to the set temperature of the magnetic core at which the application of a magnetic field is started, and when the application of a magnetic field is started.

[0065] The actual maintenance time will be further described. FIG. **2** shows a temperature profile of a heat treatment in which plotted temperatures form a set temperature profile controlled by the temperature control means. Such a controlled temperature profile may be different from the actual temperature of the magnetic core. In particular, in the cooling step, the cooling rate of the magnetic core is likely to be slower than a cooling rate set in the heat treatment furnace. The present inventors have paid attention to the actual temperature of the magnetic core. As a result, the present inventors found that it is preferable that, in addition to the temperature maintenance under the control of the temperature control means, the "period of time between when the magnetic core reaches a predetermined temperature (the range of ±5°C with respect to the temperature of the magnetic core set by the temperature control means at which the application of a magnetic field is started) and when the application of a magnetic field is started" should be managed as a target value. Note that, in the present application, when the actual maintenance time was measured, the temperature of the magnetic core was measured with a thermocouple in direct contact with the magnetic core. Note that, in the production method of this embodiment, the temperature of the magnetic core does not need to be always directly measured. In the production method of this embodiment, when the temperature profile of the heat treatment in the heat treatment furnace is determined, then if conditions are determined under which a sufficient actual maintenance time is ensured, the production may not be conducted while the temperature of the magnetic core is actually measured.

[0066] If the actual maintenance time is 1 min or more, the coercive force Hc can be sufficiently reduced. The actual maintenance time is preferably 5 min or more, more preferably 10 min or more. In addition, although the upper limit of the actual maintenance time is not particularly limited, if the actual maintenance time is 10 h or less, the time it takes to perform the heat treatment can be reduced, and therefore, an increase in mass-production cost can be reduced.

[0067] A nanocrystalline alloy magnetic core having a further reduced coercive force may be desired. To this end, in the secondary temperature maintaining step, the temperature is preferably maintained constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field. After the temperature of the magnetic core becomes constant (maintenance temperature), the temperature of the magnetic core is preferably maintained constant at the maintenance temperature in the presence of a magnetic field applied in a direction perpendicular to the magnetic path. Thereafter, the secondary temperature decreasing step is preferably performed. It is considered that as the period of time for which a magnetic field is applied increases, the slope of the B-H curve decreases, and therefore, the coercive force decreases. When this production method is employed, the coercive force is preferably reduced as follows. In the secondary temperature maintaining step, after the temperature of the magnetic core reaches the range of ±5°C with respect to the temperature at which the decrease of the temperature is started, the temperature is preferably maintained in that temperature range for 1 min or more, and thereafter, a magnetic field is preferably applied in a direction perpendicular to the magnetic path while the temperature is maintained within that temperature range. In addition, the temperature is preferably maintained for 5 min or more, more preferably 10 min or more.

[0068] A small coercive force and a high impedance relative magnetic permeability μrz may be simultaneously desired. To this end, in the secondary heat treatment step, the temperature is preferably maintained constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field. Thereafter, the temperature is preferably decreased in the presence of a magnetic field applied in a direction perpendicular to the magnetic path from the start of the temperature decrease.

[0069] Note that as the size of the nanocrystalline alloy magnetic core used increases, the cooling rate of the magnetic core is more likely to be slower than the cooling rate set in the heat treatment furnace. When a nanocrystalline alloy magnetic core having a volume of 3000 mm^3 or more is used, the effect of reducing the coercive force can be easily achieved in the production method of the present disclosure, compared to when a nanocrystalline alloy magnetic core having a volume of less than 3000 mm^3 is used. If the volume is 5000 mm^3 or more, the effect of reducing the coercive force is more likely to be achieved. Note that the volume refers to an effective volume obtained by multiplying a volume calculated from the outer shape of a magnetic core by the space factor, or by multiplying the effective magnetic path length by the effective cross-sectional area.

[0070] The applied magnetic field in the cooling step of the secondary heat treatment preferably has a magnetic field strength of 60 kA/m or more. Because the squareness ratio Br/Bm can be reduced, the coercive force Hc can be further reduced. Specifically, the coercive force Hc can be reduced to 1.0 A/m or less. In addition, induced magnetic anisotropy is easily imparted under actual operating conditions. The magnetic field strength is more preferably in the range of 100 kA/m or more.

[0071] In addition, the upper limit of the magnetic field strength is not particularly limited. Even in the case where the magnetic field strength exceeds 400 kA/m, the induced magnetic anisotropy is not further imparted. Therefore, the magnetic field strength is preferably 400 kA/m or less. In addition, the period of time for which a magnetic field is applied, which is not particularly limited in the case of the above temperature range, may be practically about 1-180 min.

[0072] When the temperature is decreased in the presence of an applied magnetic field, the magnetic field preferably continues to be applied when the temperature is between the maintenance temperature and 200°C. As a result, the B-H curve has a smaller slope and higher linearity, i.e. soft magnetic characteristics can be obtained. More preferably, the lower limit of the temperature at which a magnetic field continues to be applied is up to 150°C.

[0073] The direction of the applied magnetic field is perpendicular to the direction of the magnetic path. In the case of the wound magnetic core, a magnetic field is applied in the height direction of the magnetic core. The applied magnetic field may be any of a direct-current magnetic field, an alternating-current magnetic field, and a pulse magnetic field.

[0074] The field heat treatment reduces the residual magnetic flux density Br, although it also reduces the magnetic permeability, so that Br/Bm decreases, and therefore, non-uniform magnetization does not easily occur in the magnetic core. Therefore, the magnetic core is suitable for a common-mode choke coil and a current transformer. Note that, in the present application, the saturation flux density Bm is defined as a magnetic flux density B(80) in a magnetic field H of 80 A/m.

[0075] The primary and secondary heat treatments are preferably performed in a non-reactive atmosphere. In the case where the heat treatments are performed in nitrogen gas, a sufficient magnetic permeability is obtained. Nitrogen gas can be handled as a substantially non-reactive gas. The non-reactive gas may be an inert gas. Alternatively, the heat treatments may be performed in a vacuum. Specifically, the primary heat treatment is preferably performed in an atmosphere having an oxygen concentration of 10 ppm or less. The coercive force can be further reduced.

(Nanocrystalline alloy magnetic core)

[0076] The nanocrystalline alloy magnetic core according to the first embodiment of the present disclosure includes a wound or layered nanocrystalline alloy ribbon, has a magnetic permeability μ (1 kHz) of 70,000 or more, a squareness ratio Br/Bm of 50% or less, and a coercive force of 1.0 A/m or less, as measured at room temperature in the presence of an applied alternating-current magnetic field having a frequency f of 1 kHz and an amplitude H of 0.05 amperes/meter (A/m). The nanocrystalline alloy magnetic core preferably has a squareness ratio Br/Bm of 30% or less. As a result, the nanocrystalline alloy magnetic core can have a temperature-dependent-change ratio of the magnetic permeabilities μ (1 kHz) at 25°C and 100°C of 15% or less.

[0077] The nanocrystalline alloy magnetic core according to the first embodiment of the present disclosure also has superior impedance characteristics, i.e. an impedance relative magnetic permeability μrz of 48,000 or more at 100 kHz. The nanocrystalline alloy magnetic core according to the first embodiment of the present disclosure can also have a higher impedance relative magnetic permeability μrz over a wide frequency range, i.e. an impedance relative magnetic permeability μrz of 90,000 or more at 10 kHz and 8,500 at 1 MHz. The nanocrystalline alloy magnetic core according to the first embodiment of the present disclosure can also have an even higher impedance relative magnetic permeability μrz over a wide frequency region, i.e. 100,000 or more at 10 kHz and 10,000 at 1 MHz. The nanocrystalline alloy magnetic core according to the first embodiment of the present disclosure can also have a still even higher impedance relative magnetic permeability μrz over a wide frequency region, i.e. 105,000 or more at 10 kHz, 50,000 or more at 100 kHz, and 10,500 at 1 MHz.

[0078] Thus, the reason why the nanocrystalline alloy magnetic core of the present disclosure has a high impedance relative magnetic permeability μrz may be that if the coercive force is small, the magnetic domain wall displacement component in a magnetization process is small, and therefore, a local extraordinary eddy current loss due to the magnetic domain wall displacement can be reduced, and as a result, an increase in core loss can be reduced, so that high-frequency characteristics can be improved.

[0079] The magnetic core having a high impedance relative magnetic permeability μrz is useful as a nanocrystalline alloy magnetic core for a common-mode choke coil. It is desirable that a common-mode choke should be used in a frequency band ranging from a low frequency to a high frequency, particularly from a 10-kHz band to a 1-MHz band.

[0080] The impedance relative magnetic permeability μrz is frequently used as an index for characteristics of a common-mode choke. The impedance relative magnetic permeability μrz is described in, for example, JIS Standard C2531 (as revised in 1999). The impedance relative magnetic permeability μrz can be assumed to be equal to the absolute value of a complex relative magnetic permeability (μ' - iμ") as represented by expression (1) (see, for example, "A Guide to Selection of Magnetic Materials", issued on November 10, 1989, edited by Keizo OTA).

$$\mu rz = (\mu'^2 + \mu''^2)^{1/2} \qquad (1)$$

[0081] In expression (1), the real part μ' of the complex relative magnetic permeability represents a magnetic flux density component that does not have a phase delay with respect to a magnetic field. In general, the real part μ' corresponds to the magnitude of the impedance relative magnetic permeability μrz in a low frequency region. Meanwhile, the imaginary part μ" represents a magnetic flux density component that includes a phase delay with respect to a magnetic field, and corresponding to a loss in magnetic energy. If the impedance relative magnetic permeability μrz has a high value over a wide frequency band, the capability of absorbing and removing common-mode noise is excellent.

[0082] In addition, the nanocrystalline alloy magnetic core of the present disclosure may be impregnated with a resin. Nanocrystalline alloy magnetic cores become fragile or brittle in a heat treatment for nanocrystallization, and therefore, may be impregnated with a resin in order to increase the mechanical characteristics. In this case, the nanocrystalline alloy thin band is distorted by impregnation with a resin, so that the impedance of the wound magnetic core is altered and does not meet the customer's requirements, which poses a problem in designing characteristics. In particular, impedance characteristics tend to be important to common-mode choke coils.

[0083] Even in the case where the nanocrystalline alloy magnetic core of the present disclosure is impregnated with a resin, a change in impedance characteristics thereof can be significantly reduced. Likewise, a change in B-H curve thereof can be significantly reduced. Examples of a resin suitable for the impregnation include epoxy resins and acrylic resins. The amount of a resin solvent used in the impregnation with a resin is typically about 5-40 wt% with respect to the weight of the resin.

(Magnetic core unit)

[0084] For example, a conducting wire may be wound around or passed through the nanocrystalline alloy magnetic core according to the first embodiment of the present disclosure to provide a magnetic core unit for a common-mode choke coil, a current transformer, etc. The nanocrystalline alloy magnetic core according to the first embodiment of the present disclosure is particularly useful for common-mode choke coils.

(Nanocrystallization alloy)

[0085] An nanocrystallizable amorphous alloy is, for example, an alloy having a composition represented by a general formula: $(Fe_{1-a}M_a)_{100-x-y-z-\alpha-\beta-\gamma}Cu_xSi_yB_zM'_\alpha M''_\beta X_\gamma$ (atom%) (where M represents Co and/or Ni, M' represents at least one element selected from the group consisting of Nb, Mo, Ta, Ti, Zr, Hf, V, Cr, Mn, and W, M" represents at least one element selected from the group consisting of Al, platinum-group elements, Sc, rare-earth elements, Zn, Sn, and Re, X represents at least one element selected from the group consisting of C, Ge, P, Ga, Sb, In, Be, and As, and a, x, y, z, α, β, and γ satisfy $0 \leq a \leq 0.5$, $0.1 \leq x \leq 3$, $0 \leq y \leq 30$, $0 \leq z \leq 25$, $5 \leq y + z \leq 30$, $0 \leq \alpha \leq 20$, $0 \leq \beta \leq 20$, and $0 \leq \gamma \leq 20$, respectively). Preferably, in the above general formula, a, x, y, z, α, β, and γ satisfy the following ranges: $0 \leq a \leq 0.1$, $0.7 \leq x \leq 1.3$, $12 \leq y \leq 17$, $5 \leq z \leq 10$, $1.5 \leq \alpha \leq 5$, $0 \leq \beta \leq 1$, and $0 \leq \gamma \leq 1$, respectively.

[0086] The alloy having such a composition may be melted at the melting point thereof or higher, and the molten alloy may be rapidly cooled and solidified by a single-roller method, to obtain an elongated amorphous alloy ribbon (thin band).

[0087] The amorphous alloy ribbon may be subjected to the above primary heat treatment to obtain a nanocrystalline ribbon. At least 50%, preferably 80% or more, of the volume of the nanocrystallized alloy is occupied by microcrystal grains having an average grain size of 100 nm or less, where the grain size of each grain is defined as a greatest dimension thereof that is measured. The portion of the alloy other than the microcrystal grains is mostly amorphous. The proportion of the microcrystal grains may be substantially 100 vol%.

[0088] The proportion of the microcrystal grains is calculated as follows. A straight line having a length Lt is drawn on a TEM photograph of each sample, the sum Lc of the lengths of portions of each straight line intersecting with microcrystal grains is calculated, the ratio (Ll = Lc/Lt) of the microcrystal grains along each straight line is calculated, this procedure is performed five times, and the average of Ll values is calculated. Here, the ratio Vl = Vc/Vt (Vc represents the sum of the volumes of the microcrystal grains, and Vt represents the volume of each sample) of the microcrystal grains is approximated to $Vl \approx Lc^3/Lt^3 = Ll^3$.

[0089] The amorphous alloy ribbon used for the nanocrystalline alloy magnetic core production method of the present disclosure preferably has a thickness of 7-30 μm. If the thickness is less than 7 μm, the ribbon has insufficient mechanical strength and is highly likely to be broken during handling. If the thickness is more than 30 μm, the ribbon is less likely to have a stable amorphous state. In the case where the amorphous alloy ribbon is used as a core in a high-frequency application after nanocrystallization, an eddy current occurs in the ribbon. A loss due to the eddy current increases with an increase in the thickness of the ribbon.

[0090] The amorphous alloy ribbon more preferably has a thickness of 7-15 μm. If the thickness is 15 μm or less, the occurrence of an eddy current in a high-frequency application can be reduced, resulting in an improvement in the impedance relative magnetic permeability μrz. By using the ribbon having a thickness of 7-15 μm, the nanocrystalline alloy magnetic core of the present disclosure can have a coercive force of 0.65 A/m or less.

[0091] The amorphous alloy ribbon obtained by roller cooling preferably has a width of 10 mm or more for a practical core shape. By slitting (cutting) a wider alloy ribbon, the cost can be reduced. Although a wider alloy ribbon is thus preferable, the alloy ribbon preferably has a width of 250 mm or less for stable production. The alloy ribbon more preferably has a width of 70 mm or less for more stable production.

[0092] Next, an embodiment of a method for producing a core for a current transformer according to the present disclosure will be described. Initially, a ribbon-shaped amorphous alloy that is a soft magnetic material layer is formed of a molten alloy having the above composition using a known liquid quenching method (ultra-rapid quenching method), such as a single-roller method or a double-roller method. The peripheral speed of the cooling roller may be set to, for example, about 15-50 m/sec. The cooling roller may be formed of pure copper, or a copper alloy, such as Cu-Be, Cu-Cr, Cu-Zr, or Cu-Zr-Cr, which have good thermal conductivity. In the case of mass production, the cooling roller may be water-cooled. The formation of amorphous tissue of an alloy may vary depending on the rate of cooling. Therefore, in the formation of the amorphous alloy ribbon, a change in the temperature of the roller is maintained small. Note that the thickness t of the amorphous alloy ribbon is calculated by a weight conversion method. For example, the weight M of a sample elongated amorphous alloy ribbon of 2 m (longitudinal direction) × 50 mm (width direction) is measured, and the density d [kg/m^3] is measured by dry density measurement using a gas displacement method (e.g., measurement using AccuPyc II 1340 series, manufactured by Shimadzu Corporation). As a result, the thickness $t\,[m] = M/((2 \times 50^{-3}) \times d)$ can be calculated.

[0093] The amorphous alloy ribbon thus obtained is slit into ribbons having a desired width, which are used.

[0094] The amorphous alloy ribbon is wound or layered to produce a ring-shaped structure. In the ring-shaped structure (core material) thus produced, a plurality of amorphous alloy layers are stacked on top of each other. A small interstice or another substance may be present between each amorphous alloy layer. The space factor of the amorphous alloy layers with respect to the core material is, for example, about 70-90%.

<Magnetic permeability>

[0095] As used herein, the term "magnetic permeability" means the same as the term "relative magnetic permeability." The magnetic permeability as measured at room temperature in the presence of an applied alternating-current magnetic field having a frequency f of 1 kHz and an amplitude H of 0.05 amperes/meter (A/m) is denoted by μ (1 kHz).

[0096] The impedance magnetic permeability is denoted by μrz. Note that the impedance magnetic permeability was measured using an impedance/gain-phase analyzer (model no. 4194A), manufactured by Keysight Technologies. An insulating-sheath conducting wire was passed through a center portion of the wound magnetic core, and was connected to input and output terminals, to measure the impedance magnetic permeability.

[0097] In examples below, a core material formed by winding the amorphous alloy ribbon is used. However, the present disclosure is not limited to such examples.

(Example 1)

[0098] A molten alloy containing, in atom%, 1% of Cu, 3% of Nb, 15.5% of Si, and 6.5% of B, the balance being Fe and incidental impurities, was rapidly cooled by a single-roller method to obtain a Fe-based amorphous alloy ribbon having a width of 50 mm and a thickness of 14 μm. The Fe-based amorphous alloy ribbon was slit (cut) into a width of 6 mm. Thereafter, the ribbon was wound into an outer diameter of 21.0 mm and an inner diameter of 11.8 mm to produce a wound magnetic core (height: 6 mm). The magnetic core had a volume of 1421 mm^3. This alloy had a crystallization onset temperature of 500°C as measured by differential scanning calorimetry (DSC).

[0099] The core thus produced was subjected to the primary and secondary heat treatments according to the temperature and applied magnetic field profile of FIG. **2**. Note that the temperature shown in FIG. **2** is the temperature of an atmosphere in a heat treatment furnace that was controlled using a temperature controller (KP1000C, manufactured by Chino Corporation). The temperature that was controlled was the temperature of a peripheral portion in the furnace.

[0100] In the primary heat treatment, initially, the temperature was increased from room temperature to 450°C in 90 min (temperature increase rate: 4.8°C/min), and was maintained at 30 min, and thereafter, was increased to 580°C in 240 min (temperature increase rate: 0.5°C/min). Thereafter, the temperature was maintained at 580°C for 60 min, and thereafter, was decreased to 400°C in 130 min (temperature decrease rate: 1.4°C/min).

[0101] Thereafter, the secondary heat treatment was performed. Initially, the heat treatment furnace was set such that the temperature was maintained at 400°C for 90 min. The "actual maintenance time" as defined herein (in this example, a period of time between when the temperature reaches 405°C and when the application of a magnetic field is started (the decrease of the temperature is started)) was 60 min. The primary heat treatment and the second treatment so far were performed in the absence of an applied magnetic field. Thereafter, the temperature was decreased to 150°C in 150 min in the presence of an applied magnetic field of 159.5 kA/m. The direction in which the magnetic field was applied was the width direction of the alloy ribbon, i.e. the height direction of the core. Thereafter, the core was cooled in the absence of an applied magnetic field. Note that this field heat treatment was performed in an atmosphere having an oxygen concentration of 10 ppm or less (2 ppm).

[0102] As a result, the nanocrystalline alloy magnetic core of this example was obtained. This nanocrystalline alloy magnetic core had a magnetic permeability μ (1 kHz) of 100,000 and a squareness ratio Br/Bm of 12.7%. The magnetostriction was 1 ppm or less.

[0103] FIG. **3** is a diagram showing the B-H curve of the nanocrystalline alloy magnetic core obtained in this embodiment. The nanocrystalline alloy magnetic core had a coercive force of 1 A/m or less (0.64 A/m).

(Comparative example 1)

[0104] FIG. **4** is a diagram showing the B-H curve of a comparative nanocrystalline alloy magnetic core. This nanocrystalline alloy magnetic core was produced according to a temperature and applied magnetic field profile similar to that of FIG. **2**, except that the heat treatment furnace was set such that the temperature maintenance period was not provided in the secondary heat treatment. Specifically, the comparative nanocrystalline alloy magnetic core was produced in a manner similar to that for the nanocrystalline alloy magnetic core of Example 1, except that the magnetic core was not maintained constant at a temperature that is higher than or equal to 200°C and lower than equal to the crystallization onset temperature. As can be seen from FIG. **4**, the B-H curve of the comparative nanocrystalline alloy magnetic core is broader in the horizontal direction, and the coercive force thereof is 2.19 A/m, which is greater than that of the nanocrystalline alloy magnetic core of Example 1.

(Examples 2-1 to 2-3)

[0105] The relationship between the actual maintenance time and the coercive force was further investigated in another embodiment. A molten alloy containing, in atom%, 1% of Cu, 3% of Nb, 15.5% of Si, and 6.5% of B, the balance being Fe and incidental impurities, was rapidly cooled by a single-roller method to obtain a Fe-based amorphous alloy ribbon having a width of 50 mm and a thickness of 14 μm. The Fe-based amorphous alloy ribbon was slit (cut) into a width of 20 mm. Thereafter, the ribbon was wound into an outer diameter of 22 mm and an inner diameter of 14 mm to produce a wound magnetic core (height: 20 mm). The magnetic core had a volume of 4522 mm^3. This alloy had a crystallization onset temperature of 500°C as measured by differential scanning calorimetry (DSC).

[0106] As shown in FIG. **5**, a plurality of the wound magnetic cores were placed side by side in the axial direction in a heat treatment furnace. A field heat treatment furnace **10** was configured so that wound magnetic cores **6** are placed side by side in a container **3** having a heater **4**. A solenoid coil **5** was provided outside the container **3**. The wound magnetic cores were coaxially arranged with a non-magnetic holder **2** (SUS304) passed through the radially inner holes thereof. The solenoid coil **5** was used to apply a magnetic field in a direction perpendicular to the magnetic path of the wound magnetic cores (the height direction of the wound magnetic cores). An identical non-magnetic spacer 1 was provided every 10 contiguous wound magnetic cores. A thermocouple was interposed between the fifth and sixth magnetic cores as counted from an end, to measure the temperatures of the magnetic cores on both sides of the thermocouple.

[0107] In this situation, the primary and secondary heat treatments were performed according to a temperature and applied magnetic field profile shown in FIG. **6**. A temperature indicated by a thin dashed line is the set temperature of the heat treatment furnace.

[0108] In the primary heat treatment, initially, the temperature was increased to 470°C in 100 min (temperature increase rate: 4.5°C/min), and was maintained at 30 min, and thereafter, was increased to 560°C in 100 min (temperature increase rate: 0.9°C/min). Thereafter, the temperature was maintained at 560°C for 30 min, and thereafter, was decreased to 350°C in 40 min (temperature decrease rate: 4.7°C/min).

[0109] Thereafter, the secondary heat treatment was performed. Initially, the temperature was maintained at 350°C for 140 min. The primary heat treatment and the second treatment so far were performed in the absence of an applied magnetic field. Thereafter, the temperature was decreased to 100°C in 90 min in the presence of an applied magnetic field of 531 kA/m. The direction in which the magnetic field was applied was the width direction of the alloy ribbon, i.e. the height direction of the core.

