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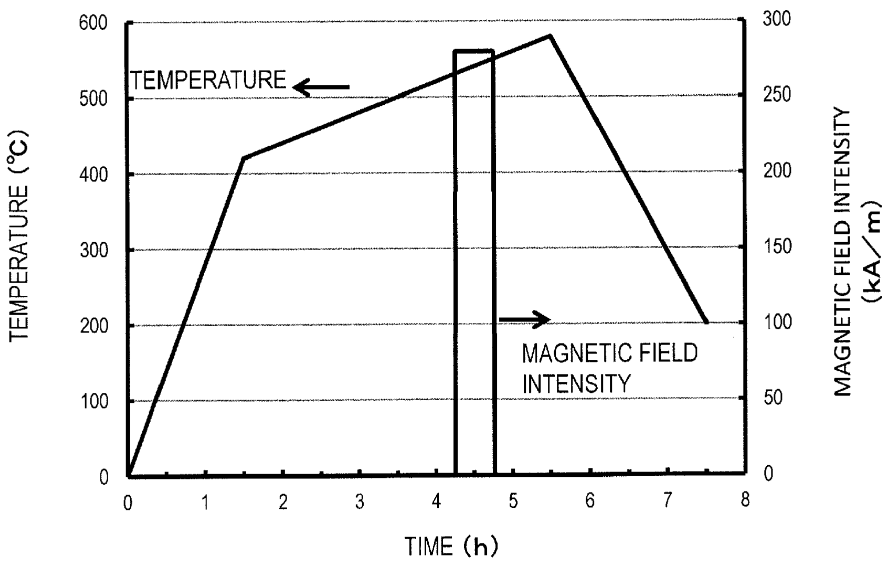
(54) FE-BASED NANOCRYSTALLINE ALLOY CORE

(57) A core is obtained by winding an Fe-based nanocrystalline alloy ribbon, the core having an impedance relative permeability μrz of 90,000 or more at a frequency of 10 kHz, 40,000 or more at a frequency of 100 kHz, and 8,500 or more at a frequency of 1 MHz. The Fe-based nanocrystalline alloy core is produced through a heat treatment step which includes a magnetic field application step of applying a magnetic field in a height direction of the core for not less than 10 minutes and not more than 60 minutes, within only a temperature range in a period of temperature elevation spanning from a temperature which is 25°C higher than a crystallization onset temperature by differential scanning calorimeter to a temperature which is 60°C higher than the crystallization onset temperature.

FIG.1



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Description

TECHNICAL FIELD

[0001] The present invention relates to an Fe-based nanocrystalline alloy core composed of a wound Fe-based nanocrystalline alloy, and a production method of an Fe-based nanocrystalline alloy core.

BACKGROUND ART

[0002] Fe-based nanocrystalline alloys have excellent soft magnetic characteristics that reconcile both high saturation flux density Bs and high relative permeability μr, and therefore are used as the cores in common mode choke coils, high-frequency transformers, and the like.

[0003] Representative compositions of Fe-based nanocrystalline alloys are the Fe-Cu-M'-Si-B type compositions (where M' is at least one element selected from the group consisting of Nb, W, Ta, Zr, Hf, Ti and Mo), as described in Patent Document 1.

[0004] An Fe-based nanocrystalline alloy is obtained by, for an alloy in liquid phase which has been heated to the melting point or a higher temperature, rapidly solidifying the alloy to obtain an amorphous alloy, and then applying a heat treatment to the amorphous alloy in order to effect fine-crystallization (nanocrystallization) thereof. As a method of rapidly solidifying a liquid phase, for example, a single-roll method may be adopted, which provides good producibility. An alloy that is obtained through rapid solidification is in a thin strip or ribbon shape.

[0005] Depending on the temperature profile during heat treatment, or with application of a magnetic field in a specific direction during heat treatment, an Fe-based nanocrystalline alloy may acquire different magnetic characteristics, with respect to the relative permeability μ, squareness ratio, and so on.

[0006] For example, Patent Document 2 proposes performing a heat treatment while applying a magnetic field in the width direction (i.e., the height direction of the core) of an alloy ribbon, in order to obtain an Fe-based nanocrystalline alloy having an initial relative permeability μi of 70,000 or more and a squareness ratio of 30% or less. While various profiles are proposed in Patent Document 2 as specific examples of the heat treatment, they can be generally classified into: profiles which keep a state under magnetic field application in a maximum reachable temperature region of the heat treatment; profiles which keep a state under magnetic field application during temperature elevation, through a maximum reachable temperature region, and over into a cooling process; and profiles which keep a state under magnetic field application from a maximum reachable temperature region and into a cooling process.

CITATION LIST

PATENT LITERATURE

[0007]

[Patent Document 1] Japanese Patent Publication for Opposition No. 4-4393
[Patent Document 2] Japanese Laid-Open Patent Publication No. 7-278764

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0008] The heat treatment method which is disclosed in Patent Document 2 above is considered effective as a means for lowering the squareness ratio.

[0009] As one application, an ability to cope with lower frequencies to higher frequencies, specifically from the 10 kHz band to the 1 MHz band, this being a frequency band for use in a common mode choke, is being desired.