[0110] In FIG. **6**, a temperature indicated by a solid line is the temperature of the magnetic core of Example 2-1.

[0111] FIG. **7** is an enlarged view of a heat treatment time range of 400-500°C of FIG. **6**. While the temperature at which the decrease of the temperature was started in the presence of an applied magnetic field was 350°C, the temperature had reached 355°C, which is 5°C higher than 350°C, 25 min before the start of the temperature decrease. In other words, the actual maintenance time as defined herein was 25 min. The resultant wound magnetic core had a coercive force of 1.29 A/m, which is relatively small, as indicated by a solid line in FIG. **8**.

[0112] Another nanocrystalline alloy magnetic core was produced in a manner similar to that of Example 2-1, except that the magnetic core was placed at a different position in the furnace. In FIGS. **6** and **7**, the temperature indicated by a dash-dot line is the temperature of the magnetic core of this embodiment (Example 2-2). While the decrease of the temperature was started from 355°C in the presence of an applied magnetic field, the temperature had reached 360°C, which is 5°C higher than 355°C, 7.7 min before the start of the temperature decrease. In other words, the actual maintenance time as defined herein was 7.7 min. In addition, as indicated by a dashed line in FIG. **8**, this wound magnetic core had a coercive force of 2.19 A/m. Another nanocrystalline alloy magnetic core was produced in a manner similar to that of Example 2-1, except that the actual maintenance time was elongated. In FIG. **9**, the temperature indicated by a dash-dot-dot line is the temperature of the magnetic core of this embodiment (Example 2-3).

[0113] FIG. **10** is a diagram showing the temperature of the magnetic core in a heat treatment temperature range of 400-500°C. While the temperature at which the application of an applied magnetic field was started was 350°C, the temperature had reached 355°C, which is 5°C higher than 350°C, 45 min before the start of the magnetic field application. In other words, the actual maintenance time as defined herein was 45 min. The resultant magnetic core had a B-H curve that substantially matches the B-H curve of the nanocrystalline alloy magnetic core of FIG. **8** for which the actual maintenance time was 25 min. The magnetic core of FIG. **10** had a coercive force of 1.17 A/m, which is relatively small. The comparison of the coercive forces of the nanocrystalline alloy magnetic cores whose actual maintenance times were 7.7 min, 25 min, and 45 min, shows that the coercive force decreases with an increase in the actual maintenance time.

[0114] In this embodiment, because the applied magnetic field had a strength of less than 60 kA/m, which is relatively small, the coercive force was not smaller than or equal to 1 A/m. Nevertheless, as described above, the coercive force tends to decrease with an increase in the actual maintenance time. Note that the nanocrystalline alloy magnetic cores whose actual maintenance times were 25 min and 45 min had coercive forces which are not very different, and in addition, almost the same B-H curves, as shown in FIG. **8**. Thus, it will be understood that even when a magnetic field having a strength of less than 60 kA/m is applied, then if the actual maintenance time is 10 min or more, the effect of sufficiently reducing the coercive force is obtained.

(Example 3)

[0115] The relationship between the actual maintenance time and coercive force of a nanocrystalline alloy magnetic core that was produced under a condition that a magnetic field having a strength of 60 kA/m or more was applied, was investigated. A molten alloy containing, in atom%, 1% of Cu, 3% of Nb, 15.5% of Si, and 6.5% of B, the balance being Fe and incidental impurities, was rapidly cooled by a single-roller method to obtain a Fe-based amorphous alloy ribbon having a width of 50 mm and a thickness of 14 μm. The Fe-based amorphous alloy ribbon was slit (cut) into a width of 8 mm. Thereafter, the ribbon was wound into an outer diameter of 96.5 mm and an inner diameter of 88.5 mm to produce a wound magnetic core (height: 8 mm). The magnetic core had a volume of 9294 mm^3. This alloy had a crystallization onset temperature of 500°C as measured by differential scanning calorimetry (DSC). Like Example 2, a plurality of the wound magnetic cores were placed side by side in the axial direction in a heat treatment furnace.

[0116] In the primary heat treatment, initially, the temperature was increased from room temperature (25°C) to 450°C in 100 min (temperature increase rate: 4.3°C/min), and was maintained at 30 min, and thereafter, was increased to 580°C in 240 min (temperature increase rate: 0.5°C/min). Thereafter, the temperature was maintained at 580°C for 60 min, and thereafter, was decreased to 420°C in 140 min (temperature decrease rate: 1.1°C/min).

[0117] Thereafter, the secondary heat treatment was performed. Initially, the heat treatment furnace was set such that the temperature was maintained at 420°C for 50 min. The "actual maintenance time" as defined herein (in this example, a period of time for which the temperature decreased from 425°C to 420°C) was 11 min as shown in FIG. **11**. The primary heat treatment and the second treatment so far were performed in the absence of an applied magnetic field. Thereafter, the temperature was decreased to room temperature in 320 min in the presence of an applied magnetic field of 159.5 kA/m. The direction in which the magnetic field was applied was the width direction of the alloy ribbon, i.e. the height direction of the core. Thereafter, the core was cooled in the absence of an applied magnetic field. Note that this field heat treatment was performed in an atmosphere having an oxygen concentration of 10 ppm or less (2 ppm).

[0118] As a result, a nanocrystalline alloy magnetic core of this embodiment (Example 3-1) was obtained. As indicated by a dashed line in FIG. **12**, the B-H curve had considerably excellent linearity, and the coercive force was small. This nanocrystalline alloy magnetic core had a coercive force of as small as 0.71 A/m. The nanocrystalline alloy magnetic core also had a magnetic permeability μ (1 kHz) of 92,000 and a squareness ratio Br/Bm of 10.7%. The magnetostriction was 3 ppm or less.

[0119] Another nanocrystalline alloy magnetic core was produced with an elongated actual maintenance time.

[0120] The wound magnetic core was subjected to the primary heat treatment in a manner similar to that of Example 3-1. The primary heat treatment was performed using the same settings as those of Example 3-1 until the step of maintaining the temperature at 580°C for 60 min, and thereafter, the temperature was decreased to 420°C in 90 min (temperature decrease rate: 1.8°C/min).

[0121] Thereafter, the secondary heat treatment was performed. The heat treatment furnace was set such that the temperature was maintained at 420°C for 100 min. The "actual maintenance time" as defined herein (in this example, a period of time between when the temperature reached 425°C and when the application of a magnetic field was started (the decrease of the temperature was started)) was 52 min as shown in FIG. 13. The primary heat treatment and the second treatment so far were performed in the absence of an applied magnetic field. Thereafter, the temperature was decreased to room temperature in 240 min in the presence of an applied magnetic field of 159.5 kA/m. The direction in which the magnetic field was applied was the width direction of the alloy ribbon, i.e. the height direction of the core. Thereafter, the core was cooled in the absence of an applied magnetic field. Note that this field heat treatment was performed in an atmosphere having an oxygen concentration of 10 ppm or less (2 ppm).

[0122] As a result, a nanocrystalline alloy magnetic core of this embodiment (Example 3-2) was obtained. As indicated by a solid line in FIG. 12, the B-H curve had considerably excellent linearity, and the coercive force was small. This nanocrystalline alloy magnetic core had a coercive force of 0.57 A/m, which is considerably small. The nanocrystalline alloy magnetic core also had a magnetic permeability μ (1 kHz) of 104,000 and a squareness ratio Br/Bm of 8.9%. The magnetostriction was 3 ppm or less.

[0123] The comparison of the coercive forces of the nanocrystalline alloy magnetic cores whose actual maintenance times were 11 min and 52 min, shows that one having the longer actual maintenance time had a smaller coercive force than that of the other. In this embodiment, the applied magnetic field had a strength of 60 kA/m or more, and therefore, the nanocrystalline alloy magnetic core having a coercive force of 1 A/m or less (0.71 A/m), although the actual maintenance time was 11 min.

(Example 4)

[0124] Another nanocrystalline alloy magnetic core was produced by a production method in which, in the secondary heat treatment, the core was maintained at a constant temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field, and thereafter, the core was maintained at that temperature in the presence of a magnetic field applied in a direction perpendicular to the magnetic path, and thereafter, the temperature was decreased in the presence of a magnetic field applied in the direction perpendicular to the magnetic path.

[0125] A molten alloy containing, in atom%, 1% of Cu, 3% of Nb, 15.5% of Si, and 6.5% of B, the balance being Fe and incidental impurities, was rapidly cooled by a single-roller method to obtain a Fe-based amorphous alloy ribbon having a width of 50 mm and a thickness of 14 μm. The Fe-based amorphous alloy ribbon was slit (cut) into a width of 6.5 mm. Thereafter, the ribbon was wound into an outer diameter of 20 mm and an inner diameter of 10 mm to produce a magnetic core material (height: 6.5 mm). This alloy had a crystallization onset temperature of 500°C as measured by differential scanning calorimetry (DSC).

[0126] The core thus produced was subjected to the primary heat treatment according to a temperature and applied magnetic field profile shown in FIG. 14. In the primary heat treatment, initially, the temperature was increased to 450°C in 90 min (temperature increase rate: 5.0°C/min), and was maintained at 30 min, and thereafter, was increased to 580°C in 240 min (temperature increase rate: 0.5°C/min). Thereafter, the temperature was maintained at 580°C for 60 min, and thereafter, was decreased to 350°C in 130 min (temperature decrease rate: 2.5°C/min).

[0127] Thereafter, the magnetic core was subjected to the secondary heat treatment. Initially, the temperature was maintained at 350°C for 60 min. The primary heat treatment and the second treatment so far were performed in the absence of an applied magnetic field.

[0128] Thereafter, the temperature was maintained at 350°C in the presence of an applied magnetic field of 159.5 kA/m. The period of time for which the temperature was maintained (hereinafter referred to as an "in-field maintenance time") was 0 min, 20 min, and 40 min. The direction in which the magnetic field was applied was the width direction of the alloy ribbon, i.e. the height direction of the magnetic core. Note that this field heat treatment was performed in an atmosphere having an oxygen concentration of 10 ppm or less (2 ppm). Note that the temperature and applied magnetic field profile of FIG. 14 corresponds to one whose in-field maintenance time is 0 min.

[0129] Thereafter, the temperature was decreased from 350°C to room temperature at a temperature decrease rate of 1.7°C/min in the presence of an applied magnetic field of 159.5 kA/m. The direction in which the magnetic field was applied was the width direction of the alloy ribbon, i.e. the height direction of the magnetic core. Note that this field heat treatment was performed in an atmosphere having an oxygen concentration of 10 ppm or less (2 ppm). As a result, the nanocrystalline alloy magnetic core of this embodiment was obtained.

[0130] As indicated by a solid line in FIG. 15, the B-H curve had considerably excellent linearity, and the coercive force was small. In the case where the in-field maintenance time was 0 min, 20 min, and 40 min, the coercive force of the nanocrystalline alloy magnetic core was 0.92 A/m, 0.87 A/m, and 0.80A/m, respectively, which are considerably small. Table **2** shows the measured values of the impedance relative magnetic permeability μrz at frequencies of 1 kHz to 10 MHz. FIG. **16** shows results of actual measurements corresponding to Table **2.**

[Table **1**]

In-field maintenance time	Magnetic permeability (1 kHz)	Squareness ratio Br/Bm	Coercive force Hc	Impedance relative magnetic permeability μrz (100 kHz)
0 min	165000	29.6%	0.92 A/m	50, 690
20 min	151000	24.4%	0.87 A/m	39, 641
40 min	147000	20.5%	0.80 A/m	29, 785

[Table **2**]

	In-field maintenance time		
Frequency	0 min	20 min	40 min
1 kHz	134,766	127,821	126,108
10 kHz	124,167	112,404	96,900
100 kHz	50,690	39,641	29,785
1 MHz	10,151	7,611	5,460
100 MHz	1,648	1,215	844

[0131] The coercive force Hc tends to decrease with an increase in the in-field maintenance time. Although the in-field maintenance time was 0 min, the nanocrystalline alloy magnetic core had a coercive force Hc of 1 A/m or less (0.92 A/m), which is sufficiently small.

[0132] Meanwhile, the impedance relative magnetic permeability μrz tends to decrease with an increase in the in-field maintenance time. As described above, it can be considered that the impedance relative magnetic permeability μrz is equal to the absolute value of the complex relative magnetic permeability (μ' - iμ").

[0133] FIG. **17** shows the result of a measurement of the real part μ' of the complex relative magnetic permeability of each of the obtained nanocrystalline alloy magnetic cores. FIG. **18** shows the result of a measurement of the imaginary part μ" of the complex relative magnetic permeability.

[0134] It was observed that the value of the real part μ' tends to decrease at 10 kHz or more with an increase in the in-field maintenance time in the range of 0-40 min. The peak of the frequency characteristics of the imaginary part μ" is shifted toward lower frequencies as the in-field maintenance time increases. This is a major factor that causes the impedance relative magnetic permeability μrz of this embodiment at 100 kHz to increase with an increase in the in-field maintenance time.

[0135] As can be seen from these experimental results, when a nanocrystalline alloy magnetic core having a smaller coercive force is desired, it is preferable to employ a production method of, in the secondary heat treatment, maintaining the core at a constant temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field, and thereafter, maintaining the temperature in the presence of a magnetic field applied in a direction perpendicular to the magnetic path, and thereafter, decreasing the temperature in the presence of a magnetic field applied in the direction perpendicular to the magnetic path.

[0136] It will also be understood that when a small coercive force and a high impedance relative magnetic permeability μrz are simultaneously desired, it is preferable to employ a production method of, in the secondary heat treatment, maintaining the core at a constant temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field, and thereafter, decreasing the temperature in the presence of a magnetic field applied in a direction perpendicular to the magnetic path without maintaining the temperature in the presence of a magnetic field applied in the direction perpendicular to the magnetic path.

(Example 5)

[0137] FIGS. **19-21** show the results of investigation of an influence on magnetic characteristics of a nanocrystalline alloy magnetic core of this embodiment in the case where the core is impregnated with a resin.
[0138] The nanocrystalline alloy magnetic core obtained in Example 1 was impregnated with a resin. The resin was an epoxy resin. The resin was diluted with an organic solvent. The magnetic core was immersed in the diluted resin and thereby impregnated with the resin.
[0139] FIG. **19** shows the overlaid B-H curves of the nanocrystalline alloy magnetic core of this embodiment before and after impregnation with a resin. The B-H curves match substantially throughout their entire loops, i.e. the B-H curve did not change, irrespective of impregnation with a resin. Table **3** shows the measured values of the residual magnetic flux density Br, the coercive force Hc, and the squareness ratio. The change ratios of the residual magnetic flux densities Br, the coercive forces Hc, and the squareness ratios before and after impregnation with a resin was about 3%, i.e. there were substantially no changes.

[Table **3**]

	Before impregnation with resin	After impregnation with resin	Change ratio
Residual magnetic flux density B [mT]	143.4	146.7	2.3%
Coercive force Hc [A/m]	0.64	0.66	3.1%
Squareness ratio [%]	12.7	13.1	3.1%

[0140] FIGS. **20** and **21** show the overlaid measurement results of the magnetic permeability-vs-frequency characteristics (the real part μ' of the complex relative magnetic permeability and the imaginary part μ" of the complex relative magnetic permeability) before and after impregnation with a resin. Table **4** shows the measurement results of the real part μ' and imaginary part μ" of the complex relative magnetic permeability at 10 kHz, 100 kHz, 1 MHz, and 10 MHz of FIGS. **20** and **21.**
[0141] There were substantially no changes in the real part μ' and imaginary part μ" of the complex relative magnetic permeability before and after impregnation with a resin. The change ratios at frequencies of 10 kHz to 10 MHz were all 2% or less. In particular, the change ratios of the real part μ' and the imaginary part μ" at 100 kHz were further reduced, i.e. both were 0.5% or less.
[0142] Thus, the impedance magnetic permeability change ratio of the nanocrystalline alloy magnetic core of this embodiment is small irrespective of impregnation with a resin.

[Table **4**]

Frequency f	μ'			μ"		
	Before impregnation with resin	After impregnation with resin	Change ratio	Before impregnation with resin	After impregnation with resin	Change ratio
10 kHz	108056	106899	-1.1%	22931	22501	-1.9%
100 kHz	35599	35504	-0.3%	40212	40114	-0.2%
1 MHz	5419	5376	-0.8%	10409	10359	-0.5%
10 MHz	548	539	-1.7%	1970	1956	-0.7%

[0143] Thus, changes in B-H curve and impedance characteristics of the nanocrystalline alloy magnetic core of this embodiment can be considerably reduced irrespective of impregnation with a resin, and therefore, it is easy to design these characteristics of a product.

(Second embodiment)

[0144] A second embodiment of the present disclosure will be described. This embodiment relates to a nanocrystalline alloy magnetic core having a high magnetic permeability and impedance relative magnetic permeability at 1 MHz or less, a magnetic core unit, and a production method for the nanocrystalline alloy magnetic core. According to this embodiment, a production method for providing a nanocrystalline alloy magnetic core having a high impedance relative magnetic permeability μrz can be established. In addition, a nanocrystalline alloy magnetic core having a high impedance relative magnetic permeability μrz can be provided. This nanocrystalline alloy magnetic core can be used as a magnetic core for a common-mode coil that has an excellent capability of absorbing and removing common-mode noise.

[0145] The present inventors preliminarily studied various field heat treatment methods. As a result, the present inventors saw the prospect of obtaining a nanocrystalline alloy magnetic core having a high impedance relative magnetic permeability μrz using field heat treatment patterns of (1)-(3) described below.

(1) Subsequent field heat treatment

[0146] A subsequent field heat treatment refers to a heat treatment having the following field heat treatment pattern.

[0147] An amorphous magnetic core material including an amorphous alloy ribbon capable of undergoing nanocrystallization is subjected to a primary heat treatment in which the magnetic core material is heated, in the absence of an applied magnetic field, from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature, for nanocrystallization. Thereafter, the magnetic core material is subjected to a secondary heat treatment in which the magnetic core material is heated at a temperature that is lower than the crystallization onset temperature in the presence of a magnetic field applied in a direction perpendicular to the magnetic path.

(2) Temperature-increase field heat treatment 1

[0148] A temperature-increase field heat treatment 1 refers to a heat treatment having the following field heat treatment pattern.

[0149] An amorphous magnetic core material including an amorphous alloy ribbon capable of undergoing nanocrystallization is subjected to a primary heat treatment in which the magnetic core material is heated from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature for nanocrystallization. During the temperature increase, the magnetic core material is subjected to a field heat treatment in which a magnetic field is applied to the magnetic core material in a direction perpendicular to the magnetic path during a temperature increase period corresponding to at least a portion of the temperature range from a temperature that is 50°C lower than the crystallization onset temperature to a temperature that is 20°C higher than the crystallization onset temperature, and the temperature range that does not exceed a temperature that is 50°C higher than the crystallization onset temperature, where the temperature is measured by differential scanning calorimetry.

(3) Temperature-increase field heat treatment 2 (corresponds to the production method disclosed in Patent Document No. 3)

[0150] A temperature-increase field heat treatment 2 refers to a heat treatment having a field heat treatment pattern.

[0151] An amorphous magnetic core material including an amorphous alloy ribbon capable of undergoing nanocrystallization is subjected to a primary heat treatment in which the magnetic core material is heated from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature for nanocrystallization. During the temperature increase, the magnetic core material is subjected to a field heat treatment in which a magnetic field is applied to the magnetic core material in a direction perpendicular to the magnetic path during a limited temperature increase period corresponding to the temperature range from a temperature that is 25°C higher than the crystallization onset temperature to a temperature that is 60°C higher than the crystallization onset temperature, for 10-60 min.

[0152] Next, the impedance relative magnetic permeability μrz varies depending on the thickness of an amorphous alloy ribbon that is used, and therefore, a nanocrystalline alloy magnetic core was produced according to each of the field heat treatment patterns of (1)-(3), using a ribbon having the same thickness (thickness: 18 μm), and the nanocrystalline alloy magnetic cores were evaluated at frequencies of 1 kHz to 10 MHz.

[0153] Firstly, the evaluation result of the nanocrystalline alloy magnetic core obtained according to the field heat treatment pattern of (3) will be described. This nanocrystalline alloy magnetic core is similar to that described in Patent Document No. 3, except that the ribbon had a thickness of 18 μm instead of 13 μm. Because of the greater thickness of the ribbon, the value of the impedance relative magnetic permeability μrz was smaller than that described in Patent Document No. 3. Specifically, the impedance relative magnetic permeability μrz was less than 48,000 at a frequency of 100 kHz.

[0154] Next, the evaluation results of nanocrystalline alloy magnetic cores obtained according to the field heat treatment patterns of (1) and (2) will be described. As shown in FIG. **22,** the nanocrystalline alloy magnetic core obtained by the temperature-increase field heat treatment 1 of (2) had a smaller impedance relative magnetic permeability μrz than that of the nanocrystalline alloy magnetic core obtained by the subsequent field heat treatment of (1).

[0155] Thus, of the nanocrystalline alloy magnetic cores obtained according to the field heat treatment patterns of (1)-(3), one that was obtained by the subsequent field heat treatment of (1) had the greatest impedance relative magnetic permeability μrz at frequencies of 1 kHz to 10 MHz.

[0156] With the above results in mind, the present inventors have further extensively studied the temperature profile in order to find a technical means for improving the impedance relative magnetic permeability μrz in the case where the subsequent field heat treatment is used. As a result, the present inventors found the following four technical means.

(a: First technical means) A nanocrystalline alloy magnetic core is produced using the subsequent field heat treatment, and in the primary heat treatment step, the temperature increase rate at the crystallization onset temperature is less than 1.0°C/m. By using this production method, the impedance relative magnetic permeability μrz of the nanocrystalline alloy magnetic core obtained by the subsequent field heat treatment can be increased. Note that, as used herein, the "temperature increase rate at the crystallization onset temperature" refers to an average temperature increase rate at which the temperature is increased between a temperature that is 5°C lower than the crystallization onset temperature and a temperature that is 5°C higher than the crystallization onset temperature, i.e. an average temperature increase rate during the temperature increase in the primary heat treatment step.

(b: Second technical means) A nanocrystalline alloy magnetic core is produced using the subsequent field heat treatment, and in the primary heat treatment step, the highest temperature is higher than 550°C and lower than or equal to 585°C. By using this production method, the impedance relative magnetic permeability μrz of the nanocrystalline alloy magnetic core obtained by the subsequent field heat treatment can be increased.

(c: Third technical means) A nanocrystalline alloy magnetic core is produced using the subsequent field heat treatment, and in the secondary heat treatment step, the highest temperature during the application of a magnetic field is higher than or equal to 200°C and lower than 400°C. By using this production method, the impedance relative magnetic permeability μrz of the nanocrystalline alloy magnetic core obtained by the subsequent field heat treatment can be increased.

(d: Fourth technical means) A nanocrystalline alloy magnetic core is produced using the subsequent field heat treatment, and in the secondary heat treatment step, a magnetic field is applied while the temperature is decreased at an average rate of 4°C/min. By using this production method, the impedance relative magnetic permeability μrz of the nanocrystalline alloy magnetic core obtained by the subsequent field heat treatment can be increased.

[0157] The features of (a) to (d) can be combined. If two or more of the features of (a) to (d) are combined, or two or more of the features of (a) to (d) and the feature of the first embodiment are combined, the impedance relative magnetic permeability μrz can be further improved.

[0158] A nanocrystalline alloy magnetic core production method and nanocrystalline alloy magnetic core according to the second embodiment of the present disclosure will now be described in detail.

(Amorphous alloy ribbon capable of undergoing nanocrystallization)

[0159] Like the first embodiment, a Fe-based amorphous alloy ribbon can be used as one that is capable of undergoing nanocrystallization.

[0160] The Fe-based amorphous alloy ribbon may, for example, be an alloy having a composition represented by a general formula: $(Fe_{1-a}M_a)_{100-x-y-z-\alpha-\beta-\gamma}Cu_xSi_yB_zM'_{\alpha}M''_{\beta}X_{\gamma}$ (atom%) (where M represents Co and/or Ni, M' represents at least one element selected from the group consisting of Nb, Mo, Ta, Ti, Zr, Hf, V, Cr, Mn, and W, M" represents at least one element selected from the group consisting of Al, platinum-group elements, Sc, rare-earth elements, Zn, Sn, and Re, X represents at least one element selected from the group consisting of C, Ge, P, Ga, Sb, In, Be, and As, and a, x, y, z, α, β, and γ satisfy $0 \leq a \leq 0.5$, $0.1 \leq x \leq 3$, $0 \leq y \leq 30$, $0 \leq z \leq 25$, $5 \leq y + z \leq 30$, $0 \leq \alpha \leq 20$, $0 \leq \beta \leq 20$, and $0 \leq \gamma \leq 20$, respectively). Preferably, in the above general formula, a, x, y, z, α, β, and γ satisfy the following ranges: $0 \leq a \leq 0.1$, $0.7 \leq x \leq 1.3$, $12 \leq y \leq 17$, $5 \leq z \leq 10$, $1.5 \leq \alpha \leq 5$, $0 \leq \beta \leq 1$, and $0 \leq \gamma \leq 1$, respectively.

[0161] The alloy having such a composition may be melted at the melting point thereof or higher, and the molten alloy may be rapidly cooled and solidified by a single-roller method, to obtain an elongated amorphous alloy ribbon.

[0162] The amorphous alloy ribbon is subjected to a heat treatment in which the ribbon is heated from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, so that the amorphous alloy is nanocrystallized. At least 50%, preferably 80% or more, of the volume of the nanocrystallized alloy is occupied by microcrystal grains having an average grain size of 100 nm or less, where the grain size of each grain is defined as a greatest dimension thereof that is measured. The portion of the alloy other than the microcrystal grains is mostly amorphous. The proportion of the microcrystal grains may be substantially 100 vol%.

[0163] A reduction in the thickness of the ribbon is a major factor for obtaining a nanocrystalline alloy magnetic core having a high impedance relative magnetic permeability μrz. Therefore, the thickness of the amorphous alloy ribbon is preferably 15 μm or less. If the thickness is 15 μm or less, the occurrence of an eddy current in a high-frequency application can be reduced, resulting in an improvement in the impedance relative magnetic permeability μrz. The thickness is more preferably 13 μm or less. The lower limit of the thickness is not particularly limited. In the case where the amorphous alloy ribbon is produced using a single-roller method, then if the thickness is 7 μm or more, it is easy to perform continuous casting, which is preferable for production.

[0164] Next, a production method for the amorphous alloy ribbon will be described. Initially, a ribbon-shaped amorphous alloy is formed of a molten alloy having the above composition using a known liquid quenching method (ultra-rapid quenching method), such as a single-roller method or a double-roller method. The peripheral speed of the cooling roller may be set to, for example, about 15-50 m/sec. The cooling roller may be formed of pure copper, or a copper alloy, such as Cu-Be, Cu-Cr, Cu-Zr, or Cu-Zr-Cr, which have good thermal conductivity. In the case of mass production, the cooling roller may be water-cooled. The formation of amorphous tissue of an alloy may vary depending on the rate of cooling. Therefore, in the formation of the amorphous alloy ribbon, a change in the temperature of the roller is maintained small. Note that the thickness t of the amorphous alloy ribbon is calculated by a weight conversion method. For example, the weight M of a sample elongated amorphous alloy ribbon of 2 m (longitudinal direction) × 50 mm (width direction) is measured, and the density d [kg/m^3] is measured by dry density measurement using a gas displacement method (e.g., measurement using AccuPyc II 1340 series, manufactured by Shimadzu Corporation). As a result, the thickness t [m] = $M/((2 \times 50^{-3}) \times d)$ can be calculated.

[0165] The amorphous alloy ribbon may be wound or layered to provide an amorphous magnetic core material. A small interstice or another substance may be present between each amorphous alloy layer in the amorphous magnetic core material. The space factor of the amorphous alloy layers with respect to the amorphous core material is, for example, about 70-90%.

[0166] If the amorphous alloy ribbon is subjected to the subsequent field heat treatment, the alloy ribbon undergoes nanocrystallization, so that a nanocrystalline alloy having a magnetic permeability μ (1 kHz) of 70,000 or more and a squareness ratio Br/Bm of 30% or less is obtained.

[0167] Note that, like the first embodiment, the crystallization onset temperature is defined as the temperature at which an exothermic reaction due to the start of nanocrystallization is detected by differential scanning calorimetry under conditions that the temperature increase rate is 10°C/min.

[0168] The subsequent field heat treatment of the present disclosure will now be described. The subsequent field heat treatment has a primary heat treatment for nanocrystallization and a secondary heat treatment for heating in the presence of a magnetic field in order to adjust magnetic characteristics. Note that a temperature described in the second embodiment refers to the set temperature of a furnace.

(Primary heat treatment)

[0169] The primary heat treatment includes a step of increasing the temperature from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature. The highest temperature of the primary heat treatment may be set in the range of 510-600°C. If the highest temperature is lower than 510°C or higher than 600°C, large magnetostriction occurs. If large magnetostriction occurs, then when the magnetic core is impregnated with a resin, the magnetic characteristics are likely to be significantly altered, i.e. the desired characteristics are unlikely to be obtained. The temperature does not necessarily need to be maintained at the highest temperature. Even if the temperature is maintained at the highest temperature for 0 min (no maintenance time), nanocrystallization can be achieved. Preferably, the maintenance time is set in the range of 5 min to 24 h. If the heat treatment time is 5 min or more, the entire alloy included in the magnetic core can be easily caused to have a uniform temperature, and thereby acquire uniform magnetic characteristics. Meanwhile, if the heat treatment time is longer than 24 h, not only productivity decreases, but also the excessive growth or non-uniform morphology of crystal grains is likely to occur, resulting in a decrease in magnetic characteristics.

[0170] The present inventors found the first technical means capable of improving the impedance relative magnetic permeability μrz in the primary heat treatment.

[0171] The first technical means is such that, in the step of increasing the temperature from a temperature that is lower than the crystallization onset temperature to a temperature that is higher than or equal to the crystallization onset temperature, the temperature increase rate is as slow as less than 1.0°C/min at the crystallization onset temperature. Note that, as used herein, the "temperature increase rate at the crystallization onset temperature" refers to an average temperature increase rate at which the temperature is increased between a temperature that is 5°C lower than the crystallization onset temperature and a temperature that is 5°C higher than the crystallization onset temperature. The reason for this will now be described.

[0172] The crystallization reaction is an exothermic reaction. Therefore, the temperature of the magnetic core material may instantaneously increase at or near the crystallization onset temperature. At this time, nanocrystals become coarse non-uniformly in the ribbon, so that uniform magnetic anisotropy is not formed, and therefore, the impedance relative magnetic permeability μrz of the magnetic core is likely to decrease. If the temperature increase rate at the crystallization onset temperature is as slow as less than 1.0°C/min, the instantaneous temperature increase can be reduced, resulting in an improvement in impedance magnetic permeability. Note that the temperature increase rate may be relatively high, e.g. 1.0°C/min or more, until a temperature that is 20°C lower than the crystallization onset temperature. As an additional effect, nanocrystallization can stably proceed, which can reduce magnetostriction, resulting in a nanocrystalline alloy magnetic core whose characteristics are not significantly altered even when the magnetic core is impregnated with a resin.

[0173] If the temperature increase rate at the crystallization onset temperature is 0.9°C/min or less, or 0.85°C/min or less, the impedance relative magnetic permeability μrz can be further improved. Although the lower limit value of the temperature increase rate is not particularly limited, the temperature increase rate at the crystallization onset temperature is preferably 0.1°C/min or more, more preferably 0.2°C/min or more, in order to reduce the production process time.

[0174] The present inventors also found the second technical means capable of improving the impedance relative magnetic permeability μrz by setting the highest temperature in the primary heat treatment to higher than 550°C and not higher 585°C. The reason for this will now be described.

[0175] If the highest temperature in the primary heat treatment is higher than 585°C, the crystal grain size of the nanocrystal becomes considerably large, resulting in a sharp increase in the coercive force of the magnetic core material. It is considered that a magnetic core material having a great coercive force contains a large magnetic domain wall displacement component in the magnetization process, and an eddy current (extraordinary eddy current) occurs due to a magnetic domain wall displacement, resulting in a decrease in the impedance relative magnetic permeability μrz. Conversely, it is considered that if the highest temperature in the primary heat treatment is 550°C or less, the coercive force of the magnetic core material decreases, and the magnetostriction increases, and therefore, the magnetic domain structure is disturbed due to the influence of external stress, resulting in a decrease in the impedance relative magnetic permeability μrz.

[0176] In addition, if the temperature is in this temperature range, the effect of reducing the magnetostriction is achieved. Specifically, the magnetostriction can be reduced to 3 ppm or less, 2 ppm or less, or 1 ppm or less. The lower limit value of the highest temperature is preferably higher than or equal to 555°C. The upper limit value of the highest temperature is preferably lower than or equal to 583°C. As a result, the impedance relative magnetic permeability μrz can be further increased.

(Secondary heat treatment)

[0177] After the primary heat treatment, the secondary heat treatment is performed in which a magnetic field is applied in a direction perpendicular to the magnetic path at a temperature that is lower than the crystallization onset temperature. The application of a magnetic field may be performed either while the temperature is maintained constant or while the temperature is increased or decreased. It is particularly preferable that a magnetic field be applied while the temperature is decreased. This is because the slope of the hysteresis BH curve decreases, and the sloped portion becomes linear.

[0178] The direction of the applied magnetic field is perpendicular to the direction of the magnetic path. In the case of the wound magnetic core, a magnetic field is applied in the height direction of the magnetic core (the axial direction of the wound magnetic core). The applied magnetic field may be any of a direct-current magnetic field, an alternating-current magnetic field, and a pulse magnetic field.

[0179] The field heat treatment reduces the residual magnetic flux density Br, although it also reduces the magnetic permeability, so that Br/Bm decreases, and therefore, non-uniform magnetization does not easily occur in the magnetic core. Therefore, the magnetic core is suitable for a common-mode choke coil.

[0180] Note that it is preferable that the highest temperature at which a magnetic field is applied be in the range of not lower than 200°C and lower than the crystallization onset temperature. This is because the magnetic permeability can be easily changed, and magnetic characteristics required for a common-mode choke coil can be easily obtained. If a magnetic field is applied at a temperature that is higher than or equal to the crystallization onset temperature, the crystal grain growth of the nanocrystal phase is accelerated, and therefore, the coercive force is likely to increase. It is more preferable that the highest temperature at which a magnetic field is applied be lower than or equal to 500°C (and lower than the crystallization onset temperature).

[0181] In this case, the temperature is preferably decreased to 100°C or lower in the presence of an applied magnetic field. As a result, the impedance relative magnetic permeability μrz can be increased. In addition, the B-H curve has a smaller slope and higher linearity, i.e. soft magnetic characteristics can be obtained.

[0182] The applied magnetic field preferably has a magnetic field strength of 50 kA/m or more. As a result, the impedance relative magnetic permeability μrz can be increased. The magnetic field strength is more preferably in the range of 60 kA/m or more, even more preferably 150 kA/m or more. Although the upper limit of the magnetic field strength is not particularly limited, the magnetic field strength is practically 500 kA/m or less according to the relationship between the magnetic field strength and the amount of a current that can be passed through the magnetic field generating coil. Although the period of time for which a magnetic field is applied is not particularly limited, the period of time is practically about 1-180 min.

[0183] The primary heat treatment and the secondary heat treatment can be continuously performed. Specifically, after the temperature reaches the highest temperature in the primary heat treatment, the temperature may be decreased to the temperature of the secondary heat treatment, and the secondary heat treatment may be performed at that temperature in the presence of an applied magnetic field.

[0184] Of course, the primary heat treatment and the secondary heat treatment may be separately performed. Specifically, after the primary heat treatment is performed, the temperature may be decreased to a temperature that is lower than or equal to the temperature of the secondary heat treatment, and thereafter, the temperature may be increased to the temperature of the secondary heat treatment and a magnetic field may be applied.

[0185] The present inventors found the third technical means capable of improving the impedance relative magnetic permeability μrz in the secondary heat treatment. The third technical means is such that the highest temperature at which a magnetic field is applied is higher than or equal to 200°C and lower than 400°C. The reason for this will now be described.

[0186] The impedance relative magnetic permeability μrz is greatest at a frequency that is as low as about 1 kHz, and starts to decrease as the frequency increases, and finally decreases along a Snoek's limit line. At a frequency of 2 MHz or more, the impedance relative magnetic permeability μrz is along the Snoek's limit line, and does not depend on the highest temperature at which a magnetic field is applied. However, the impedance relative magnetic permeability μrz at about 1-100 kHz varies depending on the highest temperature at which a magnetic field is applied as described below. This is because magnetic anisotropy in the height direction of the magnetic core material varies, and therefore, if the highest temperature at which a magnetic field is applied is low, the slope of the B-H curve increases. If the highest temperature at which a magnetic field is applied is higher than or equal to 200°C and lower than 400°C, the impedance relative magnetic permeability μrz at 100 kHz is sufficiently high. The highest temperature at which a magnetic field is applied is preferably lower than or equal to 370°C. The impedance relative magnetic permeability μrz can be further improved.

[0187] The present inventors also found the fourth technical means capable of improving the impedance relative magnetic permeability μrz in the secondary heat treatment. The fourth technical means is to apply a magnetic field in the secondary heat treatment while decreasing the temperature at an average rate of 4°C/min or less.

[0188] Although the reason why this improves the impedance relative magnetic permeability μrz has not been clarified, it is considered that when the temperature is rapidly decreased in the presence of an applied magnetic field, a non-uniform temperature distribution occurs in the magnetic core material in the heat treatment, so that magnetic anisotropy varies from position to position in the magnetic core material, and therefore, a uniform magnetic domain is not formed.

[0189] Note that the "average rate of 4°C/min or less in the presence of an applied magnetic field in the secondary heat treatment" refers to an average rate between when the application of a magnetic field is started and when the decreased temperature reaches 100°C.

[0190] Note that the temperature decrease rate at 100°C is preferable 4°C/min or less. The impedance relative magnetic permeability μrz can be further improved. Note that, as used herein, the "temperature decrease rate at 100°C" refers to an average temperature decrease rate between 105°C and 95°C.

[0191] The primary and secondary heat treatments are preferably performed in a non-reactive atmosphere. When the heat treatments are performed in nitrogen gas, a sufficient magnetic permeability is obtained. Nitrogen gas can be handled as a substantially non-reactive gas. The non-reactive gas may be an inert gas. Alternatively, the heat treatments may be performed in a vacuum.

[0192] The primary heat treatment is preferably performed in an atmosphere having an oxygen concentration of 10 ppm or less. The resultant coercive force can be further reduced.

(Nanocrystalline alloy magnetic core)

[0193] The nanocrystalline alloy magnetic core of the present disclosure can have a magnetic permeability μ (1 kHz) of 70,000 or more as measured in the presence of an applied alternating-current magnetic field having a frequency f of 1 kHz and an amplitude H of 0.05 amperes/meter (A/m).

[0194] In addition, by using the above production method, the nanocrystalline alloy magnetic core can have an impedance relative magnetic permeability μrz of 48,000 or more at 100 kHz. The nanocrystalline alloy magnetic core can also have an impedance relative magnetic permeability μrz of 90,000 or more at 10 kHz, and 8,500 or more at 1 MHz, i.e. a high impedance relative magnetic permeability μrz over a wide frequency region. The nanocrystalline alloy magnetic core can also have an impedance relative magnetic permeability μrz of 49,000 or more, or 50,000 or more, at 100 kHz. The nanocrystalline alloy magnetic core can also have an impedance relative magnetic permeability μrz of 95,000 or more, or 100,000 or more, at 10 kHz. The nanocrystalline alloy magnetic core can also have an impedance relative magnetic permeability μrz of 8,800 or more, or 9,000 or more, at 1 MHz.

(Magnetic core unit)

[0195] For example, a conducting wire may be wound around or passed through the nanocrystalline alloy magnetic core of the present disclosure to provide a magnetic core unit for a common-mode choke coil.

<Impedance relative magnetic permeability prz, and real part u' and imaginary part μ" of complex relative magnetic permeability>

[0196] The impedance relative magnetic permeability μrz, and the real part μ' and imaginary part μ" of the complex relative magnetic permeability, were measured using HP4194A, manufactured by Agilent Technologies, Inc., under conditions that the oscillation level was 0.5V and the average was 16. An insulating-sheath conducting wire was passed through a center portion of the toroidal magnetic core, and was connected to input and output terminals, to perform measurement.

[0197] The production method will now be described in greater detail.

(Example 6)

[0198] A molten alloy containing, in atom%, 1% of Cu, 3% of Nb, 15.5% of Si, and 6.5% of B, the balance being Fe and incidental impurities, was rapidly cooled by a single-roller method to obtain a Fe-based amorphous alloy ribbon having a width of 50 mm and a thickness of 14 μm. The Fe-based amorphous alloy ribbon was slit (cut) into a width of 6.5 mm. Thereafter, the ribbon was wound into an outer diameter of 20 mm and an inner diameter of 10 mm to produce a magnetic core material (height: 6.5 mm). This alloy had a crystallization onset temperature of 500°C as measured by differential scanning calorimetry (DSC).

[0199] The core thus produced was subjected to the primary and second heat treatments according to a temperature and applied magnetic field profile shown in FIG. **23.** In the primary heat treatment, initially, the temperature was increased to 450°C in 90 min (temperature increase rate: 5.0°C/min), and was maintained at 30 min, and thereafter, was increased to 580°C in 240 min (temperature increase rate: 0.5°C/min). Thereafter, the temperature was maintained at 580°C for 60 min, and thereafter, was decreased to 350°C in 130 min (temperature decrease rate: 2.5°C/min).

[0200] Thereafter, the magnetic core was subjected to the secondary heat treatment. Initially, the temperature was maintained at 350°C for 60 min. The primary heat treatment and the second treatment so far were performed in the absence of an applied magnetic field. Thereafter, the temperature was decreased from 350°C to room temperature at a temperature decrease rate of 1.7°C/min in the presence of an applied magnetic field of 159.5 kA/m. The direction in which the magnetic field was applied was the width direction of the alloy ribbon, i.e. the height direction of the magnetic core. Note that this field heat treatment was performed in an atmosphere having an oxygen concentration of 10 ppm or less (2 ppm). As a result, the nanocrystalline alloy magnetic core of this embodiment was obtained. The nanocrystalline alloy magnetic core had an impedance relative magnetic permeability μrz of 126,524 at 10 kHz, 50,644 at 100 kHz, and 9,938 at 1 MHz. The nanocrystalline alloy magnetic core also had a magnetic permeability μ (1 kHz) of 100,000 and a squareness ratio Br/Bm of 12.7%.

(Example 7)

[0201] An influence on the impedance relative magnetic permeability μrz was investigated by varying the temperature increase rate in the range of 0.5-4.4°C/min when the temperature was increased from 450°C to 580°C in the temperature and applied magnetic field profile of FIG. 23.

[0202] Specifically, the time it takes to increase the temperature from 450°C to 580°C was set to 180 min (temperature increase rate: 0.8°C/min), 120 min (temperature increase rate: 1.1°C/min), 60 min (temperature increase rate: 2.2°C/min), and 30 min (temperature increase rate: 4.4°C/min), in addition to 240 min (temperature increase rate:: 0.5°C/min). Except for that, the magnetic core material was subjected to the subsequent field heat treatment in a manner similar to that of Example 6.

[0203] FIG. **24** shows a relationship between the temperature increase rate and the impedance relative magnetic permeability μrz at several frequencies. Table **5** shows the numerical values thereof. As shown in FIG. **24** and Table **5,** if the temperature increase rate is low (lower than 1.0°C/min), the impedance relative magnetic permeability μrz is high. In the case where the temperature increase rate was 0.8°C/min and 0.5°C/min, the measured values of the impedance relative magnetic permeability μrz at 100 kHz were 50,000 or more in both cases, and were substantially the same. As the temperature increase rate increases, the production time increases. Therefore, when a high impedance relative magnetic permeability μrz at 100 kHz is desired, it is preferable to set the temperature increase rate to around 0.8°C/min (0.4-0.9°C/min) in the production.

[0204] When a high impedance relative magnetic permeability μrz at 1 MHz or 10 MHz is desired, it is preferable to set the temperature increase rate to around 0.5°C/min (0.3-0.7°C/min) in the production, because the impedance relative magnetic permeability μrz is higher in the case of 0.5°C/min than 0.8°C/min.

[0205] In addition, in the case where the temperature increase rate was 0.5°C/min, the nanocrystalline alloy magnetic core had a magnetic permeability μ (1 kHz) of 134,766 and a squareness ratio Br/Bm of 29.6%. In the case where the temperature increase rate was 0.8°C/min, the nanocrystalline alloy magnetic core had a magnetic permeability μ (1 kHz) of 137,116 and a squareness ratio Br/Bm of 32.8%.

[Table 5]

Frequency	Impedance relative magnetic permeability μrz				
	0.5°C/min	0.8°C/min	1.1°C/min	2.2°C/min	4.4°C/min
1 kHz	134,766	137,116	135,291	139,317	121,415
10 kHz	124,167	126,524	121,915	122,043	106,617
100 kHz	50,690	50,644	44,521	42,153	39,139
1 MHz	10,151	9,938	8,423	8,033	7,575
10 MHz	1,648	1,581	1,323	1,271	1,216

[0206] FIG. 25 shows a relationship between frequency and the real part μ' of the complex relative magnetic permeability of each of the nanocrystalline alloy magnetic cores of Example 7. The nanocrystalline alloy magnetic cores obtained in the case where the temperature increase rate was less than 1°C/min (0.5°C/min and 0.8°C/min) had a smaller reduction in the real part μ' at a frequency of 10 kHz or more than that of the nanocrystalline alloy magnetic core obtained in the case where the temperature increase rate was lower than that rate. Note that the real parts μ' for the temperature increase rates of 0.5°C/min and 0.8°C/min have substantially the same value over the entire frequency region.

[0207] FIG. **26** shows a relationship between frequency and the imaginary part μ" of the complex relative magnetic permeability of each of the same nanocrystalline alloy magnetic cores as those of FIG. **25.** The nanocrystalline alloy magnetic cores obtained in the case where the temperature increase rate was less than 1°C/min (0.5°C/min and 0.8°C/min) had the peak of the imaginary part μ" at a higher frequency than those of the nanocrystalline alloy magnetic cores obtained in the case where the temperature increase rate was lower than that rate. Specifically, the imaginary parts μ" of the nanocrystalline alloy magnetic cores obtained in the case where the temperature increase rate was less than 1°C/min are smaller at a frequency that is higher than or equal to 2 kHz and lower than 50 kHz, and are greater at a frequency of 50 kHz or more, than those of the nanocrystalline alloy magnetic cores obtained in the case where the temperature increase rate was lower than that rate. Note that the real parts μ' for the temperature increase rates of 0.5°C/min and 0.8°C/min have substantially the same value over the entire frequency region. This phenomenon is a major factor for the significant increase in the impedance relative magnetic permeability μrz at 100 kHz in this embodiment, in the case where the temperature increase rate at which the temperature is increased from 450°C to 580°C is less than 1.0°C/min.