[0010] A characteristic index which is often used of a common mode choke is the impedance relative permeability μrz. The impedance relative permeability μrz is described in, for example, C2531 of the JIS standards (revised 1999). As indicated by the expression below, an impedance relative permeability μrz can be considered equal to an absolute value of complex relative permeability (μr'-iμr")(see, for example, "Know-hows on Magnetic Material Selection", November 10, 1989, editor: Keizo OHTA):

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

[0011] In the above expression, the real part μr' of complex relative permeability represents a magnetic flux density component without a phase lag relative to the magnetic field, and generally corresponds to the magnitude of impedance relative permeability μrz in a low frequency region. On the other hand, the imaginary part μr" represents a magnetic flux density component including a phase lag relative to the magnetic field, and is equivalent to a loss in magnetic energy. In a high frequency region (e.g., 50 kHz or above), the effect of noise suppression is greater as the imaginary part μr" becomes higher.
[0012] The impedance relative permeability μrz that is represented by the above expression is used as an index for assessing the effect of noise suppression for a wide frequency band. The impedance relative permeability μrz having a high value across a wide frequency band means a good ability to absorb or remove common mode noise.
[0013] The inventor has conducted a study in order to enhance the aforementioned impedance relative permeability μrz in a wide band across frequencies from 10 kHz to 1 MHz. As a result, they have realized that it is difficult to obtain a high impedance relative permeability μrz across a wide frequency band with the heat treatment profiles described in Patent Document 1 and Patent Document 2.
[0014] The present invention, which has been made in view of the above, aims to provide an Fe-based nanocrystalline alloy core having a high impedance relative permeability μrz in a wide frequency band across frequencies from 10 kHz to 1 MHz, and a method of producing the Fe-based nanocrystalline alloy core.

SOLUTION TO PROBLEM

[0015] The inventor has found that, in effecting fine-crystallization (nanocrystallization) of an Fe-based amorphous alloy through a heat treatment, applying a magnetic field within only a specific temperature range in a period of temperature elevation produces an Fe-based nanocrystalline alloy core which has a high impedance relative permeability μrz in a wide band across frequencies from 10 kHz to 1 MHz, thus arriving at the present invention.

<1> Fe-based nanocrystalline alloy core

[0016] A core according to an embodiment of the present invention is a core which is produced, after winding an Fe-based amorphous alloy ribbon that is capable of nanocrystallization, through a heat treatment step of heating the Fe-based amorphous alloy ribbon up to a crystallization temperature region and cooling the Fe-based amorphous alloy ribbon, wherein
the core has an impedance relative permeability μrz of
90,000 or more at a frequency of 10 kHz,
40,000 or more at a frequency of 100 kHz, and
8,500 or more at a frequency of 1 MHz.
[0017] In one embodiment of the present invention, it is preferable that the core has an impedance relative permeability μrz of
105,000 or more at a frequency of 10 kHz,
45,000 or more at a frequency of 100 kHz, and
9,000 or more at a frequency of 1 MHz.
[0018] In one embodiment of the present invention, it is preferable that the Fe-based nanocrystalline alloy ribbon has a thickness of not less than 9 μm and not more than 20 μm.

<2> Production method for Fe-based nanocrystalline alloy core

[0019] A production method for a core according to an embodiment of the present invention comprises, after winding an Fe-based amorphous alloy ribbon that is capable of nanocrystallization, a heat treatment step of heating the Fe-based amorphous alloy ribbon up to a crystallization temperature region and cooling the Fe-based amorphous alloy ribbon, wherein the heat treatment step comprises a magnetic field application step of applying a magnetic field in a height direction of the core for not less than 10 minutes and not more than 60 minutes, within only a temperature range in a period of temperature elevation spanning from a temperature which is 25°C higher than a crystallization onset temperature by differential scanning calorimeter to a temperature which is 60°C higher than the crystallization onset temperature.
[0020] In a production method according to an embodiment of the present invention, it is preferable that the heat treatment step comprises a magnetic field application step of applying a magnetic field in the height direction of the core for not less than 15 minutes and not more than 40 minutes, within only a temperature range in the period of temperature elevation from a temperature which is 30°C higher than a crystallization onset temperature by differential scanning calorimeter to a temperature which is 50°C higher than the crystallization onset temperature.
[0021] In a production method according to an embodiment of the present invention, it is preferable that, in the magnetic

field application step, a magnetic field with a magnetic field intensity of not less than 50 kA/m and not more than 300 kA/m is applied in the height direction of the core.

[0022] In a production method according to an embodiment of the present invention, an Fe-based nanocrystalline alloy ribbon having a thickness of not less than 9 μm and not more than 20 μm is preferably used.

[0023] In an embodiment of the present invention, a production method for an Fe-based nanocrystalline alloy ribbon comprises: a step of providing an Fe-based amorphous alloy ribbon that is capable of nanocrystallization; a step of winding the Fe-based amorphous alloy ribbon to form a wound body; a heat treatment step of heating the wound body up to a crystallization temperature region and cooling the wound body; and a step of, during the heat treatment step, applying a magnetic field to the wound body, wherein, in a period of temperature elevation during the heat treatment step, within at least a partial period in a temperature range from a temperature which is 25°C higher than a crystallization onset temperature as indicated by a differential scanning calorimeter to a temperature which is 60°C higher than the crystallization onset temperature, the step of applying a magnetic field applies a magnetic field of a predetermined intensity (e.g., 50 kA/m) or greater in a height direction of the wound body (i.e., a width direction of the alloy ribbon), but does not apply a magnetic field of the predetermined intensity or greater to the wound body within a partial period in the period of temperature elevation. More specifically, a magnetic field is applied within only a temperature range from a temperature which is 25°C higher than the crystallization onset temperature to a temperature which is 60°C higher than the crystallization onset temperature, for a period of time which is not less than 10 minutes and not more than 60 minutes, whereas no magnetic field application is performed in temperature regions other than the aforementioned temperature range in the period of temperature elevation. In this step, a magnetic field of the predetermined intensity or greater is not applied in a period of temperature elevation at the crystallization onset temperature or below, or when at the highest temperature of the heat treatment step (i.e., a temperature which is more than 60°C higher than the crystallization onset temperature).

ADVANTAGEOUS EFFECTS OF INVENTION

[0024] According to an embodiment of the present invention, an Fe-based nanocrystalline alloy core which has a high impedance relative permeability μrz in a wide frequency band across frequencies from 10 kHz to 1 MHz can be obtained. Moreover, it is possible to fabricate such an Fe-based nanocrystalline alloy core. Therefore, it finds optimum use in a common mode choke or the like where characteristics in a wide frequency band across frequencies from 10 kHz to 1 MHz are important.