[0208] In addition, the nanocrystalline alloys obtained in the case where the temperature increase rate was 0.5°C/min and 0.8°C/min have substantially same frequency characteristics in terms of both the real part μ' and the imaginary part μ". This suggests that if the temperature increase rate is less than 1°C/min, a nanocrystalline alloy having a stable impedance relative magnetic permeability μrz can be easily produced.

(Example 8)

[0209] An influence on the impedance relative magnetic permeability μrz was investigated by varying the highest temperature in the range of 500-600°C in the temperature and applied magnetic field profile of FIG. **23.** Specifically, the highest temperature was 500°C, 520°C, 540°C, 560°C, 580°C, 590°C, and 600°C. Except for that, the magnetic core material was subjected to the subsequent field heat treatment in a manner similar to that of Example 6. Note that the time it took to reach from 450°C to the highest temperature was 4 h.

[0210] FIG. **27** is a diagram showing a relationship between the highest temperature of the primary heat treatment and the impedance relative magnetic permeability μrz as measured at several frequencies. Table **6** shows the numerical values thereof. As shown in FIG. **27** and Table **6,** the nanocrystalline alloy magnetic core obtained in the case where the highest temperature was 580°C in the primary heat treatment, had an impedance relative magnetic permeability μrz of as great as 50,000 or more (50,690) at 100 kHz. The nanocrystalline alloy magnetic core obtained in the case where the highest temperature was 560°C had an impedance relative magnetic permeability μrz of 49,000 or more (49,540), which is the next highest.

[0211] The impedance relative magnetic permeability μrz obtained in the case where the highest temperature was 540°C had an impedance relative magnetic permeability μrz of 48,198 at 100 kHz, which is slightly lower than in the case of 560°C. The impedance relative magnetic permeability μrz obtained in the case where the highest temperature was 590°C had an impedance relative magnetic permeability μrz of 39,136, which is sharply lower than in the case of 580°C (50,690). In view of this, if the highest temperature of the primary heat treatment is in the range of higher than 550°C and lower than or equal to 585°C, the impedance relative magnetic permeability μrz is likely to be 49,000. If the highest temperature of the primary heat treatment is in the range of 555-590°C, the impedance relative magnetic permeability μrz is likely to be 49,000.

[0212] The nanocrystalline alloy magnetic core obtained in the case where the highest temperature was 560°C had a magnetic permeability μ (1 kHz) of 143,248 and a squareness ratio Br/Bm of 28.3%. The nanocrystalline alloy magnetic core obtained in the case where the highest temperature was 580°C had a magnetic permeability μ (1 kHz) of 134,766 and a squareness ratio Br/Bm of 29.6%.

[Table **6**]

Frequency	Impedance relative magnetic permeability μrz						
	500°C	520°C	540°C	560°C	580°C	590°C	600°C
1 kH z	101,098	115,291	136,886	143,248	134,766	108,730	105,796
10 kHz	82,888	101,071	122,701	129,776	124,167	98,711	83,959
100 kHz	30,572	42,463	48,198	49,540	50,690	39,136	28,652
1 MHz	5,758	8,649	9,961	9,971	10,151	7,655	5,348
10 MHz	1,073	1,607	1,741	1,583	1,648	1,241	838

[0213] FIG. **28** shows a relationship between frequency and the real part μ' of the complex relative magnetic permeability of each of the nanocrystalline alloy magnetic cores of Example 8. The nanocrystalline alloy magnetic cores obtained in the case where the highest temperature in the primary heat treatment step was higher than 550°C and lower than or equal to 585°C (560°C and 580°C), had a great real part μ' in the range of 1 kHz to 10 MHz.

[0214] FIG. **29** shows a relationship between frequency and the imaginary part μ" of the complex relative magnetic permeability of each of the same nanocrystalline alloy magnetic cores as those of FIG. **28.** As in FIG. **28,** The nanocrystalline alloy magnetic cores obtained in the case where the highest temperature in the primary heat treatment step was higher than 550°C and lower than or equal to 585°C (560°C and 580°C), had a great imaginary part μ" in the range of 10 MHz or more.

[0215] Note that the nanocrystalline alloy magnetic core obtained in the case where the highest temperature in the primary heat treatment was 540°C had a great real part μ' like those obtained in the case of 560°C and 580°C as shown in FIG. **28,** and had an imaginary part μ" slightly smaller than those obtained in the case of 560°C and 580°C, at 100 kHz, as shown in FIG. **29.** This phenomenon is a major factor for the great impedance relative magnetic permeability μrz of this embodiment at 100 kHz in the case where the highest temperature in the primary heat treatment step was higher than 550°C and lower than or equal to 585°C (560°C and 580°C) .

(Example 9)

[0216] An influence on the impedance relative magnetic permeability μrz was investigated by varying the temperature range in which a magnetic field is applied in the second heat treatment, in the temperature and applied magnetic field profile of FIG. **23.** Specifically, the highest temperature at which a magnetic field is applied in the secondary heat treatment was 350°C, 400°C, 450°C, and 500°C, and the temperature was decreased to room temperature in the presence of an applied magnetic field. The Fe-based amorphous alloy ribbon had a thickness of 10.6 μm. Except for that, the magnetic core material was subjected to the subsequent field heat treatment in a manner similar to that of Example 6.

[0217] FIG. **30** shows a relationship between frequency and the impedance relative magnetic permeability μrz for several temperature ranges in which a magnetic field is applied. Table **7** shows the numerical values thereof. As shown in FIG. **30** and Table **7,** if the temperature range in which a magnetic field is applied in the secondary heat treatment was limited to a low range, a higher impedance relative magnetic permeability μrz at 100 kHz was achieved. In the case where the highest temperature was 350°C, the impedance relative magnetic permeability μrz was 66,003. Note that, referring to frequencies other than 100 kHz, at a frequency of 2 MHz or less, the impedance relative magnetic permeability μrz tends to increase with a decrease in the temperature range in which a magnetic field is applied, and at a frequency of more than 2 MHz, the impedance relative magnetic permeability μrz tends to decrease with a decrease in the temperature range in which a magnetic field is applied.

[0218] The nanocrystalline alloy magnetic core of this embodiment obtained in the case where the highest temperature was 350°C had an impedance relative magnetic permeability μrz of 120,000 or more (129,625) at 10 kHz. The impedance relative magnetic permeability μrz was 13,000 or more (13,488) at 1 MHz. The nanocrystalline alloy magnetic core obtained in the case where the highest temperature at which a magnetic field is applied was 350°C in the secondary heat treatment had a magnetic permeability μ (1 kHz) of 135,998 and a squareness ratio Br/Bm of 20.8%.

[Table **7**]

Frequency	Impedance relative magnetic permeability μrz			
	350°C	400°C	450°C	500°C
1 kHz	135,998	109,658	84,543	64,751
10 kHz	129,625	107,770	82,847	63,308
100 kHz	66,003	64,813	56,374	48,504
1 MHz	13,488	14,283	13,456	12,925
10 MHz	2,292	2,568	2,580	2,674

[0219] FIG. **31** shows a relationship between frequency and the real part μ' of the complex relative magnetic permeability of each of the nanocrystalline alloy magnetic cores of Example 9. The nanocrystalline alloy magnetic core obtained in the case where the highest temperature at which a magnetic field is applied in the second heat treatment was 350°C, had a greater real part μ' at 100 MHz or less and a smaller real part μ' at more than 100 MHz than those of the nanocrystalline alloy magnetic cores obtained in the case where the highest temperature was other than 350°C.

[0220] FIG. **32** shows a relationship between frequency and the imaginary part μ" of the complex relative magnetic permeability of each of the same nanocrystalline alloy magnetic cores as those of FIG. **31.** The nanocrystalline alloy magnetic core obtained in the case where the highest temperature at which a magnetic field is applied in the second heat treatment was 350°C, had a greater imaginary part μ" than those of the nanocrystalline alloy magnetic cores obtained in the case where the highest temperature in the second heat treatment was other than 350°C. In particular, the difference in imaginary part μ" becomes more significant at a frequency of 100 kHz or less. This phenomenon is a major factor for the high impedance relative magnetic permeability μrz of this embodiment at 100 kHz in the case where the highest temperature at which a magnetic field is applied in the second heat treatment was 350°C.

[0221] An influence on the impedance relative magnetic permeability μrz was investigated by decreasing the thickness of the ribbon. The nanocrystalline alloy magnetic core of Example 6 (the thickness of the thin band was 14 μm, and the temperature range in which the magnetic field is applied was only 350°C or less) had an impedance relative magnetic permeability μrz of 126,524 at 10 kHz, 50,644 at 100 kHz, and 9, 938 at 1 MHz. In contrast to this, the nanocrystalline alloy magnetic core of this embodiment (the thickness of the thin band was 10.6 μm, and the temperature range in which a magnetic field is applied was also only 350°C or less) had an impedance relative magnetic permeability μrz of 129,625 at 10 kHz, 66,003 at 100 kHz, and 13,488 at 1 MHz. The nanocrystalline alloy magnetic core of this embodiment, which had a ribbon thickness of 10.6 μm, also had a higher impedance relative magnetic permeability μrz at frequencies of 1 kHz and 10 MHz.

(Example 10)

[0222] An influence on the impedance relative magnetic permeability μrz was investigated by varying a temperature decrease rate in the range of 4.4-1.0°C/min in the case where a magnetic field was applied while the temperature was decreased in the secondary heat treatment, in the temperature and applied magnetic field profile of FIG. **23.**

[0223] FIG. **33** shows a relationship between frequency and the impedance relative magnetic permeability μrz for several temperature decrease rates. Table **8** shows the numerical values thereof. As show in FIG. **33** and Table **8,** in this embodiment, the temperature decrease rate during the application of a magnetic field was 3.0°C/min, 1.7°C/min, and 1.0°C/min. In these cases, the impedance relative magnetic permeability μrz at 100 kHz was 50,000 or more (50,770, 50,690, and 52,194). The highest impedance relative magnetic permeability μrz at 10 kHz was 134,326, which was obtained in the case where the temperature decrease rate was 3.0°C/min. In all of the three cases, the impedance relative magnetic permeability μrz was 11,500 or more (134,326, 124,167, and 125,205). Also, in all the cases, the impedance relative magnetic permeability μrz at 1 MHz was 10,000 or more (10,041, 10,151, and 10,793).

[0224] The nanocrystalline alloy magnetic core obtained in the case where the temperature decrease rate was 3.0°C/min had a magnetic permeability μ (1kHz) of 147,915 and a squareness ratio Br/Bm of 36.6%. The nanocrystalline alloy magnetic core obtained in the case where the temperature decrease rate was 1.7°C/min had a magnetic permeability μ (1 kHz) of 134,776 and a squareness ratio Br/Bm of 29.6%. The nanocrystalline alloy magnetic core obtained in the case where the temperature decrease rate was 1.0°C/min had a magnetic permeability μ (1 kHz) of 125,205 and a squareness ratio Br/Bm of 20.8%.

[Table **8**]

Frequency	Impedance relative magnetic permeability μrz			
	4.9°C/min	3.0°C/min	1.7°C/min	1.0°C/min
1 kHz	144,885	147,915	134,766	125,205
10 kHz	110,877	134,326	124,167	118,686
100 kHz	32,382	50,770	50,690	52,194
1 MHz	5,887	10,041	10,151	10,793
10 MHz	907	1,610	1,648	1,796

[0225] FIG. **34** shows a relationship between frequency and the real part μ' of the complex relative magnetic permeability of each of the nanocrystalline alloy magnetic cores of Example 10. The nanocrystalline alloy magnetic cores obtained in the case where the temperature decrease rate was 4°C/min or less (3.0°C/min, 1.7°C/min, and 1.0°C/min) had substantially the same frequency characteristics. These nanocrystalline alloy magnetic cores had a greater real part μ' in the range of 5 kHz or more than in the case of 4.4°C/min.

[0226] FIG. **35** shows a relationship between frequency and the imaginary part μ" of the complex relative magnetic permeability of each of the same nanocrystalline alloy magnetic cores as those of FIG. **34.** As the temperature decrease rate decreases, the peak of the imaginary part μ"-vs-frequency characteristics is shifted toward higher frequencies. Note that the nanocrystalline alloy magnetic cores obtained in the case where the temperature decrease rate was 3.0-1.0°C/min had substantially the same frequency characteristics in the frequency range of about 80 kHz or more.

[0227] In the case where the temperature decrease rate was 4°C/min or less in the presence of an applied magnetic field, the imaginary part μ" had a great value at a frequency of 80 kHz or more. This is a major factor for the high impedance relative magnetic permeability μrz of this embodiment.

(Example 11)

[0228] An influence on the impedance relative magnetic permeability μrz was investigated by varying a lowest temperature in the range of 100-300°C when a magnetic field is applied while the temperature was decreased in the secondary heat treatment, in the temperature and applied magnetic field profile of FIG. **23.** Specifically, the lowest temperature during the application of a magnetic field was 100°C, 200°C, 250°C, and 300°C.

[0229] FIG. **36** shows a relationship between frequency and the impedance relative magnetic permeability μrz for several lowest temperatures in the secondary heat treatment. Table **9** shows the numerical values thereof. As shown in FIG. **36** and Table **9,** the nanocrystalline alloy magnetic core obtained in the case where the lowest temperature during the application of a magnetic field was 100°C had an impedance relative magnetic permeability μrz of 50,000 or more (50,690) at 100 kHz. The impedance relative magnetic permeability μrz at 10 kHz was 12,000 or more (124,167). The impedance relative magnetic permeability μrz at 1 MHz was 10,000 or more (10,151).

[0230] The nanocrystalline alloy magnetic core obtained in the case where the lowest temperature during the application of a magnetic field was 100°C also had a magnetic permeability μ (1 kHz) of 134,766 and a squareness ratio Br/Bm of 29.6%.

[Table **9**]

Frequency	Impedance relative magnetic permeability μrz			
	100°C	200°C	250°C	300°C
1 kHz	134,766	140,198	140,220	127,649
10 kHz	124,167	125,544	120,309	100,140
100 kHz	50,690	44,947	39,217	30,016
1 MHz	10,151	8,520	7,400	5,516

(continued)

Frequency	Impedance relative magnetic permeability μrz			
	100°C	200°C	250°C	300°C
10 MHz	1,648	1,323	1,162	846

[0231] FIG. **37** shows a relationship between frequency and the real part μ' of the complex relative magnetic permeability of each of the nanocrystalline alloy magnetic cores of Example 11. The real part μ' at frequencies of 10 kHz or more tends to increase with a decrease in the lowest temperature during the application of a magnetic field in the secondary heat treatment.

[0232] FIG. **38** shows a relationship between frequency and the imaginary part μ" of the complex relative magnetic permeability of each of the same nanocrystalline alloy magnetic cores as those of FIG. **37.** Likewise, the imaginary part μ" at a frequency of 10 kHz or more tends to increase with a decrease in the lowest temperature during the application of a magnetic field. This phenomenon is a major factor for the feature that the impedance relative magnetic permeability μrz at 100 kHz in this embodiment increases with a decrease in the lowest temperature during the application of a magnetic field.

(Example 12)

[0233] An influence on the impedance relative magnetic permeability μrz was investigated by varying the strength of the applied magnetic field in the range of 39.9-319.2 kA/m in the secondary heat treatment, in the temperature and applied magnetic field profile of FIG. **23.** Specifically, the strength of the applied magnetic field was 39.9 kA/m, 79.8 kA/m, and 319.2 kA/m.

[0234] FIG. **39** is a diagram showing a relationship between the strength of the applied magnetic field and the impedance relative magnetic permeability μrz for several measurement frequencies. Table **10** shows the numerical values thereof. As shown in FIG. **39** and Table **10,** the impedance relative magnetic permeability μrz tends to increase with an increase in the strength of the applied magnetic field. The nanocrystalline alloy magnetic core obtained in the case where a magnetic field of 79.8 kA/m was applied had a 30% or more increase in the impedance relative magnetic permeability μrz at frequencies of 1 kHz, 10 kHz, 100 kHz, 1 MHz, and 10 MHz compared to the case where the strength of the applied magnetic field was 39.9 kA/m. Meanwhile, the nanocrystalline alloy magnetic cores obtained in the cases where the magnetic fields having a strength of 79.8 kA/m and 319.2 kA/m were applied had a 6% or less increase in the impedance relative magnetic permeability μrz at all the frequencies. Note that the nanocrystalline alloy magnetic cores obtained in the cases of 79.8 kA/m and 319.2 kA/m both had an impedance relative magnetic permeability μrz of 48,000 or more (48,677 and 50, 690) at 100 kHz. These results show that if the strength of the applied magnetic field is 79.8 kA/m, a sufficiently high impedance relative magnetic permeability μrz is obtained.

[0235] The nanocrystalline alloy magnetic core obtained in the case where the strength of the applied magnetic field was 79.8 kA/m also had a magnetic permeability μ (1 kHz) of 132,983 and a squareness ratio Br/Bm of 32.6%. The nanocrystalline alloy magnetic core obtained in the case where the strength of the applied magnetic field was 319.2 kA/m also had a magnetic permeability μ (1 kHz) of 134,766 and a squareness ratio Br/Bm of 29.6%.

[Table **10**]

Frequency	Impedance relative magnetic permeability μrz		
	39.9 kA/m	79.8 kA/m	319.2 kA/m
1 kHz	98,777	132,983	134,766
10 kHz	81,491	121,897	124,167
100 kHz	27,640	48,677	50,690
1 MHz	5, 253	9,666	10,151
10 MHz	814	1,555	1,648

[0236] FIG. **40** shows a relationship between frequency and the real part μ' of the complex relative magnetic permeability of each of the nanocrystalline alloy magnetic cores of Example 12. The real part μ' of the nanocrystalline alloy magnetic core obtained in the case where the strength of the applied magnetic field was 50 kA/m or more (79.8 kA/m and 319.2 kA/m) in the secondary heat treatment had a greater real part μ' in the range of 1 kHz to 10 MHz than in the case of 39.9 kA/m. The nanocrystalline alloy magnetic cores obtained in the cases where the strengths of the applied magnetic field were 79.8 kA/m and 319.2 kA/m both had substantially the same frequency characteristics.

[0237] FIG. **41** shows a relationship between frequency and the imaginary part μ" of the complex relative magnetic permeability of each of the same nanocrystalline alloy magnetic cores as those of FIG. **40.** The nanocrystalline alloy magnetic core obtained in the case where the strength of the applied magnetic field was 50 kA/m or more (79.8 kA/m and 319.2 kA/m) had a smaller imaginary part μ" at a frequency of less than 10 kHz, and a greater imaginary part μ" at a frequency of 10 kHz or more, than in the case of 39.9 kA/m. This phenomenon is a major factor for the great impedance relative magnetic permeability μrz at 100 kHz of this embodiment obtained in the case where the strength of the applied magnetic field was 50 kA/m or more.

INDUSTRIAL APPLICABILITY

[0238] The nanocrystalline alloy magnetic core, magnetic core unit, and nanocrystalline alloy magnetic core production method of the present disclosure are suitably useful for common-mode choke coils, current transformers, etc.

REFERENCE SIGNS LIST

[0239]

- **1** spacer
- **2** holder
- **3** container
- **4** heater
- **5** solenoid coil
- **6** wound magnetic core
- **10** field heat treatment furnace

Claims

1. A nanocrystalline alloy magnetic core production method for nanocrystallization of a magnetic core formed of a wound or layered amorphous alloy ribbon by a heat treatment, the method comprising:

    a primary heat treatment step of performing a primary heat treatment in the absence of an applied magnetic field to increase a temperature of the magnetic core from a temperature that is lower than a crystallization onset temperature of the magnetic core to a temperature that is higher than or equal to the crystallization onset temperature; and
    a secondary heat treatment step performed after the primary heat treatment step,
    wherein the secondary heat treatment step includes

        a secondary temperature maintaining step of maintaining the temperature constant at a temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature, in the absence of an applied magnetic field, and
        a secondary temperature decreasing step of, after the secondary temperature maintaining step, decreasing the temperature in the presence of a magnetic field applied in a direction perpendicular to a magnetic path.

2. The nanocrystalline alloy magnetic core production method of claim 1, wherein
in the secondary temperature maintaining step, after the temperature of the magnetic core is in the range of ±5°C with respect to the temperature at the time when the application of the magnetic field is started, the temperature is maintained in the range of ±5°C for 1 min or more.

3. The nanocrystalline alloy magnetic core production method of claim 1 or 2, wherein
the applied magnetic field has a strength of 60 kA/m or more.

4. The nanocrystalline alloy magnetic core production method of any of claims 1-3, wherein
the maintenance temperature in the secondary heat treatment is 200-500°C.

5. The nanocrystalline alloy magnetic core production method of any of claims 1-4, wherein

the maintenance temperature in the primary heat treatment is 550-600°C.

6. The nanocrystalline alloy magnetic core production method of any of claims 1-5, wherein the amorphous alloy ribbon has a thickness of 7-15 μm.

7. The nanocrystalline alloy magnetic core production method of any of claims 1-6, wherein the amorphous alloy ribbon has a composition represented by a general formula: $(Fe_{1-a}M_a)_{100-x-y-z-\alpha-\beta-\gamma}Cu_xSi_yB_zM'_\alpha M''_\beta X_\gamma$ (atom%) (where M represents Co and/or Ni, M' represents at least one element selected from the group consisting of Nb, Mo, Ta, Ti, Zr, Hf, V, Cr, Mn, and W, M" represents at least one element selected from the group consisting of Al, platinum-group elements, Sc, rare-earth elements, Zn, Sn, and Re, X represents at least one element selected from the group consisting of C, Ge, P, Ga, Sb, In, Be, and As, and a, x, y, z, α, β, and γ satisfy $0 \leq a \leq 0.5$, $0.1 \leq x \leq 3$, $0 \leq y \leq 30$, $0 \leq z \leq 25$, $5 \leq y + z \leq 30$, $0 \leq \alpha \leq 20$, $0 \leq \beta \leq 20$, and $0 \leq \gamma \leq 20$, respectively).

8. The nanocrystalline alloy magnetic core production method of any of claims 1-7, further comprising: a step of, after the secondary heat treatment, performing impregnation with a resin.

9. The nanocrystalline alloy magnetic core production method of any of claims 1-8, wherein in the secondary heat treatment, after the temperature of the magnetic core is maintained constant at the temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature in the absence of an applied magnetic field, the temperature is maintained in the presence of a magnetic field applied in the direction perpendicular to the magnetic path, and thereafter, the temperature is decreased in the presence of a magnetic field applied in the direction perpendicular to the magnetic path.

10. The nanocrystalline alloy magnetic core production method of any of claims 1-9, wherein in the secondary temperature maintaining step, after the temperature of the magnetic core is in the range of ±5°C with respect to the temperature at which the temperature decrease is started, the temperature is maintained in the temperature range of ±5°C for 1 min or more, and thereafter, a magnetic field is applied in the direction perpendicular to the magnetic path while the temperature is maintained in the temperature range of ±5°C.

11. The nanocrystalline alloy magnetic core production method of any of claims 1-10, wherein in the secondary heat treatment step, after the temperature of the magnetic core is maintained constant at the temperature that is higher than or equal to 200°C and lower than the crystallization onset temperature, in the absence of an applied magnetic field, the temperature is decreased in the presence of a magnetic field applied in the direction perpendicular to the magnetic path from the start of the temperature decrease.

12. The nanocrystalline alloy magnetic core production method of any of claims 1-11, wherein the magnetic core has a volume of 3000 mm^3 or more.