BRIEF DESCRIPTION OF DRAWINGS

[0025]

[FIG. 1] A diagram describing a profile of heat treatment and magnetic field application according to Example 1 of the present invention.

[FIG. **2]** A diagram describing a profile of heat treatment and magnetic field application according to Example 2 of the present invention.

[FIG. **3]** A diagram describing a profile of heat treatment and magnetic field application (no magnetic field) according to Comparative Example 1.

[FIG. **4]** A diagram describing a profile of heat treatment and magnetic field application according to Comparative Example 2.

[FIG. **5]** A diagram showing results of measurement for an Fe-based amorphous alloy ribbon according to Example 1 by a differential scanning calorimeter (DSC).

[FIG. **6]** A graph showing how impedance relative permeability μrz may change in frequency characteristics, between different manners of magnetic field application during a heat treatment.

DESCRIPTION OF EMBODIMENTS

[0026] Hereinafter, with reference to the drawings, embodiments of the present invention will be specifically described.

[0027] In an embodiment of the present invention, when applying a magnetic field in the width direction of the wound ribbon (i.e., the height direction of the core) to obtain an Fe-based nanocrystalline alloy, a heat treatment step is conducted while applying a magnetic field within only a specific temperature range in a period of temperature elevation.

[0028] Specifically, in a heat treatment step according to an embodiment of the present invention, within only a temperature range in a period of temperature elevation from a temperature which is 25°C higher than a crystallization onset temperature by differential scanning calorimeter to a temperature which is 60°C higher than the crystallization onset temperature, a magnetic field application step of applying a magnetic field in the height direction of the core for a period of time which is not less than 10 minutes and not more than 60 minutes is performed.

[0029] Thus, core fabrication according to an embodiment of the present invention involves applying a magnetic field within only a specific period in a period of temperature elevation, while not applying any magnetic field when at the highest temperature of heat treatment or in a period through the highest temperature into the cooling process. In an embodiment of the present invention, the highest temperature of heat treatment is typically a temperature that is higher than a temperature which is 60°C higher than the crystallization onset temperature.

[0030] In the present specification, a "period of temperature elevation" means a period before reaching the maximum reachable temperature, and may encompass any state of warming, cooling, or retaining a constant temperature that may exist before the maximum reachable temperature is reached. For example, as performed within a temperature range in a period of temperature elevation from a temperature which is 25°C higher than the aforementioned crystallization onset temperature to a temperature which is 60°C higher than the crystallization onset temperature, the heat treatment may take place in a manner of retaining a certain temperature within the aforementioned temperature range for a certain period of time. Moreover, the temperature may be increased monotonically with a constant temperature elevation rate, or the temperature elevation rate may be changed along the way.

[0031] Now, the reasoning as to how the inventor has arrived at the aforementioned idea of applying a magnetic field within only a specific temperature range in a period of temperature elevation during the heat treatment step will be described.

[0032] FIG. **6** is a graph showing frequency characteristics of impedance relative permeability as ascertained through an experiment by the inventor, illustrating the frequency characteristics of impedance relative permeability of a core (core **C1**) which was not subjected to magnetic field application during heat treatment, and the frequency characteristics of impedance relative permeability of a core (core **C2)** which was subjected to magnetic field application throughout the entire heat treatment period.

[0033] As can be seen from FIG. **6,** in a low frequency region of e.g. 100 kHz or less, the impedance relative permeability μrz of the core **C1** (i.e., no magnetic field application) is considerably greater than the impedance permeability μrz of the core **C2** (i.e., always under magnetic field application). On the other hand, in a high frequency region above 1 MHz, the impedance permeability μrz of the core **C2** is observed to be higher than the impedance permeability μrz of the core **C1**. From this, it was confirmed that applying a magnetic field during heat treatment in order to confer magnetic anisotropy to the core tends to lower the impedance relative permeability μrz (especially the real part $\mu r'$ of complex relative permeability according to the experiment by the inventor) in the low frequency region, but tends to improve the impedance relative permeability μrz in the high frequency region.

[0034] Thus, the inventor saw a tradeoff between an improvement in impedance relative permeability μrz on the low frequency side and an improvement in impedance relative permeability μrz on the high frequency side. However, while going through various experiments related to heat treatment in a magnetic field, the inventor came to realize that, in a heat treatment at a low temperature and over a short period of time, conditions may exist which would induce little decrease in impedance relative permeability on the low frequency side, upon which they conducted further studies.

[0035] Consequently, it was found that: in a heat treatment step, a magnetic field in the height direction of the core may be applied within only a temperature range in a period of temperature elevation spanning from a temperature which is 25°C higher than a crystallization onset temperature by differential scanning calorimeter to a temperature which is 60°C higher than the crystallization onset temperature, for a period of time which is not less than 10 minutes and not more than 60 minutes, whereby impedance relative permeability μrz in the high frequency region can be improved while reducing a decrease in impedance relative permeability μrz in the low frequency region. In particular, it was found that applying a magnetic field within the aforementioned temperature range and for only the aforementioned period of time not only reduces a decrease in impedance permeability μrz in the low frequency region, but also may possibly provide an improvement over the case of applying no magnetic field. As a result of this, a core having a high impedance relative permeability μrz in a wide frequency band across frequencies from 10 kHz to 1 MHz was obtained.

[0036] As described above, with the heat treatment method which applies a magnetic field within only a specific temperature range in a period of temperature elevation for only a certain period of time, it is possible to obtain a core with a μrz of 90,000 to 115,000 at a frequency of 10 kHz, a μrz of 40,000 to 49,000 at a frequency of 100 kHz, and a μrz of 8,500 to 15,000 at a frequency of 1 MHz.