13. The nanocrystalline alloy magnetic core production method of any of claims 1-12, wherein in the primary heat treatment step, the rate of the temperature increase is lower than 1.0°C/min.

14. The nanocrystalline alloy magnetic core production method of any of claims 1-13, wherein in the primary heat treatment step, a highest value of the temperature is higher than 550°C and lower than or equal to 585°C.

15. The nanocrystalline alloy magnetic core production method of any of claims 1-14, wherein in the secondary heat treatment step, a highest value of the temperature during the application of the magnetic field is higher than or equal to 200°C and lower than 400°C.

16. The nanocrystalline alloy magnetic core production method of any of claims 1-15, wherein in the secondary heat treatment step, the magnetic field is applied while the temperature is decreased at an average rate of 4°C/min or less.

17. A nanocrystalline alloy magnetic core production method having a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature, wherein in the primary heat treatment step, the rate of the temperature increase is lower than 1.0°C/min.

18. A nanocrystalline alloy magnetic core production method having a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature, wherein in the primary heat treatment step, a highest value of the temperature is higher than 550°C and lower than or equal to 585°C.

19. A nanocrystalline alloy magnetic core production method having a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature, wherein in the secondary heat treatment step, a highest value of the temperature during the application of the magnetic field is higher than or equal to 200°C and lower than 400°C.

20. A nanocrystalline alloy magnetic core production method having a primary heat treatment step of increasing a temperature of an amorphous magnetic core material formed of an amorphous alloy ribbon capable of undergoing nanocrystallization, from a temperature that is lower than a crystallization onset temperature of the magnetic core material to a temperature that is higher than or equal to the crystallization onset temperature, in the absence of an applied magnetic field, and a secondary heat treatment step of applying a magnetic field in a direction perpendicular to a magnetic path, at a temperature that is lower than the crystallization onset temperature, wherein in the secondary heat treatment step, the magnetic field is applied while the temperature is decreased at an average rate of 4°C/min or less.

21. The nanocrystalline alloy magnetic core production method of any of claims 18-20, wherein in the primary heat treatment step, the rate of the temperature increase is lower than 1.0°C/min.

22. The nanocrystalline alloy magnetic core production method of any of claims 17, 19, and 20, wherein in the primary heat treatment step, a highest value of the temperature is higher than 550°C and lower than or equal to 585°C.

23. The nanocrystalline alloy magnetic core production method of any of claims 17, 18, and 20, wherein in the secondary heat treatment step, a highest value of the temperature during the application of the magnetic field is higher than or equal to 200°C and lower than 400°C.

24. The nanocrystalline alloy magnetic core production method of any of claims 17, 18, and 20, wherein in the secondary heat treatment step, the magnetic field is applied while the temperature is decreased at an average rate of 4°C/min or less.

25. The nanocrystalline alloy magnetic core production method of any of claims 17-24, wherein the secondary heat treatment step includes a step of decreasing the temperature to 100°C or lower in the presence of the applied magnetic field.

26. The nanocrystalline alloy magnetic core production method of any of claims 17-25, wherein the applied magnetic field has a strength of 50 kA/m or more.

27. The nanocrystalline alloy magnetic core production method of any of claims 17-26, wherein the amorphous alloy ribbon has a thickness of 7-15 μm.

28. A nanocrystalline alloy magnetic core comprising:
a wound or layered nanocrystalline alloy ribbon,
wherein, as measured at room temperature in the presence of an applied alternating-current magnetic field having

a frequency f of 1 kHz and an amplitude H of 0.05 amperes/meter (A/m), the nanocrystalline alloy magnetic core has a magnetic permeability μ (1 kHz) of 70,000 or more,
a squareness ratio Br/Bm of 50% or less, and
a coercive force of 1.0 A/m or less.

29. A nanocrystalline alloy magnetic core comprising:

a wound or layered nanocrystalline alloy ribbon,
wherein the nanocrystalline alloy ribbon contains a Fe-based material, and
the nanocrystalline alloy magnetic core has an impedance relative magnetic permeability μrz of 48,000 or more at a frequency of 100 kHz.

30. The nanocrystalline alloy magnetic core of claim 29, wherein
the impedance relative magnetic permeability μrz is

90,000 or more at a frequency of 10 kHz,
48,000 or more at a frequency of 100 kHz, and
8,500 or more at a frequency of 1 MHz.

31. The nanocrystalline alloy magnetic core of claim 29 or 30, wherein
the amorphous alloy ribbon has a thickness of 7-15 μm.

32. The nanocrystalline alloy magnetic core of any of claims 29-31, wherein
the nanocrystalline alloy magnetic core is impregnated with a resin.

33. The nanocrystalline alloy magnetic core of any of claims 29-32, wherein
the nanocrystalline alloy magnetic core is for a common-mode choke coil.

34. A magnetic unit comprising:

the nanocrystalline alloy magnetic core of any of claims 29-33; and
a conducting wire wound around the nanocrystalline alloy magnetic core.

FIG.1

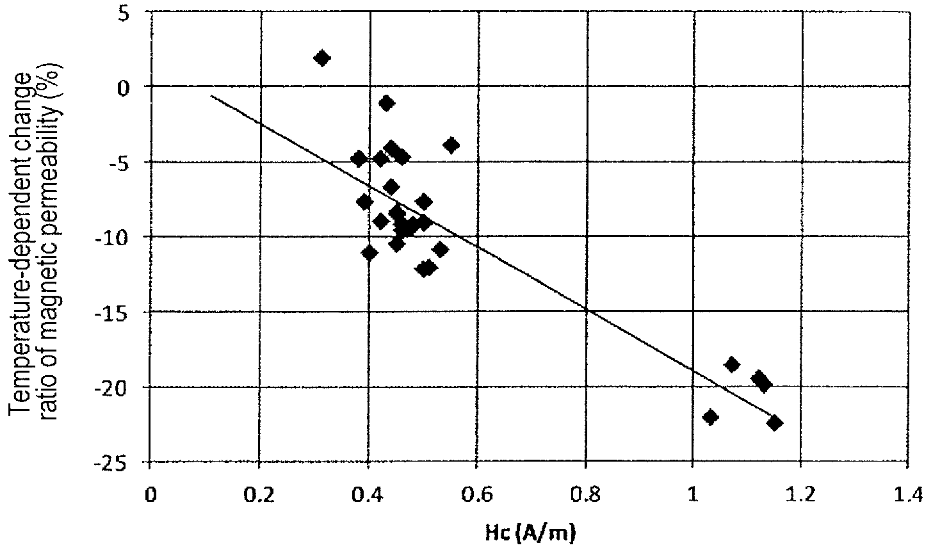

Temperature-dependent change ratio of magnetic permeability (%)
5
0
-5
-10
-15
-20
-25
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Hc (A/m)

FIG.2

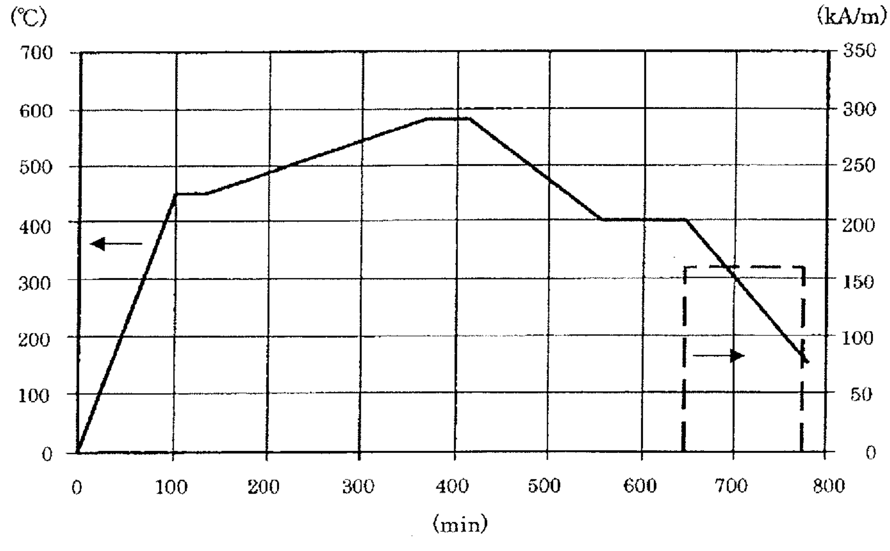

(℃)
(kA/m)
700
600
500
400
300
200
100
0
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800
(min)

FIG.3

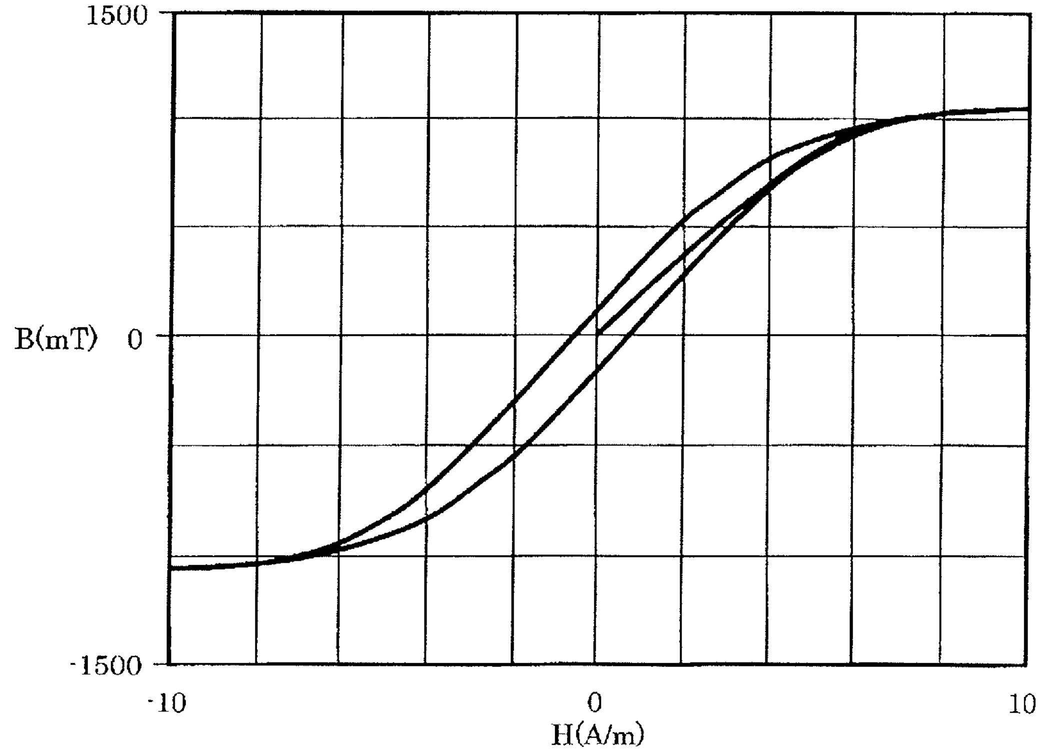


FIG.4

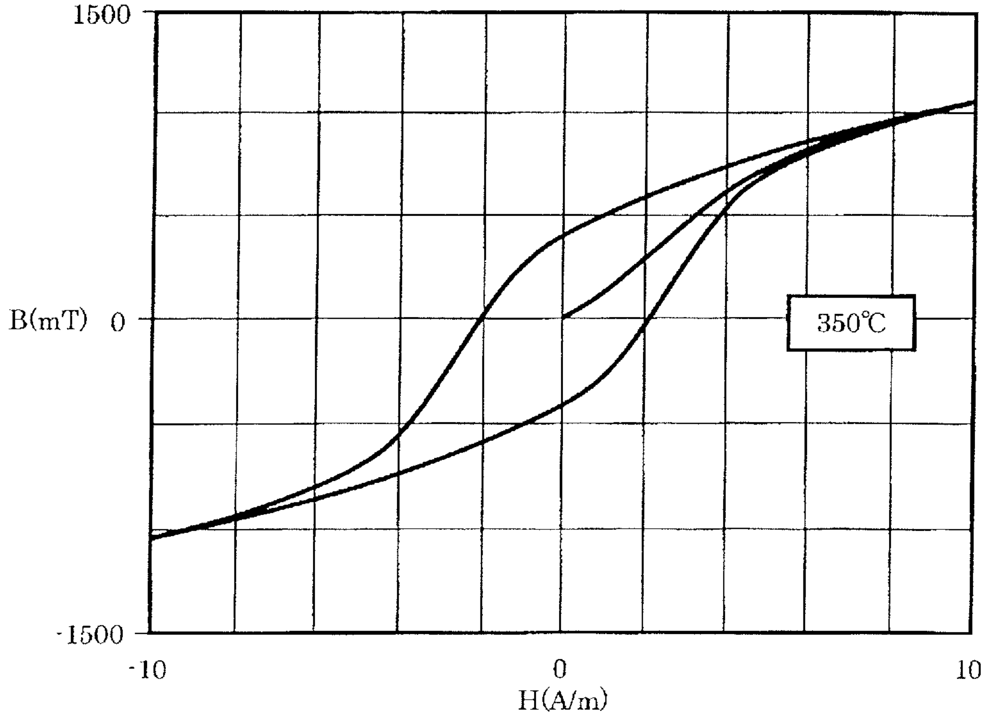


FIG.5

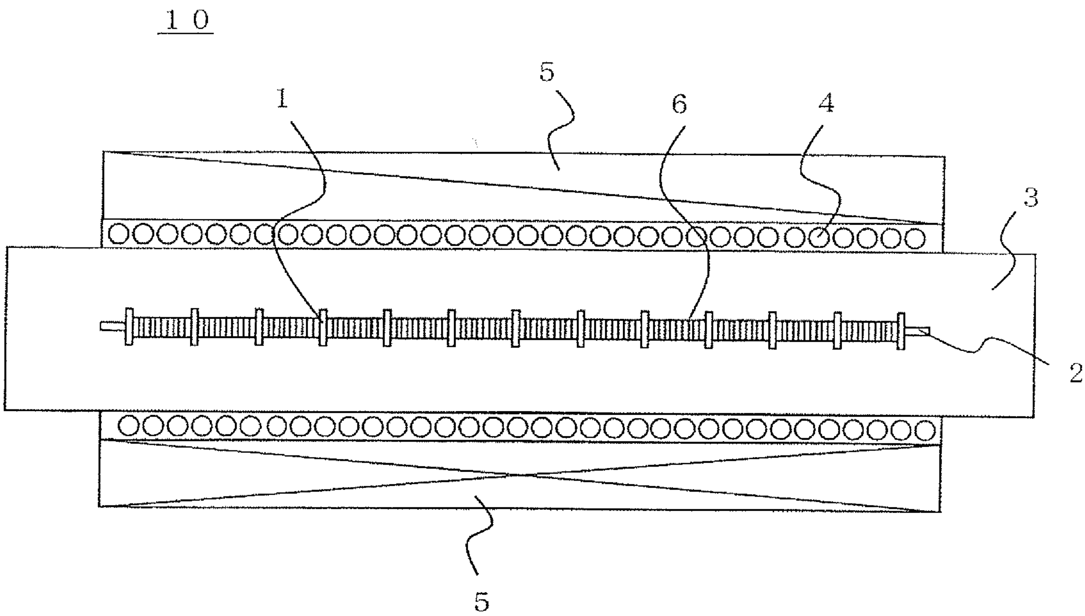

10
5
1
6
4
3
2
5

FIG.6

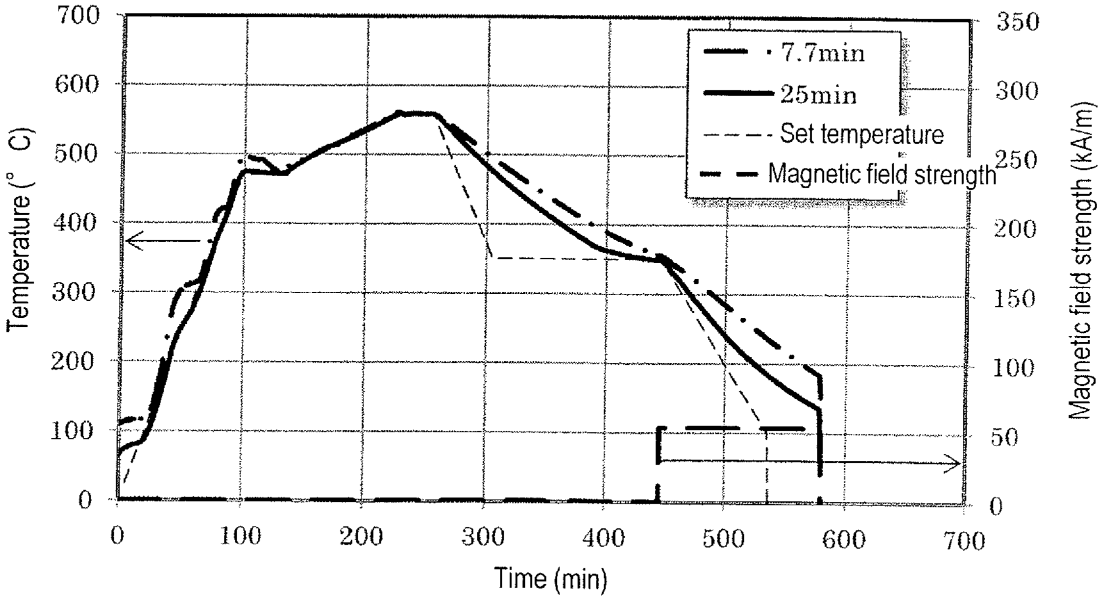

7.7min
25min
Set temperature
Magnetic field strength
Temperature (° C)
Magnetic field strength (kA/m)
Time (min)
0
100
200
300
400
500
600
700
0
50
100
150
200
250
300
350

FIG. 7

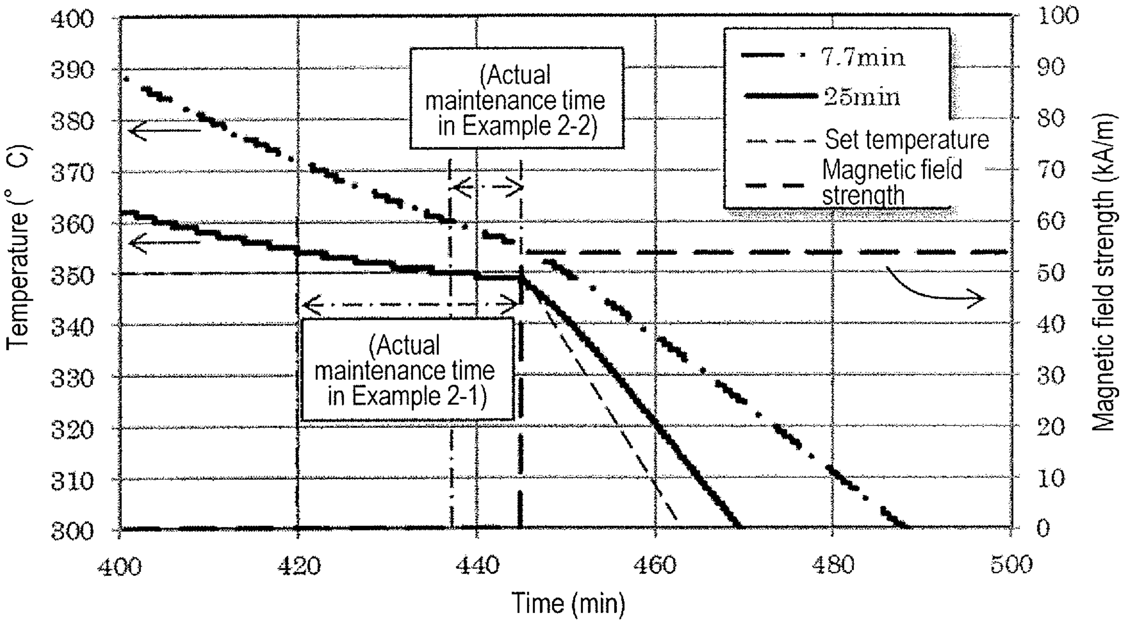

400
390
380
370
360
350
340
330
320
310
300
Temperature (° C)
(Actual maintenance time in Example 2-2)
(Actual maintenance time in Example 2-1)
7.7min
25min
Set temperature
Magnetic field strength
100
90
80
70
60
50
40
30
20
10
0
Magnetic field strength (kA/m)
400
420
440
460
480
500
Time (min)

FIG. 8

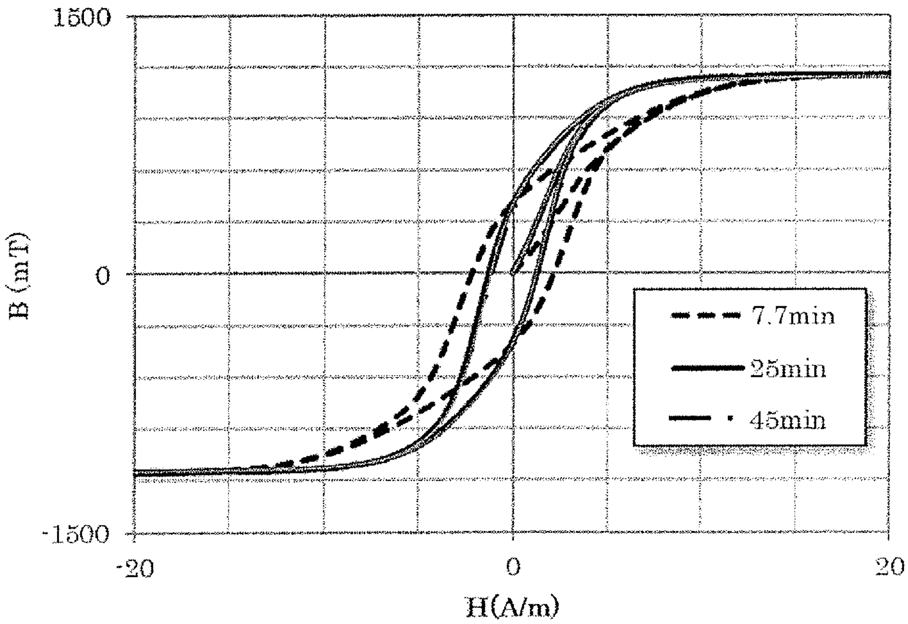

1500
0
-1500
B (mT)
7.7min
25min
45min
-20
0
20
H(A/m)

FIG.9

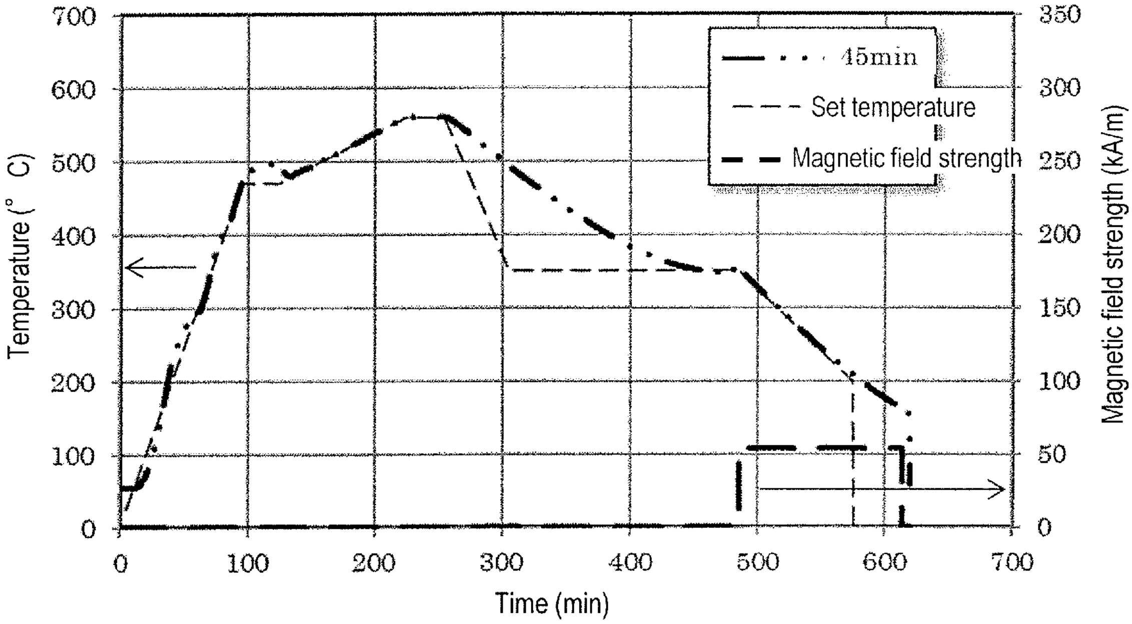

700
600
500
400
300
200
100
0
Temperature (° C)
350
300
250
200
150
100
50
0
Magnetic field strength (kA/m)
0
100
200
300
400
500
600
700
Time (min)
45min
Set temperature
Magnetic field strength

FIG.10

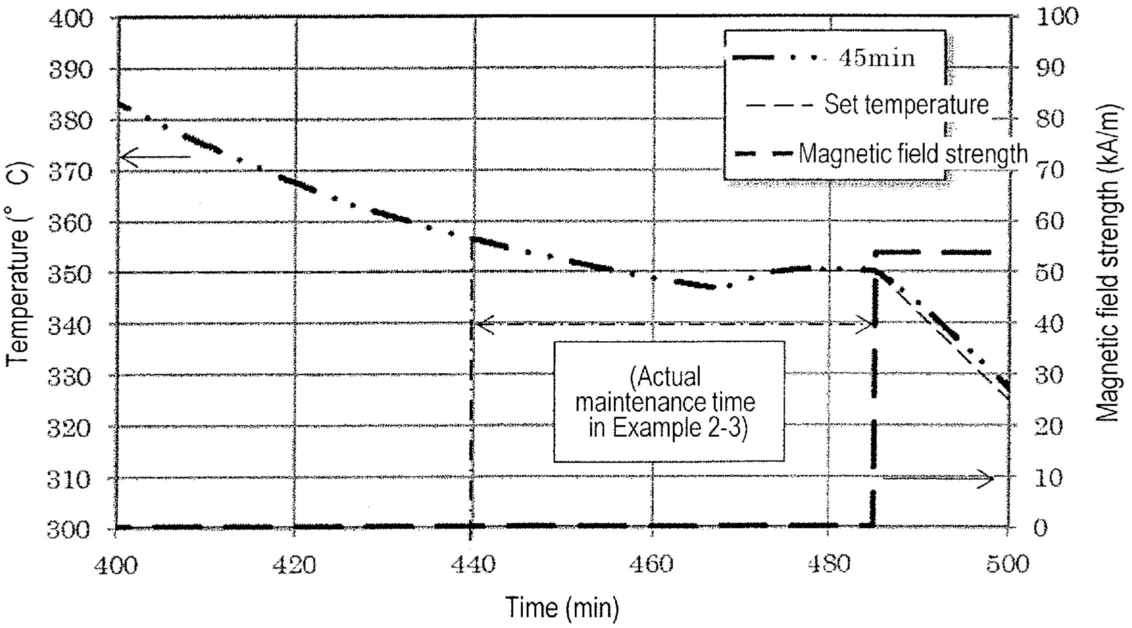

400
390
380
370
360
350
340
330
320
310
300
Temperature (° C)
100
90
80
70
60
50
40
30
20
10
0
Magnetic field strength (kA/m)
400
420
440
460
480
500
Time (min)
45min
Set temperature
Magnetic field strength
(Actual maintenance time in Example 2-3)

FIG.11

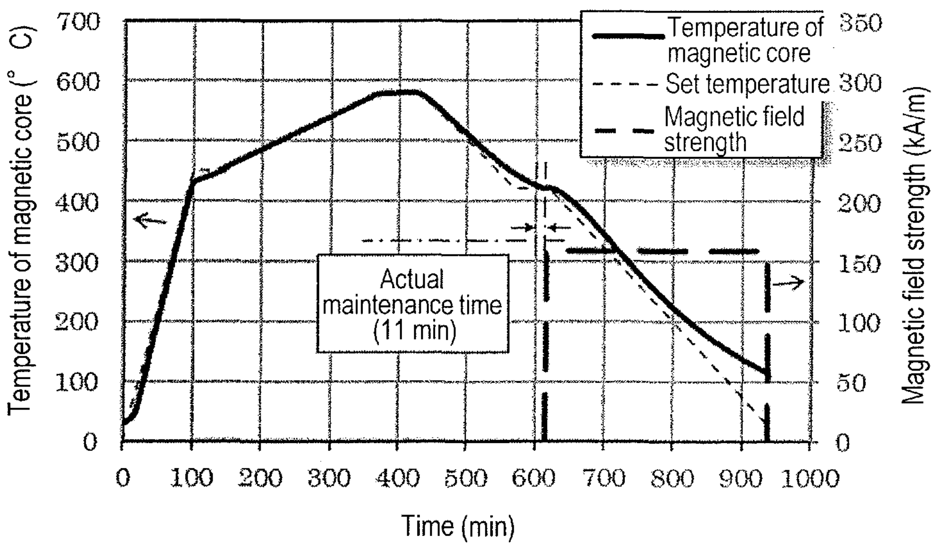

Temperature of magnetic core (° C)
700
600
500
400
300
200
100
0
Temperature of magnetic core
Set temperature
Magnetic field strength
Actual maintenance time (11 min)
350
300
250
200
150
100
50
0
Magnetic field strength (kA/m)
0 100 200 300 400 500 600 700 800 900 1000
Time (min)

FIG.12

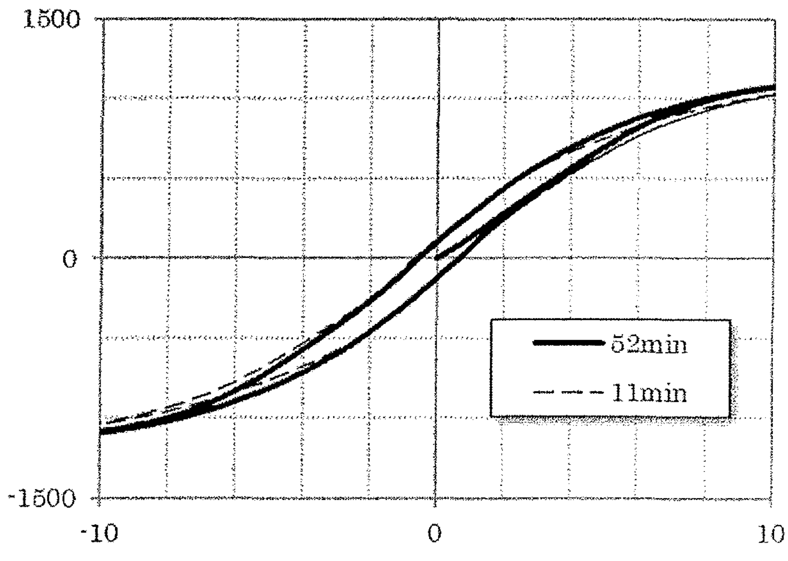

1500
0
-1500
-10
0
10
52min
11min

FIG.13

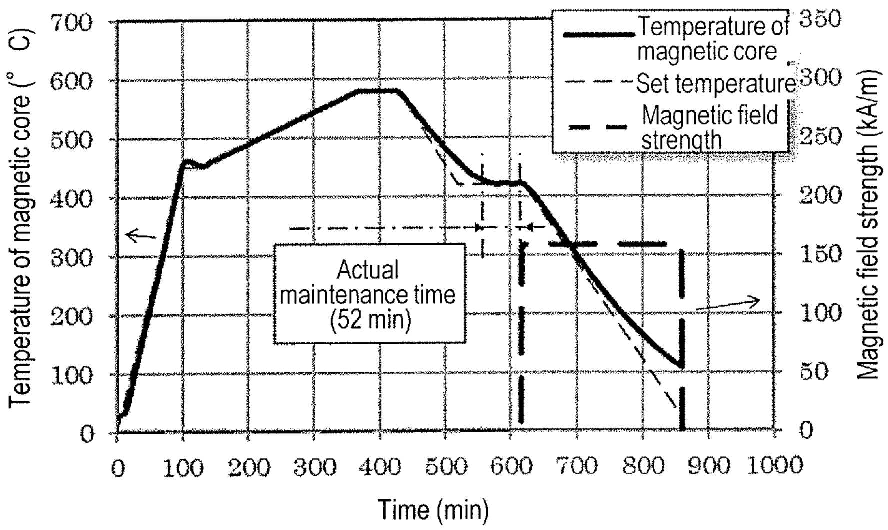

Temperature of magnetic core (° C)
700
600
500
400
300
200
100
0
0 100 200 300 400 500 600 700 800 900 1000
Time (min)
350
300
250
200
150
100
50
0
Magnetic field strength (kA/m)
Temperature of magnetic core
Set temperature
Magnetic field strength
Actual maintenance time (52 min)

FIG.14

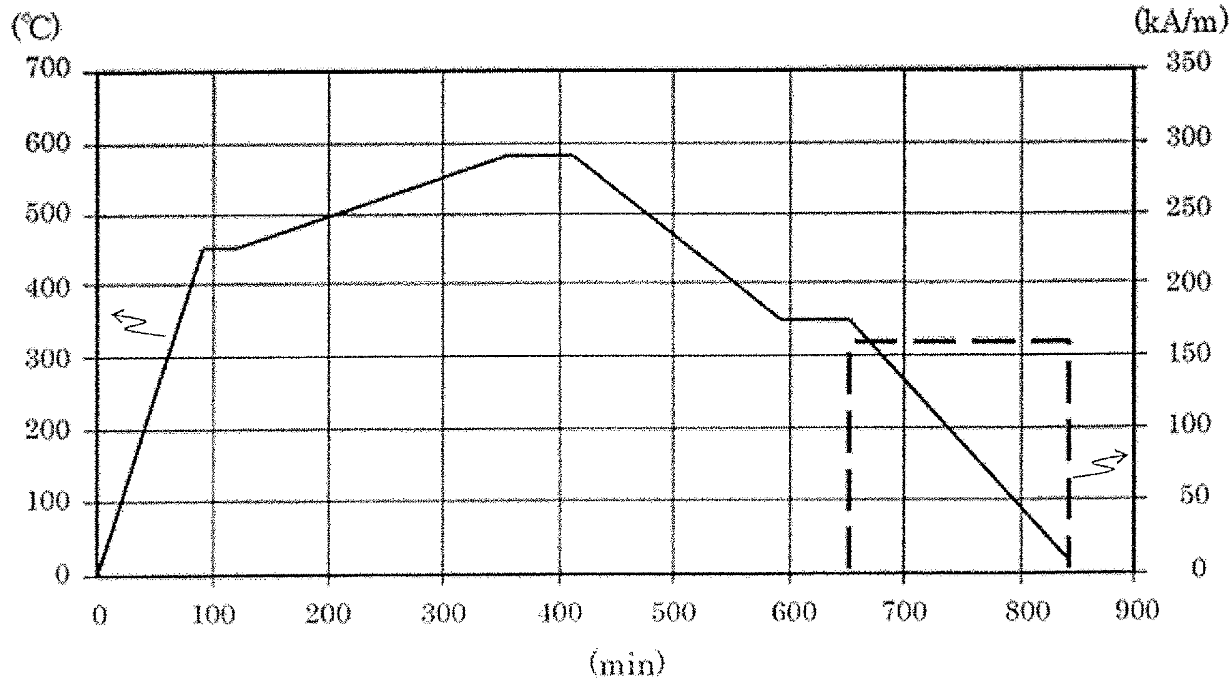

(℃)
700
600
500
400
300
200
100
0
0 100 200 300 400 500 600 700 800 900
(min)
(kA/m)
350
300
250
200
150
100
50
0

FIG.15

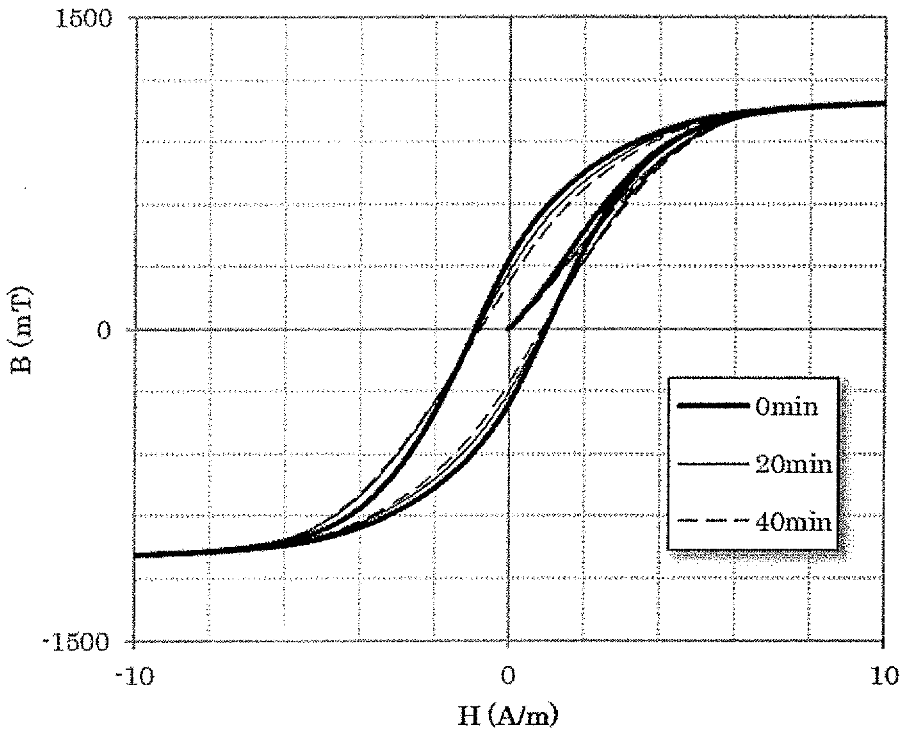

1500
0
-1500
B (mT)
-10
0
10
H (A/m)
0min
20min
40min

FIG.16

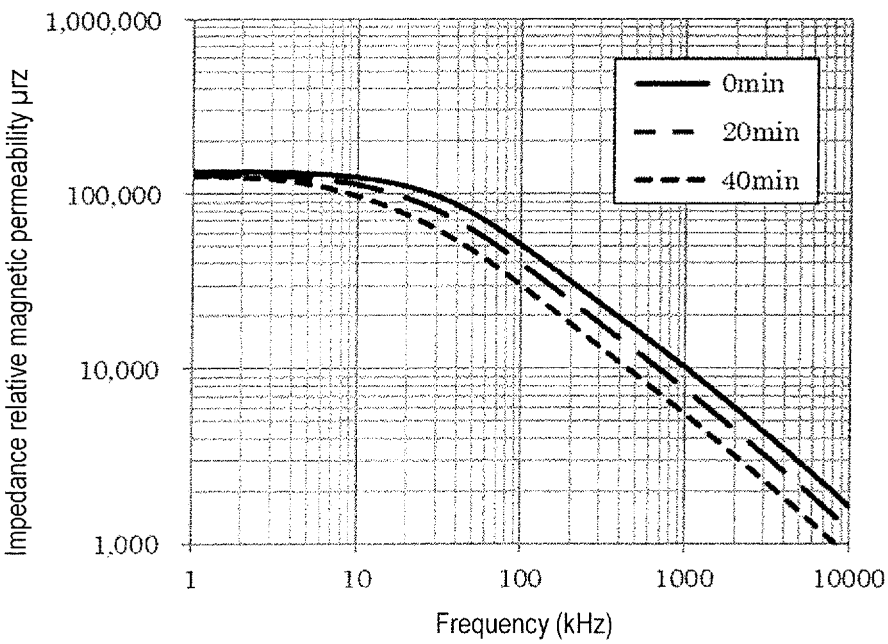

1,000,000
100,000
10,000
1,000
Impedance relative magnetic permeability μrz
1
10
100
1000
10000
Frequency (kHz)
0min
20min
40min

FIG.17

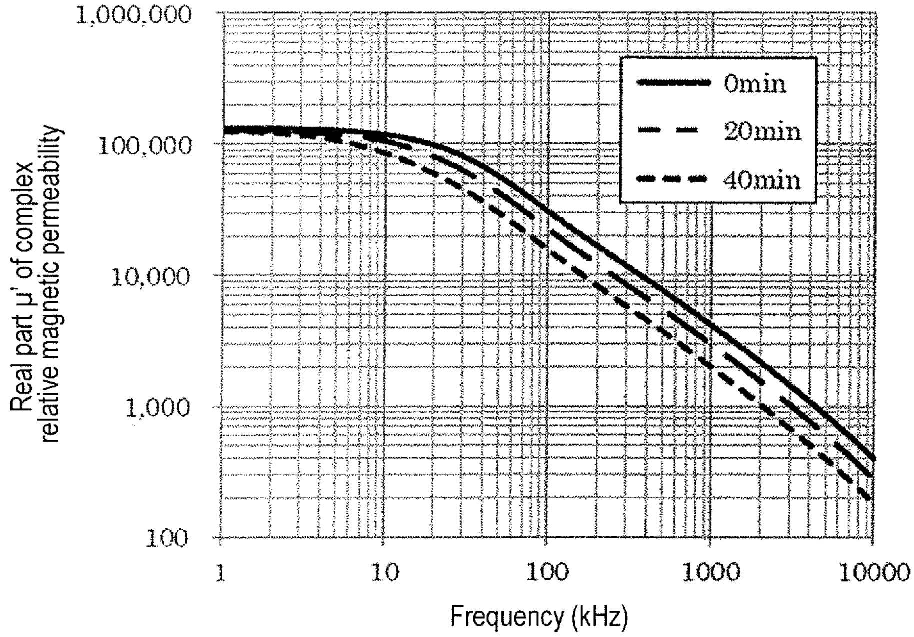

1,000,000
100,000
10,000
1,000
100
Real part μ' of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
0min
20min
40min

FIG.18

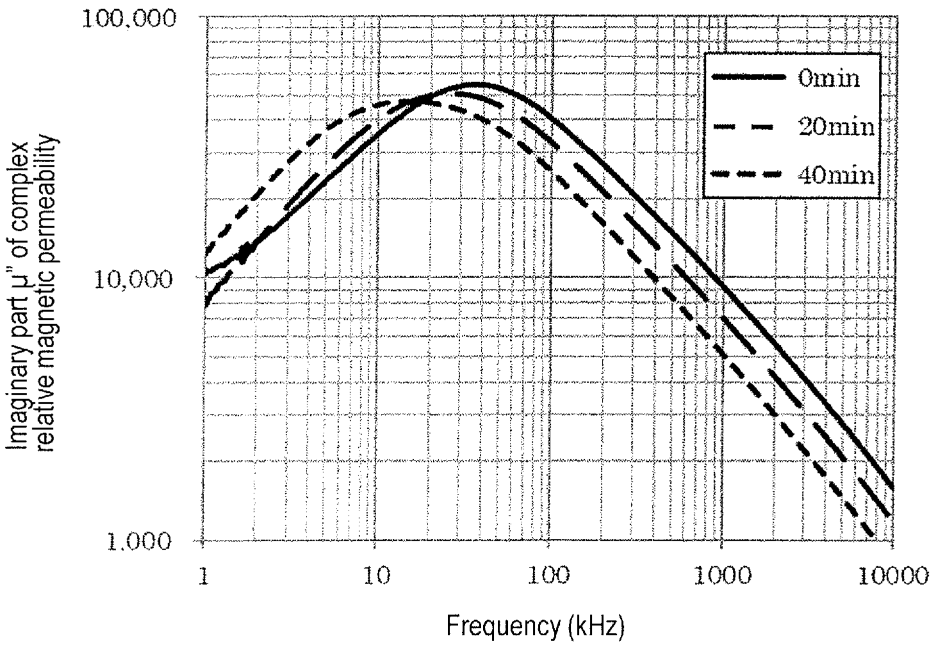

100,000
10,000
1,000
Imaginary part μ'' of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
0min
20min
40min

FIG.19

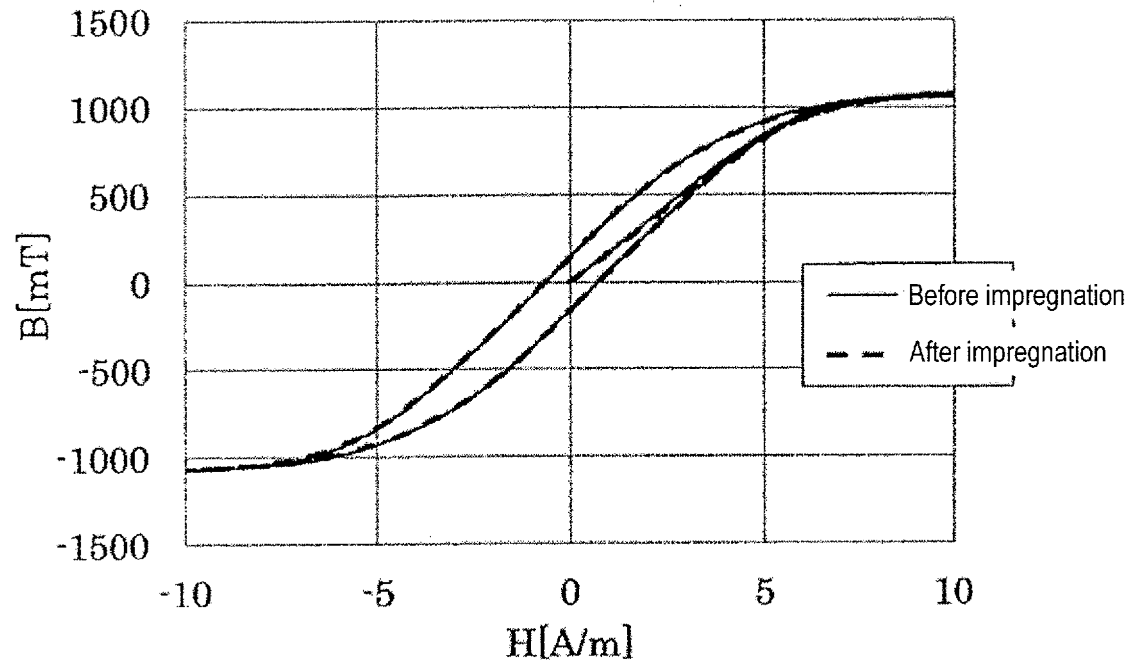

1500
1000
500
0
-500
-1000
-1500
B[mT]
-10
-5
0
5
10
H[A/m]
Before impregnation
After impregnation