[0037] It is estimated that the aforementioned magnetic field application within only a certain temperature range in a period of temperature elevation has enabled maximization of the impedance relative permeability μrz in a wide frequency band across frequencies from 10 kHz to 1 MHz. However, the mechanism as how to magnetic field application within only a certain temperature range in a period of temperature elevation contribute to each of μ' and μ'' is yet undiscovered.

[0038] Note also that the aforementioned crystallization onset temperature is defined with a differential scanning calorimeter. It is difficult to accurately measure the true crystallization onset temperature, and it would be effective to identify it with a differential scanning calorimeter (DSC: Differential Scanning Calorimetry). A temperature at which an exothermic reaction that is due to nanocrystallization being begun during ascending temperature is detected is defined as the crystallization onset temperature (see FIG. 5). In the present specification, a crystallization onset temperature means what is determined by using a differential scanning calorimeter under a measurement condition such that the temperature elevation rate is 10°C/minute.

[0039] Control of the heat treatment temperature is preferably performed so that the temperature distribution within the actual heat treatment furnace is within ± 5°C, while taking into account the capacity of the heat treatment furnace and a calorific value associated with crystallization of the amorphous alloy ribbon to be heat-treated. As a result, magnetic characteristics of the heat-treated alloy can be stabilized.

[0040] The intensity of the magnetic field to be applied is preferably not less than 50 kA/m and not more than 300 kA/m. If the applied magnetic field is too weak, it will be difficult to confer an induced magnetic anisotropy under practical operation conditions; if it is too high, too much induced magnetic anisotropy tends to be conferred. A more preferable range is from 60 kA/m to 280 kA/m.

[0041] It has been confirmed by the inventor that, when the applied magnetic field is a relatively weak magnetic field which is less than 50 kA/m, the impedance relative permeability is hardly affected even if it is applied in any period during the heat treatment step. Therefore, in an embodiment of the present invention, application of a weak magnetic field of less than 50 kA/m may well be regarded as no magnetic field being applied at all.

[0042] As an Fe-based amorphous alloy that is capable of nanocrystallization, for example, an alloy of a composition expressed by the general formula: $(Fe_{1-a}M_a)_{100-x-y-z}$-$\alpha$-$\beta$-$\gamma Cu_xSi_yB_zM'\alpha M''\beta X\gamma$ (at%) (where M is Co and/or Ni; M' is at least one element selected from the group consisting of Nb, Mo, Ta, Ti, Zr, Hf, V, Cr, Mn and W; M" is at least one element selected from the group consisting of Al, platinum group elements, Sc, rare-earth elements, Zn, Sn and Re; X is at least one element selected from the group consisting of C, Ge, P, Ga, Sb, In, Be and As; a, x, y, z, α, β and γ respectively 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 $0 \leq \gamma \leq 20$) can be used.

[0043] By allowing an alloy of the above composition to be melted to its melting point or above, and rapidly solidified by the single-roll method, a long length of amorphous alloy ribbon (thin strip) can be obtained.

[0044] The thickness of the amorphous alloy ribbon is preferably not less than 9 μm and not more than 30 μm. If it is less than 9 μm, the ribbon has insufficient mechanical strength so that it is likely to break during handling. If it is above 30 μm, an amorphous state cannot be stably obtained. When the amorphous alloy ribbon after nanocrystallization is used as a core for a high frequency application, an eddy current will occur in the ribbon; the loss due to the eddy current will be greater as the ribbon becomes thicker. Therefore, a more preferable thickness is 9 μm to 20 μm, and a thickness of 15 μm or less is still more preferable.

[0045] For a practical core shape, the width of the amorphous alloy ribbon is preferably 10 mm or more. While a wide width is preferable because slitting (i.e., cutting up) a wide-width alloy ribbon permits low cost, a width of 250 mm or less is preferable for stable fabrication of an alloy ribbon. In order to attain more stable fabrication, a width of 70 mm or less is more preferable.

[0046] The heat treatment for nanocrystallization is preferably performed in an inert gas such as nitrogen, and the maximum reachable temperature is preferably greater than 560°C but not more than 600°C. That of 560°C or less, or above 600°C is unpreferable because of resulting in large magnetostriction. No particular time of retention at the maximum reachable temperature may be set, i.e., 0 minutes (that is, no time of retention), and nanocrystallization is still possible. Retention for 3 hours or less may be observed in order to account for the heat capacity of the total amount of alloy to be heat-treated and the stability of characteristics.

[0047] As a temperature profile of heat treatment, relatively rapid warming with a temperature elevation rate of e.g. 3 to 5°C/minute may be effected from room temperature to near a temperature at which nanocrystallize begins (typically, to a temperature which is 20°C lower than the crystallization onset temperature); and thereafter, warming may be effected with a gentle temperature elevation rate with an average of 0.2 to 1.0°C/minute from near the aforementioned nanocrystallization onset temperature to a temperature which is 60°C higher than the nanocrystallization onset temperature (or alternatively to the maximum reachable temperature), whereby stable nanocrystallization can take place. Note that, from the maximum reachable temperature to 200°C, it is preferable to perform cooling at a cooling rate of 2 to 5°C/minute. Usually at 100°C or less, the alloy can be taken out into the atmospheric air.

[0048] For use as a magnetic part, an Fe-based amorphous alloy ribbon that is capable of nanocrystallization may be wound into a toroidal body, and subjected to a heat treatment step which involves heating up to the crystallization temperature region and then cooling. By ensuring that application of a magnetic field at this time is in the height direction of the aforementioned toroidal body (core), whereby a predetermined induced magnetic anisotropy can be conferred.

[Examples]

(Example 1)

[0049] An alloy melt composed of Cu:1%, Nb:3%, Si:15.5% and B:6.5%, all by at%, with a balance of Fe and inevitable impurities, was quenched by single-roll method, thereby obtaining an Fe-based amorphous alloy ribbon having a width of 50 mm and a thickness of 13 μm. After this Fe-based amorphous alloy ribbon was slit (cut up) in a width of 15 mm, it was wound so as to have an outer diameter of 31 mm and an inner diameter of 21 mm, thereby producing a toroidal core (height: 15 mm). As shown in FIG. **5,** a measurement with a differential scanning calorimeter (DSC) indicated the crystallization onset temperature of this alloy to be 500°C.