FIG.20

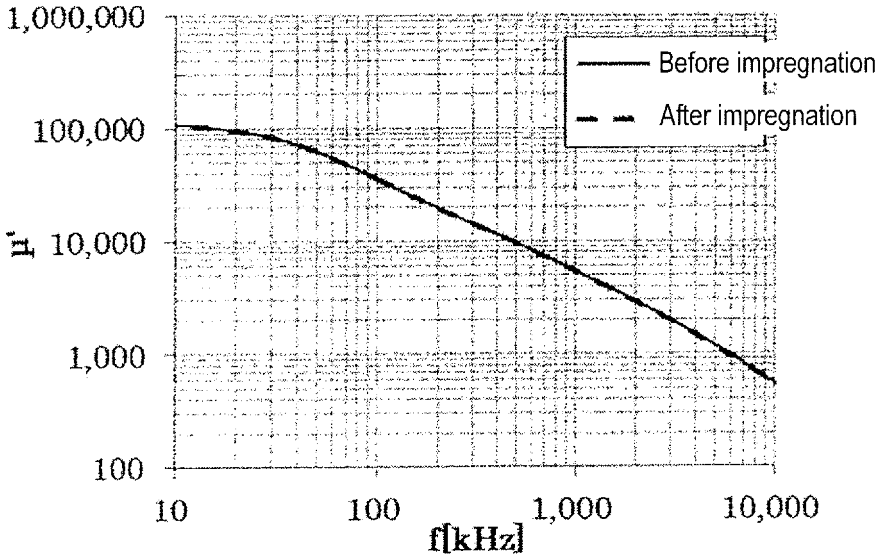

1,000,000
100,000
10,000
1,000
100
μ'
10
100
1,000
10,000
f[kHz]
Before impregnation
After impregnation

FIG.21

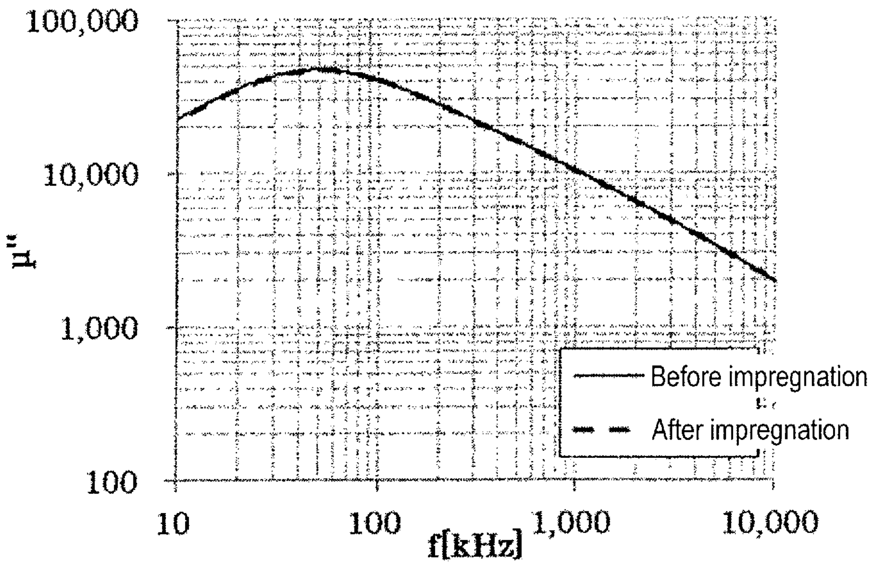

100,000
10,000
1,000
100
μ''
10
100
1,000
10,000
f[kHz]
Before impregnation
After impregnation

FIG.22

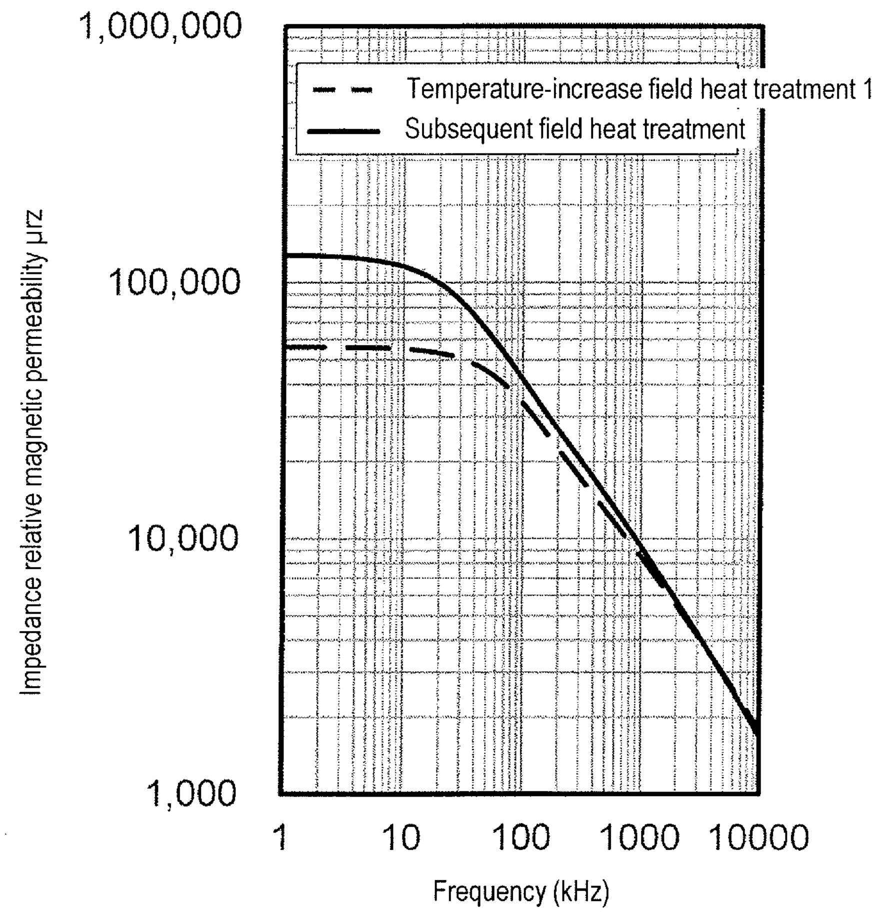

1,000,000
100,000
10,000
1,000
Impedance relative magnetic permeability μrz
Temperature-increase field heat treatment 1
Subsequent field heat treatment
1
10
100
1000
10000
Frequency (kHz)

FIG.23

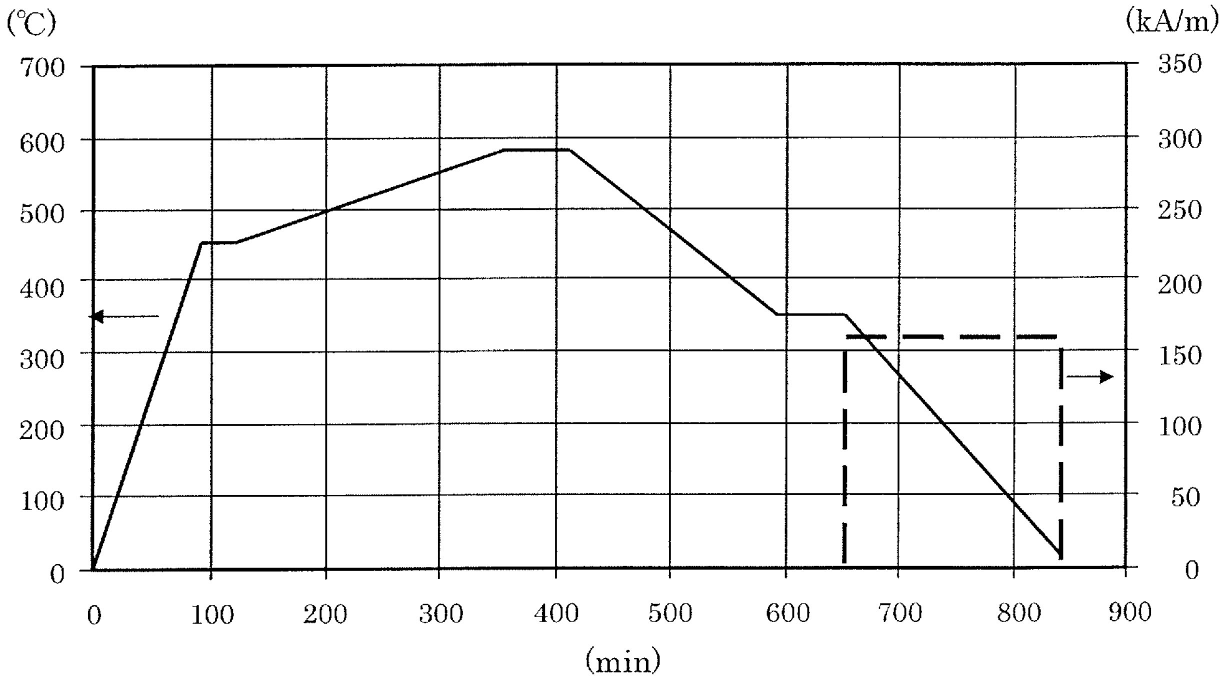

(℃)
(kA/m)
700
600
500
400
300
200
100
0
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800
900
(min)

FIG.24

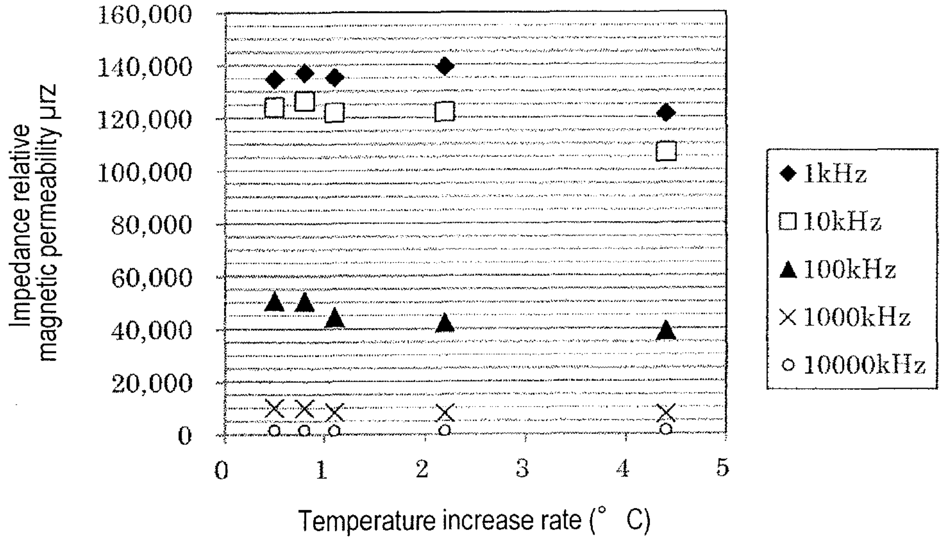

160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Impedance relative magnetic permeability μrz
0
1
2
3
4
5
Temperature increase rate (° C)
1kHz
10kHz
100kHz
1000kHz
10000kHz

FIG.25

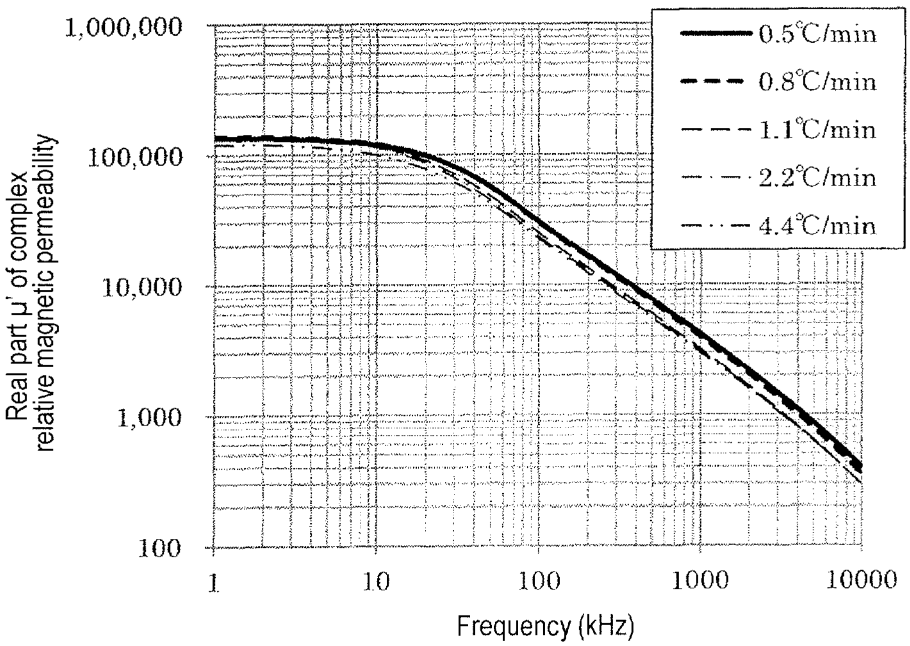

1,000,000
100,000
10,000
1,000
100
Real part μ' of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
0.5℃/min
0.8℃/min
1.1℃/min
2.2℃/min
4.4℃/min

FIG.26

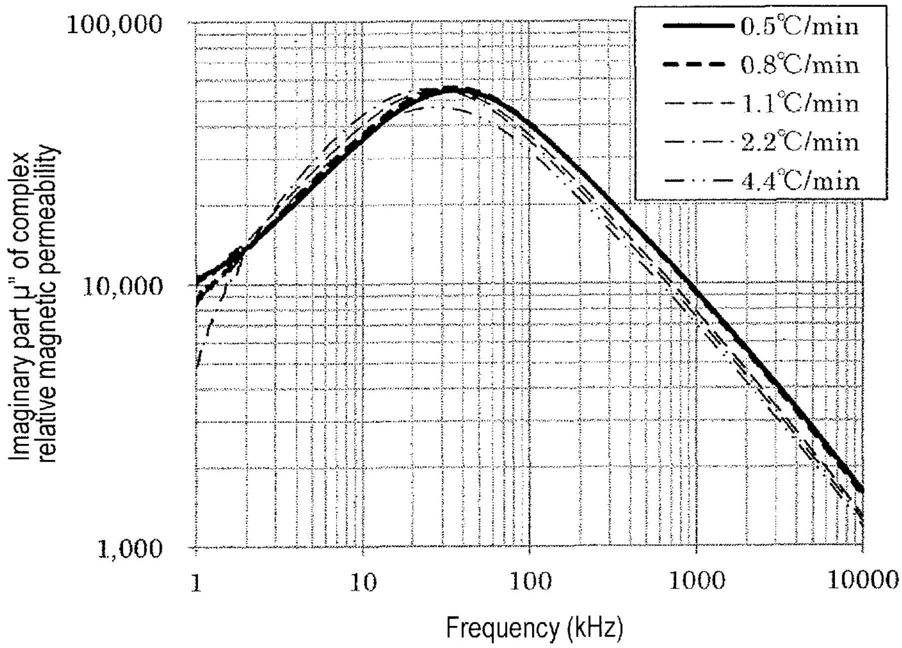

100,000
10,000
1,000
Imaginary part μ" of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
0.5℃/min
0.8℃/min
1.1℃/min
2.2℃/min
4.4℃/min

FIG.27

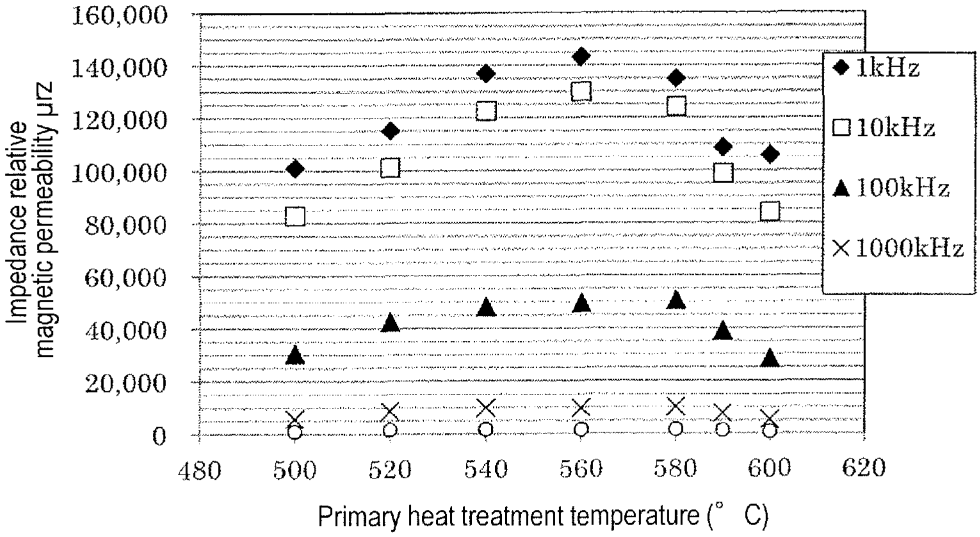

160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Impedance relative magnetic permeability μrz
480
500
520
540
560
580
600
620
Primary heat treatment temperature (° C)
1kHz
10kHz
100kHz
1000kHz

FIG.28

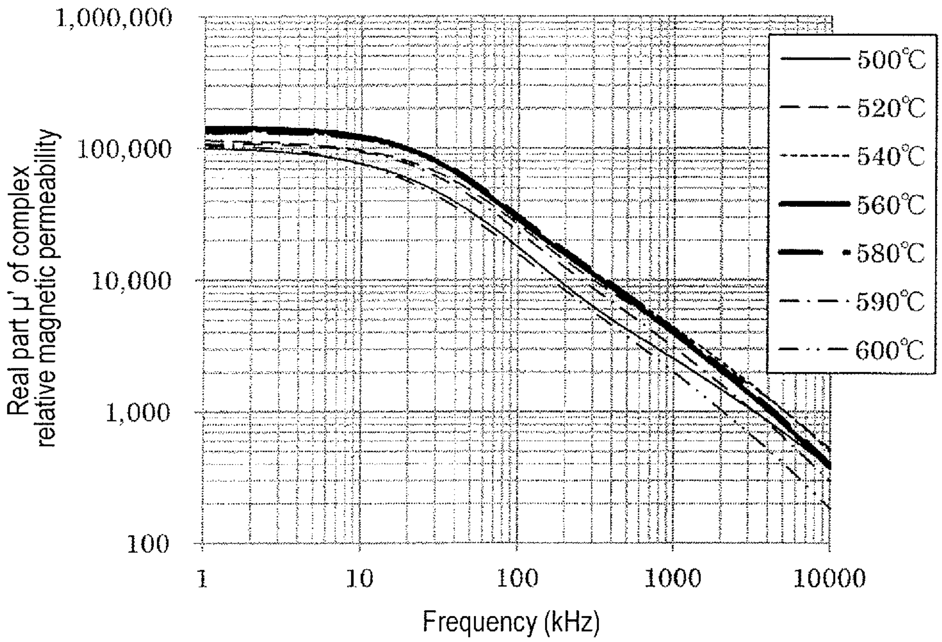

1,000,000
100,000
10,000
1,000
100
Real part μ' of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
500℃
520℃
540℃
560℃
580℃
590℃
600℃

FIG.29

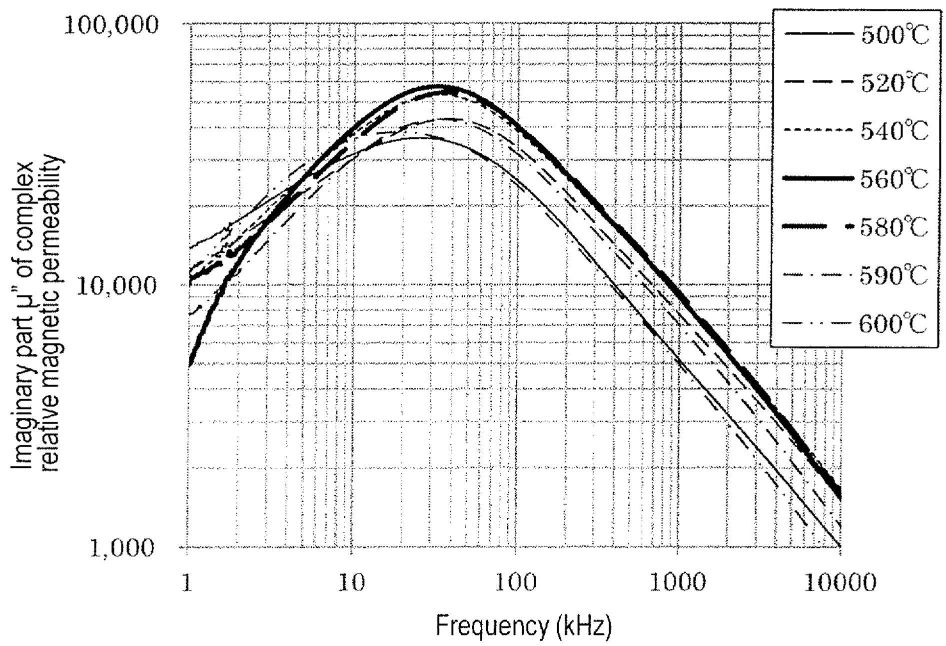

100,000
10,000
1,000
Imaginary part μ" of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
500℃
520℃
540℃
560℃
580℃
590℃
600℃

FIG.30

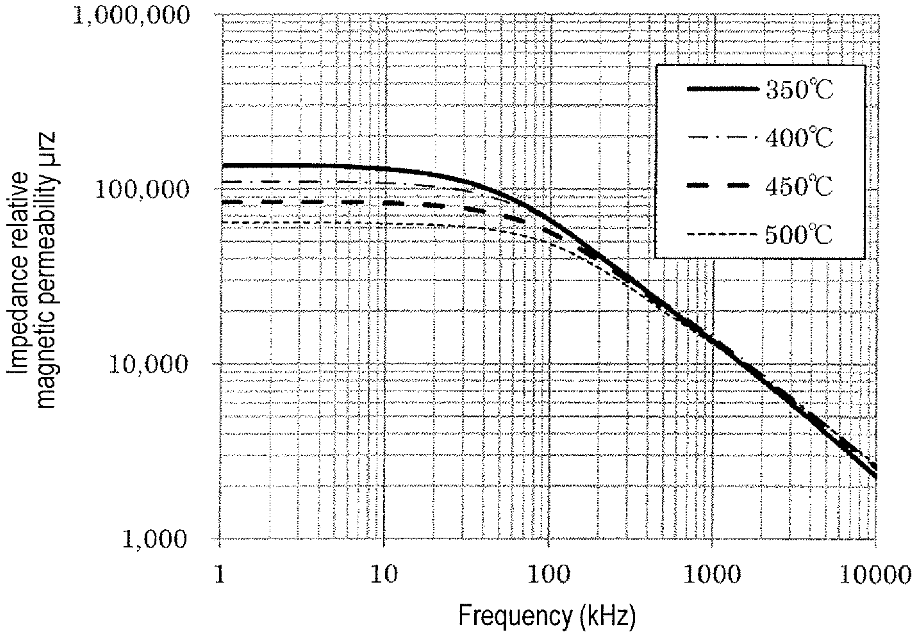

1,000,000
100,000
10,000
1,000
Impedance relative magnetic permeability μrz
1
10
100
1000
10000
Frequency (kHz)
350℃
400℃
450℃
500℃

FIG.31

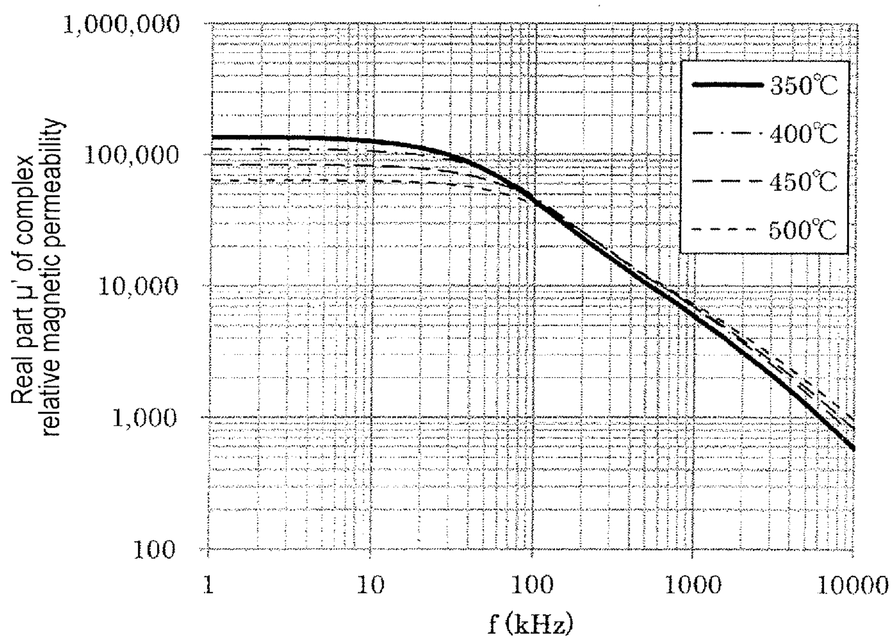

1,000,000
100,000
10,000
1,000
100
Real part μ' of complex relative magnetic permeability
1
10
100
1000
10000
f (kHz)
350℃
400℃
450℃
500℃