[0050] The produced core was subjected to a heat treatment and magnetic field application according to the profile of temperature-and-magnetic field application as shown in FIG. 1. The magnetic field application was performed in a temperature range from 530 to 550°C (a temperature range from a temperature which is 30°C higher than the crystallization onset temperature to a temperature which is 50°C higher than the crystallization onset temperature) for 30 minutes. The direction of magnetic field application was the width direction of the alloy ribbon, i.e., the height direction of the core. The magnetic field intensity was 280 kA/m. Note that the maximum reachable temperature during the heat treatment was 580°C.

[0051] An impedance relative permeability μrz of the heat-treated core was measured at 10 kHz, 100 kHz and 1 MHz. The results are shown in Table 1.

[0052] Measurements of the impedance relative permeability μrz were taken by using HP4194A, manufactured by Agilent Technologies, under conditions with an oscillation level of 0.5 V and an average of 16. Insulation coated leads were passed through the central portion of the toroidal core, so as to be connected to input/output terminals, whereby the measurements were taken.

[0053] In Example 1, the impedance relative permeability μrz was 98,000 at 10 kHz, 42,000 at 100 kHz, and 8,600 at 1 MHz.

[Table 1]

Frequency	Example	Example	Example	Example	Comparative Example 1	Comparative Example 2	Reference Example
10 kHz	98,000	109,000	91,000	90, 000	88,000	18,000	52,000
100 kHz	42,000	47,000	46,000	46,000	41,000	17,500	37,000
1 MHz	8,600	9,500	9,300	10,000	7,200	6,900	9,500

(Example 2)

[0054] By using the Fe-based amorphous alloy described in Example 1, a toroidal core was similarly produced. The produced core was subjected to a heat treatment and magnetic field application according to the profile of temperature-and-magnetic field application as shown in FIG. **2.** Only the temperature range and the magnetic field intensity of magnetic field application were different from those in Example 1 (FIG. **1**), while the other conditions were similar to those in Example 1.

[0055] The magnetic field application was performed for 15 minutes in a temperature range from 540 to 550°C (a temperature range from a temperature which is 40°C higher than the crystallization onset temperature to a temperature which is 50°C higher than the crystallization onset temperature). The magnetic field intensity was 160 kA/m. Measurement results of the impedance relative permeability μrz of the heat-treated core, at 10 kHz, 100 kHz and 1 MHz, are shown in Table 1.

[0056] In Example 2, the impedance relative permeability μrz was 109,000 at 10 kHz, 47,000 at 100 kHz, and 9,500 at 1 MHz. In other words, a higher impedance relative permeability μrz than that of Example 1 was attained at each of the frequencies of 10 kHz, 100 kHz and 1 MHz.

(Example 3)

[0057] An alloy melt composed of Cu:1%, Nb:3%, Si:15.5% and B:6.5%, all by at%, with a balance of Fe and inevitable impurities (similar to Example 1), was quenched by single-roll method, thereby obtaining an Fe-based amorphous alloy ribbon having a width of 50 mm and a thickness of 10 μm. By using this Fe-based amorphous alloy ribbon having a thickness of 10 μm (which was 13 μm in Example 1), a toroidal core was similarly produced. Similarly to Example 2, the produced core was subjected to a heat treatment and magnetic field application according to the profile of temperature-and-magnetic field application as shown in FIG. **2**. Measurement results of the impedance relative permeability μrz of the heat-treated core at 10 kHz, 100 kHz and 1 MHz are shown in Table 1.

[0058] In Example 3, the impedance relative permeability μrz was 91,000 at 10 kHz, 46,000 at 100 kHz, and 9,300 at 1 MHz.

(Example 4)

[0059] By using the Fe-based amorphous alloy ribbon having a thickness of 13 μm described in Example 1, a toroidal core was similarly produced. To the produced core, a magnetic field was applied for 15 minutes in a heat treatment temperature range from 530°C to 540°C and with an intensity of 160 kA/m. Measurement results of the impedance relative permeability rz of the heat-treated core at 10 kHz, 100 kHz and 1 MHz are shown in Table 1.
[0060] In Example 4, the impedance permeability μrz was 90,000 at 10 kHz, 46,000 at 100 kHz, and 10,000 at 1 MHz.

(Comparative Example 1)

[0061] By using the Fe-based amorphous alloy described in Example 1, a toroidal core was similarly produced. According to the profile of temperature-and-magnetic field application as shown in FIG. 3, the produced core was subjected to a heat treatment without any magnetic field application (i.e., under no magnetic field). As can be seen from FIG. **3**, the temperature profile in Comparative Example 1 was similar to that in Example 1.
[0062] Measurement results of the impedance relative permeability μrz of the heat-treated core at 10 kHz, 100 kHz and 1 MHz are shown in Table 1.
[0063] A comparison between Comparative Example 1 under no magnetic field application and Examples 1 and 2 indicates that, at each frequency, the value of impedance relative permeability μrz in Comparative Example 1 is smaller than the values in Examples 1 and 2.

(Comparative Example 2)

[0064] By using the Fe-based amorphous alloy described in Example 1, a toroidal core was similarly produced. The produced core was subjected to a heat treatment and magnetic field application, according to a profile of temperature-and-magnetic field application which is shown in FIG. **4.** As can be seen from FIG. **4,** the temperature profile in Comparative Example 2 was similar to that in Example 1.
[0065] In Comparative Example 2, although the magnetic field intensity during magnetic field application is similar to that in Example 1 (FIG. 1), the temperature range of magnetic field application spans from the beginning of the heat treatment, through the maximum reachable temperature of 580°C, over into the cooling. This temperature range of magnetic field application lies outside the range according to the present invention.
[0066] Measurement results of the impedance relative permeability μrz of the heat-treated core at 10 kHz, 100 kHz and 1 MHz are shown in Table 1.
[0067] A comparison between Comparative Example 2 and Examples 1 and 2 indicates that, at each frequency, the value of impedance relative permeability μrz in Comparative Example 2 is smaller than the values in Examples 1 and 2.

(Reference Example)

[0068] As Reference Example, a magnetic field was applied to a toroidal core which was similar in composition and shape to Example 2, in a lower temperature region and for a longer time in a period of temperature elevation during the heat treatment step, and the resultant impedance relative permeability thereof will now be described.
[0069] In this Reference Example, the magnetic field application was performed continuously for about 60 minutes in a temperature range from 480 to 520°C (a temperature range from a temperature which is 20°C lower than the crystallization onset temperature to a temperature which is 20°C higher than the crystallization onset temperature). The direction of magnetic field application was the width direction of the alloy ribbon, i.e., the height direction of the core, and the magnetic field intensity was 120 kA/m.
[0070] Measurement results of the impedance relative permeability μrz of the heat-treated core at 10 kHz, 100 kHz and 1 MHz are shown in Table 1.
[0071] FIG. **6** shows frequency characteristics of impedance relative permeability μrz of a core (core **E1**) according to an embodiment of the present invention (similar to Example 2) and a core (core **R1**) according to Reference Example above. FIG. **6** also shows a core (core **C1**) under no magnetic field being applied, corresponding to Comparative Example 1, and a core (core **C2)** under continuous magnetic field application, corresponding to Comparative Example 2 above.
[0072] FIG. **6** would indicate that, as in the core **R1**, if a magnetic field is applied for about 60 minutes in a temperature region near the crystallization onset temperature that is lower than a temperature which is 25°C higher than the crystallization onset temperature, the impedance relative permeability μrz in the low frequency region may become lower than that under no magnetic field application (core **C1**). However, in a high frequency region above 100 kHz, the impedance relative permeability tends to be higher for the core **R1** than for the core **C1**.
[0073] On the other hand, as in an embodiment of the present invention (core E1**),** if a magnetic field is applied only for a relatively short period of time above or at 25°C from and below or at 60°C from the crystallization onset temperature

(such that typically no magnetic field is applied when at the highest temperature), improvements in the impedance relative permeability μrz were confirmed not only in the high frequency region but also in the low frequency region. Thus, among those modes of magnetic field application which apply a magnetic field in a specific period before the maximum reachable temperature, an embodiment of the present invention exhibits an outstanding effect of improving the impedance relative permeability μrz in the low frequency region.

INDUSTRIAL APPLICABILITY

[0074] According to an embodiment of the present invention, there is provided a core which exhibits a high impedance relative permeability μrz in a manner of supporting a wide frequency band, which is suitably used for a common mode choke coil, a high-frequency transformer, or the like.

Claims

1. An Fe-based nanocrystalline alloy core composed of a wound Fe-based nanocrystalline alloy ribbon, wherein the core has an impedance relative permeability μrz of

    90,000 or more at a frequency of 10 kHz,
    40,000 or more at a frequency of 100 kHz, and
    8,500 or more at a frequency of 1 MHz.

2. The Fe-based nanocrystalline alloy core of 1, wherein the core has an impedance relative permeability μrz of

    105,000 or more at a frequency of 10 kHz,
    45,000 or more at a frequency of 100 kHz, and
    9,000 or more at a frequency of 1 MHz.

3. The Fe-based nanocrystalline alloy core of claim 1 or 2, wherein the Fe-based nanocrystalline alloy ribbon has a thickness of not less than 9 μm and not more than 20 μm.

4. A common mode choke coil comprising the Fe-based nanocrystalline alloy core according to any one of claims 1 to 3.

FIG.1

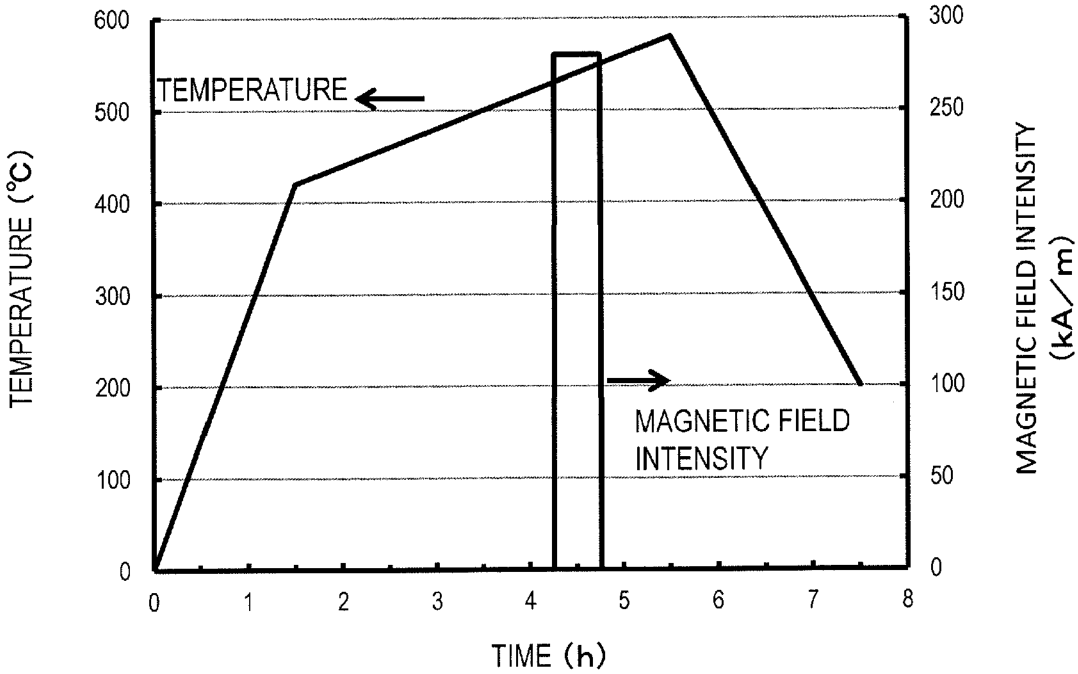

600
500
400
300
200
100
0
TEMPERATURE (°C)
TEMPERATURE
MAGNETIC FIELD
INTENSITY
0
1
2
3
4
5
6
7
8
TIME (h)
300
250
200
150
100
50
0
MAGNETIC FIELD INTENSITY
(kA/m)