FIG.32

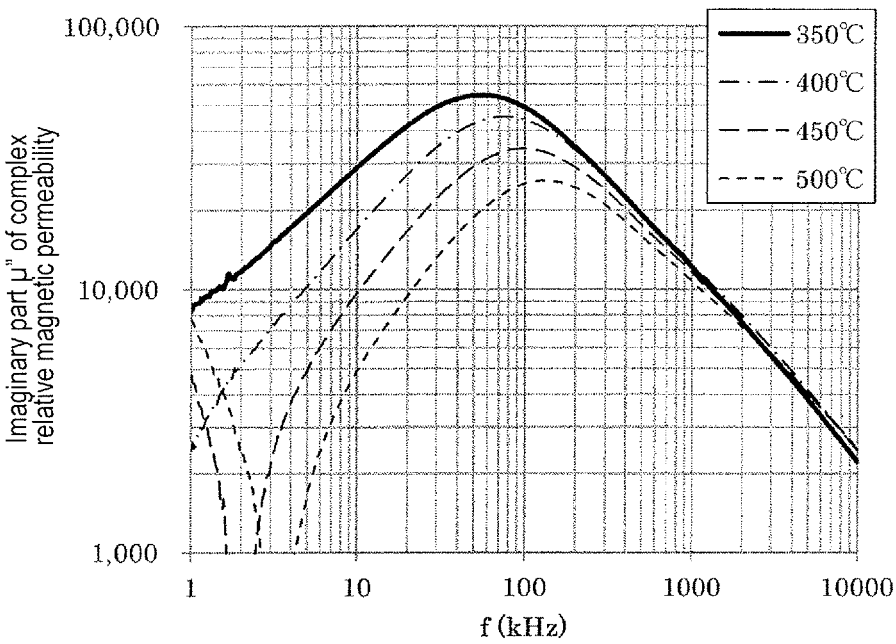

100,000
10,000
1,000
Imaginary part μ" of complex relative magnetic permeability
1
10
100
1000
10000
f (kHz)
350℃
400℃
450℃
500℃

FIG.33

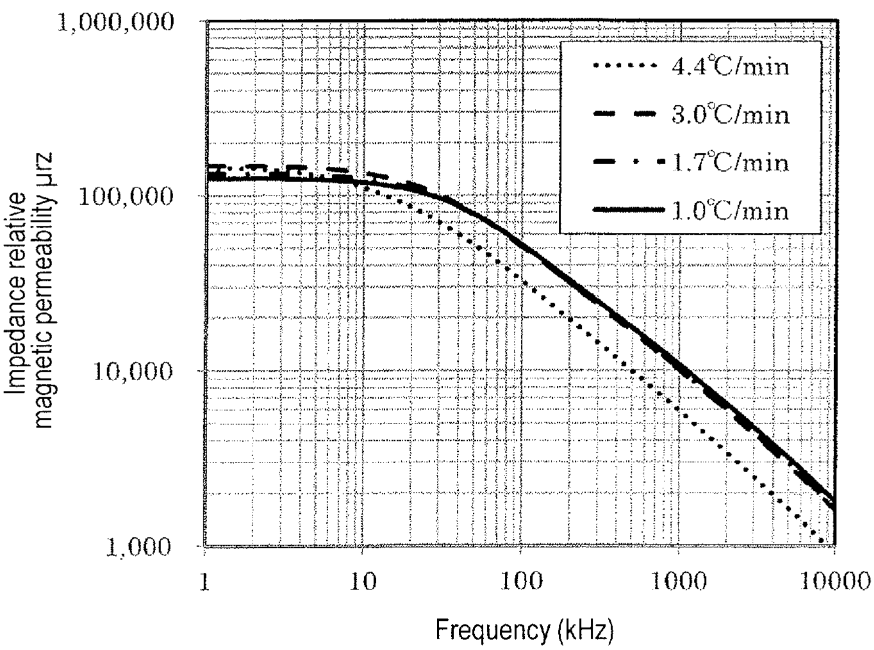

1,000,000
100,000
10,000
1,000
Impedance relative magnetic permeability μrz
1
10
100
1000
10000
Frequency (kHz)
4.4℃/min
3.0℃/min
1.7℃/min
1.0℃/min

FIG.34

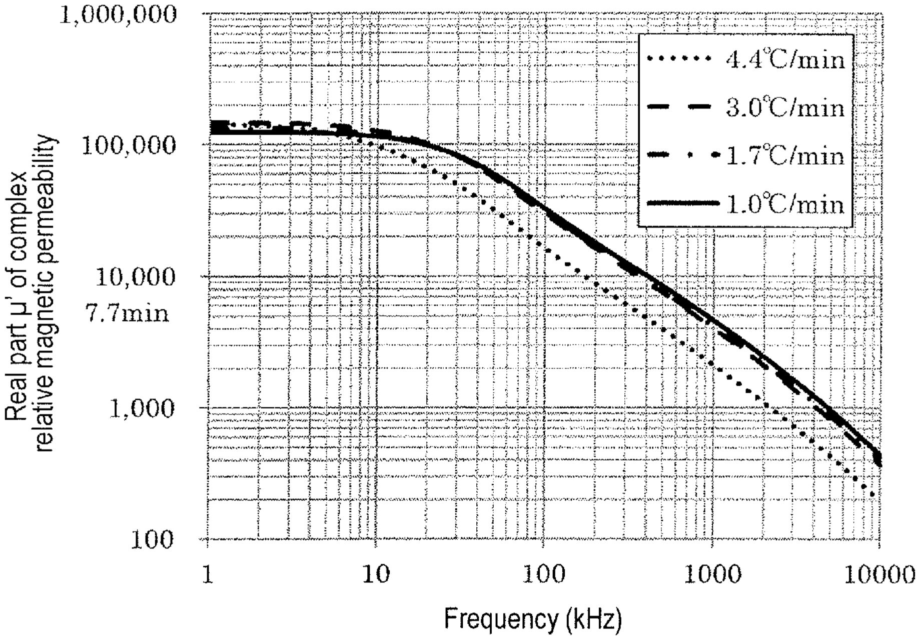

1,000,000
100,000
10,000
7.7min
1,000
100
Real part μ' of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
4.4℃/min
3.0℃/min
1.7℃/min
1.0℃/min

FIG.35

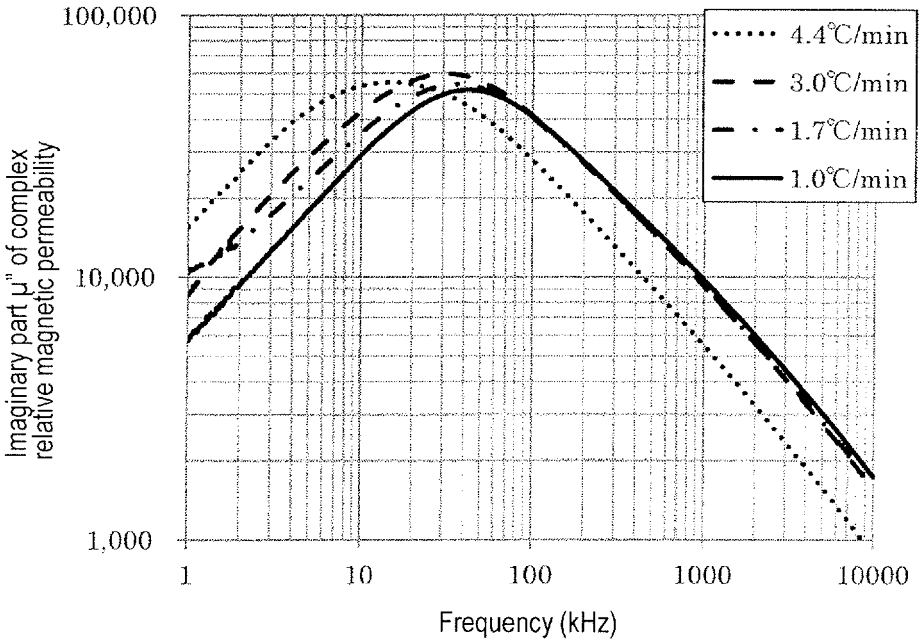

100,000
10,000
1,000
Imaginary part μ" of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
4.4℃/min
3.0℃/min
1.7℃/min
1.0℃/min

FIG.36

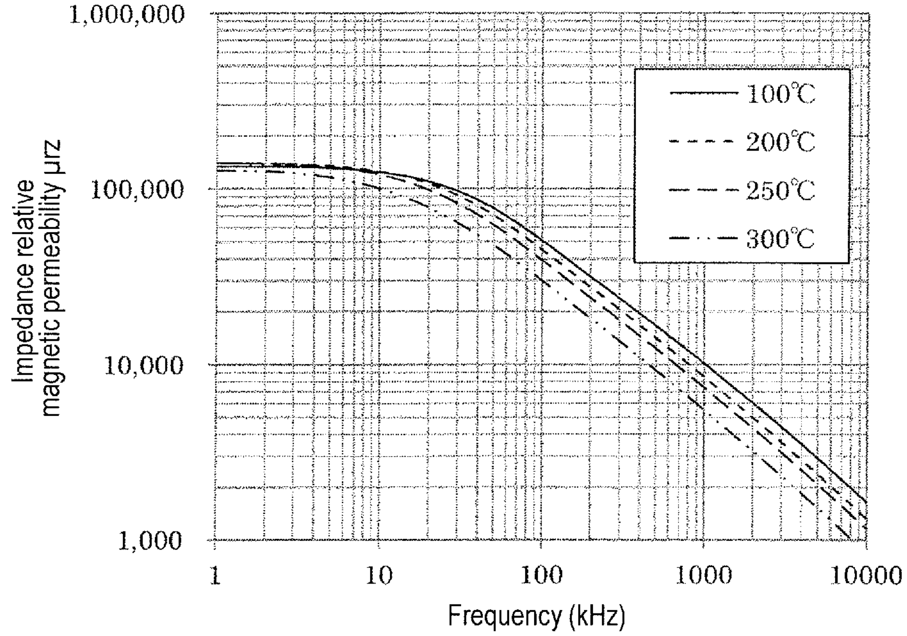

1,000,000
100,000
10,000
1,000
Impedance relative magnetic permeability μrz
1
10
100
1000
10000
Frequency (kHz)
100℃
200℃
250℃
300℃

FIG.37

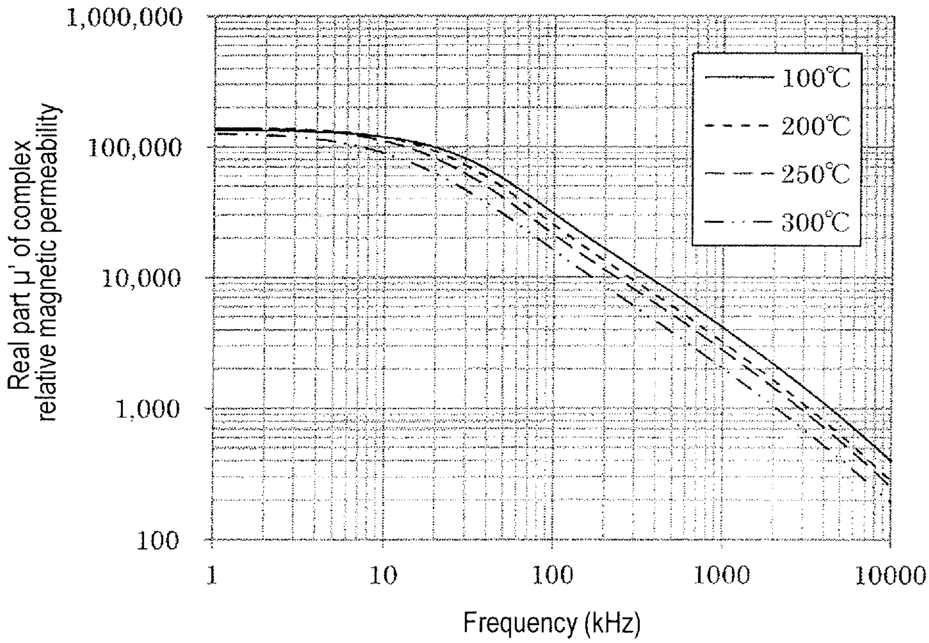

1,000,000
100,000
10,000
1,000
100
Real part μ' of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
100℃
200℃
250℃
300℃

FIG.38

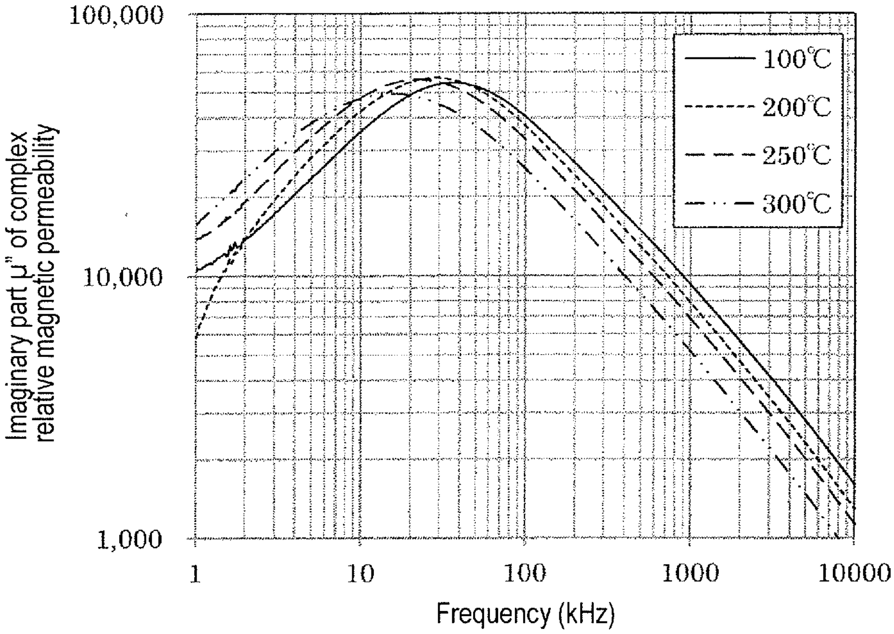

100,000
10,000
1,000
Imaginary part μ" of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
100℃
200℃
250℃
300℃

FIG.39

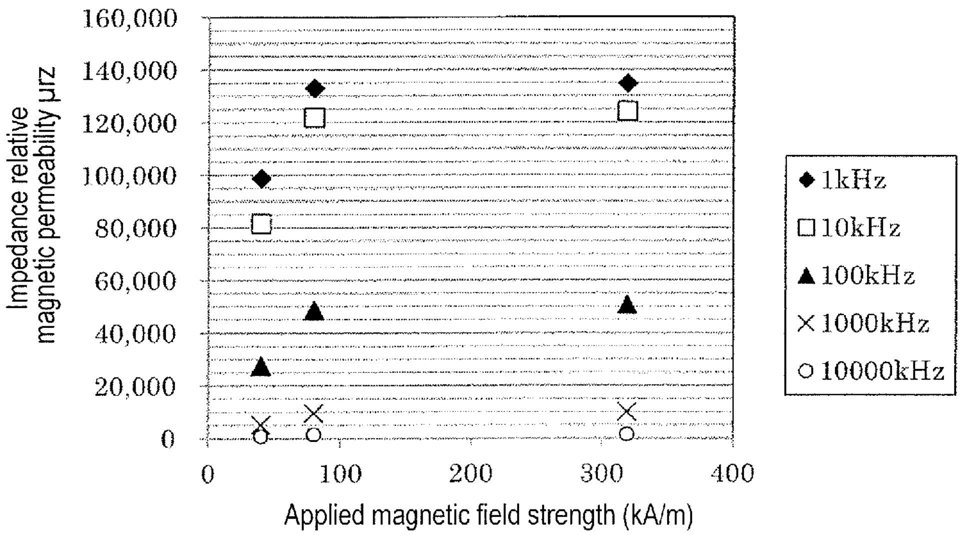

160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Impedance relative magnetic permeability μrz
0
100
200
300
400
Applied magnetic field strength (kA/m)
1kHz
10kHz
100kHz
1000kHz
10000kHz

FIG.40

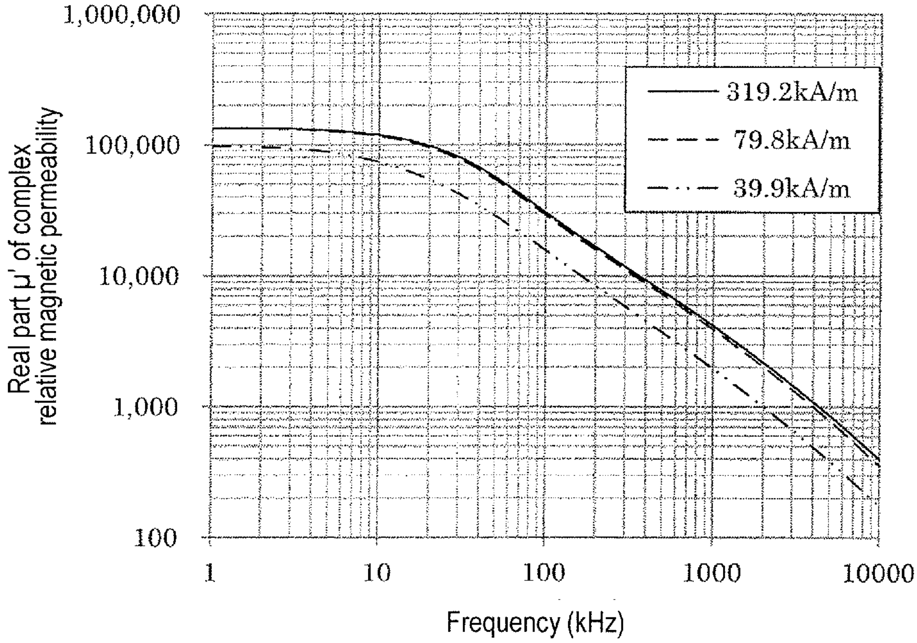
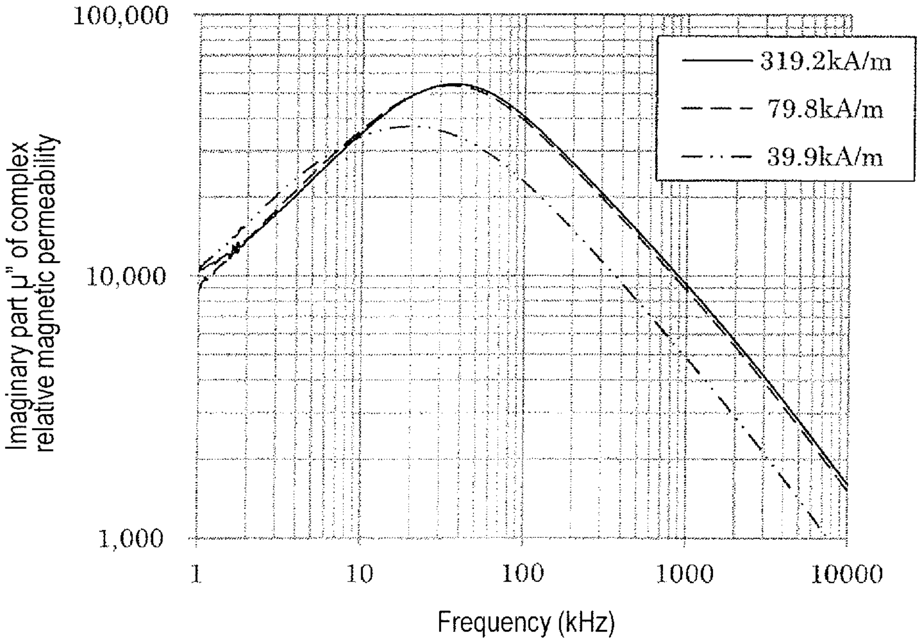

1,000,000
100,000
10,000
1,000
100
Real part μ' of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
319.2kA/m
79.8kA/m
39.9kA/m

FIG.41


100,000
10,000
1,000
Imaginary part μ" of complex relative magnetic permeability
1
10
100
1000
10000
Frequency (kHz)
319.2kA/m
79.8kA/m
39.9kA/m

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2017/035030

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl. H01F41/02(2006.01)i, C21D6/00(2006.01)i, H01F1/153(2006.01)i, H01F27/24(2006.01)i, C22C38/00(2006.01)n

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)
Int.Cl. H01F41/02, C21D6/00, H01F1/153, H01F27/24, C22C38/00

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

Published examined utility model applications of Japan	1922-1996
Published unexamined utility model applications of Japan	1971-2017
Registered utility model specifications of Japan	1996-2017
Published registered utility model applications of Japan	1994-2017

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.
Y A	JP 2004-509459 A (VACUUMSCHMELZE GMBH & CO. KG) 25 March 2004, paragraphs [0001], [0027]-[0035], [0051]-[0055], fig. 4a & US 2004/0027220 A1, paragraphs [0002], [0032]-[0040], [0058]-[0064], fig. 4a & EP 1317758 A1 & DE 10045705 A & CN 1475018 A	1-15, 17-19, 21-23, 25-27 16, 20, 24, 28-34

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 December 2017	09 January 2018

Name and mailing address of the ISA/	Authorized officer
Japan Patent Office 3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan	Telephone No.

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT

International application No. PCT/JP2017/035030

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	JP 3-107417 A (HITACHI METALS LTD.) 07 May 1991, claims, page 2, lower left column, line 14 to page 2, lower right column, line 10, page 3, upper left column, line 4 to page 3, upper right column, line 4, page 3, lower right column, line 15 to page 3, lower right column, line 20, fig. 1, 2 (Family: none)	1-15, 17-19, 21-23, 25-27 16, 20, 24, 28-34
Y A	JP 8-85821 A (HITACHI METALS LTD.) 02 April 1996, claims, paragraphs [0012]-[0027] & US 5611871 A, claims, column 4, line 15 to column 7, line 25	3-15, 26-27 16, 20, 24, 28-34
Y A	JP 2000-328206 A (HITACHI METALS LTD.) 28 November 2000, paragraphs [0021]-[0023] (Family: none)	3-15, 26-27 16, 20, 24, 28-34
Y A	JP 2007-103404 A (HITACHI METALS LTD.) 19 April 2007, paragraphs [0008]-[0012] (Family: none)	8-15 16, 20, 24, 28-34
Y A	JP 2003-7540 A (TOSHIBA CORPORATION) 10 January 2003, paragraphs [0018]-[0023] (Family: none)	8-15 16, 20, 24, 28-34

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Patent documents cited in the description

- JP 2501860 B **[0007]**
- JP H044393 B **[0007]**
- JP H07278764 B **[0007]**
- JP H0794314 B **[0007]**
- JP H0885821 B **[0007]**

Non-patent literature cited in the description

- A Guide to Selection of Magnetic Materials. 10 November 1989 **[0080]**