FIG.2

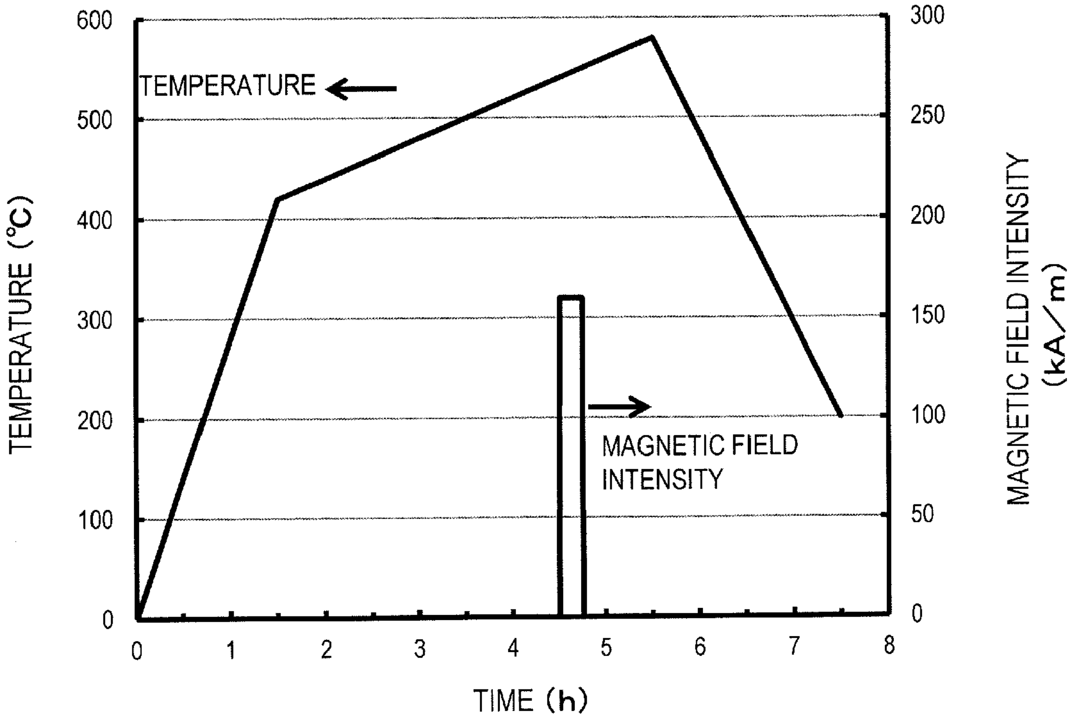

600
500
400
300
200
100
0
TEMPERATURE (°C)
TEMPERATURE
MAGNETIC FIELD
INTENSITY
0
1
2
3
4
5
6
7
8
TIME (h)
300
250
200
150
100
50
0
MAGNETIC FIELD INTENSITY
(kA/m)

FIG.3

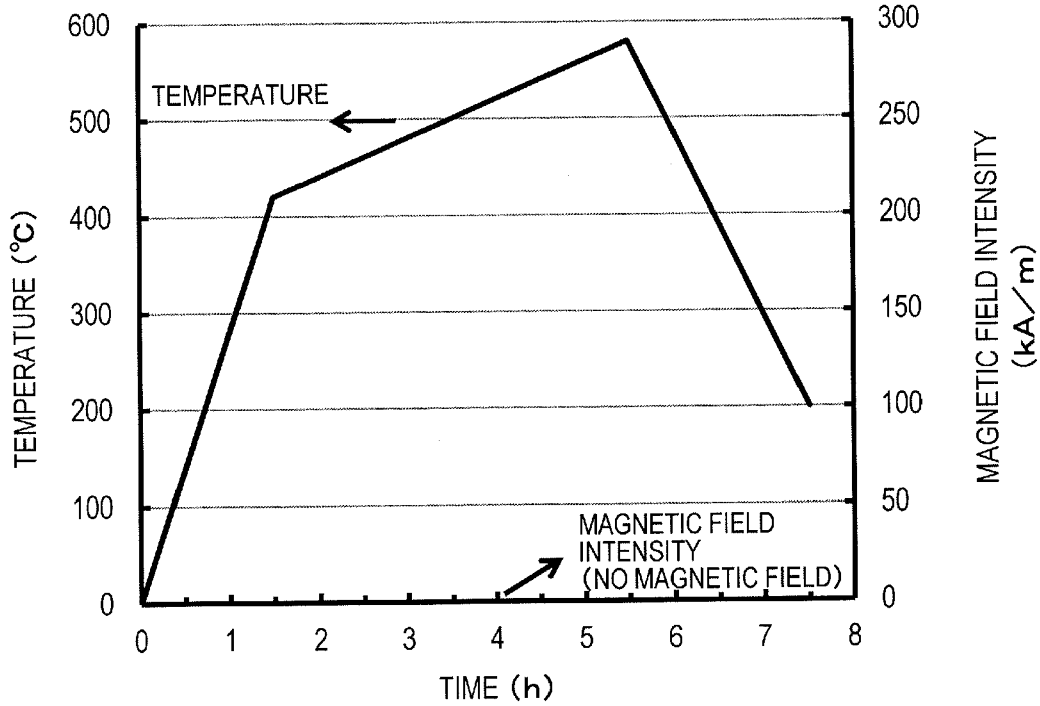

600
500
400
300
200
100
0
TEMPERATURE (°C)
TEMPERATURE
300
250
200
150
100
50
0
MAGNETIC FIELD INTENSITY (kA/m)
MAGNETIC FIELD INTENSITY (NO MAGNETIC FIELD)
0
1
2
3
4
5
6
7
8
TIME (h)

FIG.4

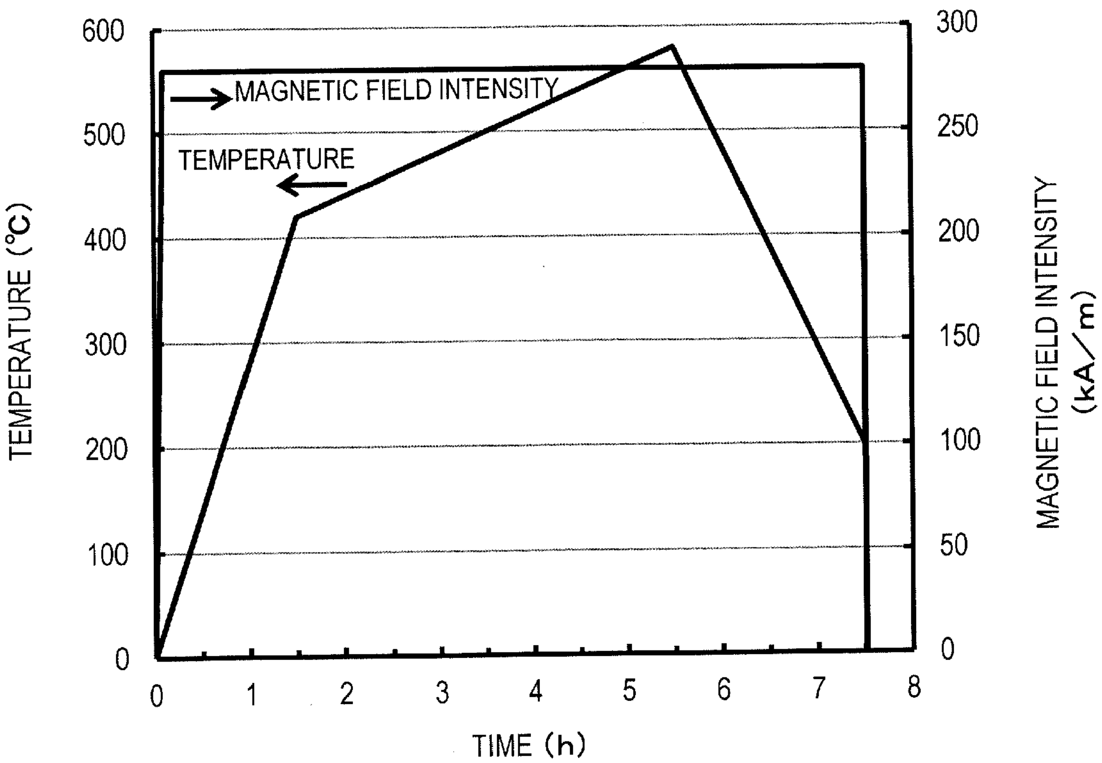

600
500
400
300
200
100
0
TEMPERATURE (°C)
MAGNETIC FIELD INTENSITY
TEMPERATURE
300
250
200
150
100
50
0
MAGNETIC FIELD INTENSITY (kA/m)
0
1
2
3
4
5
6
7
8
TIME (h)

FIG.5

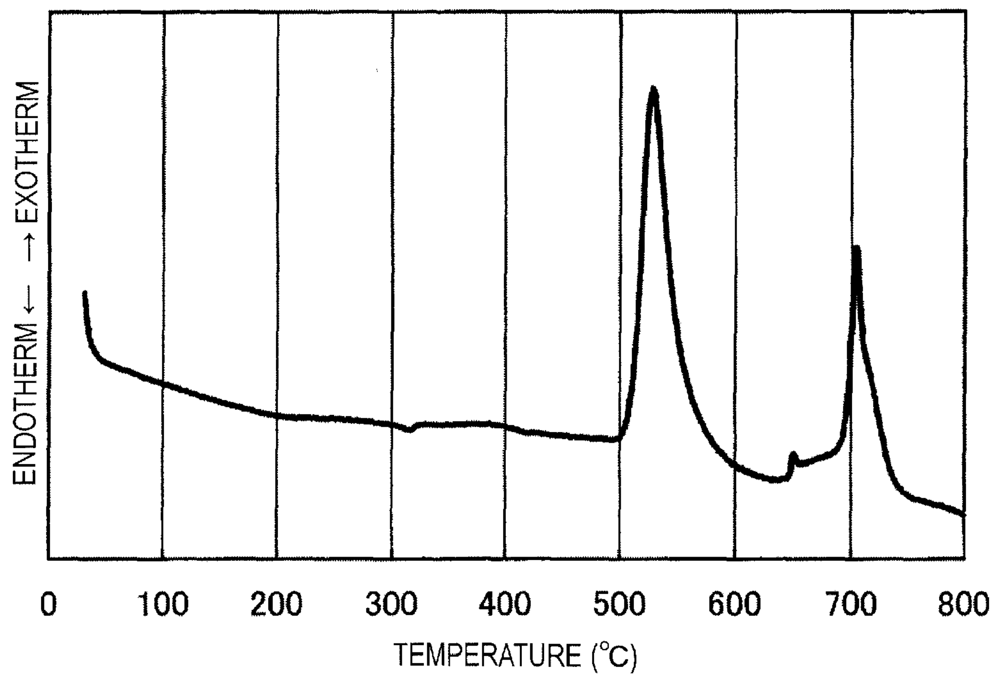
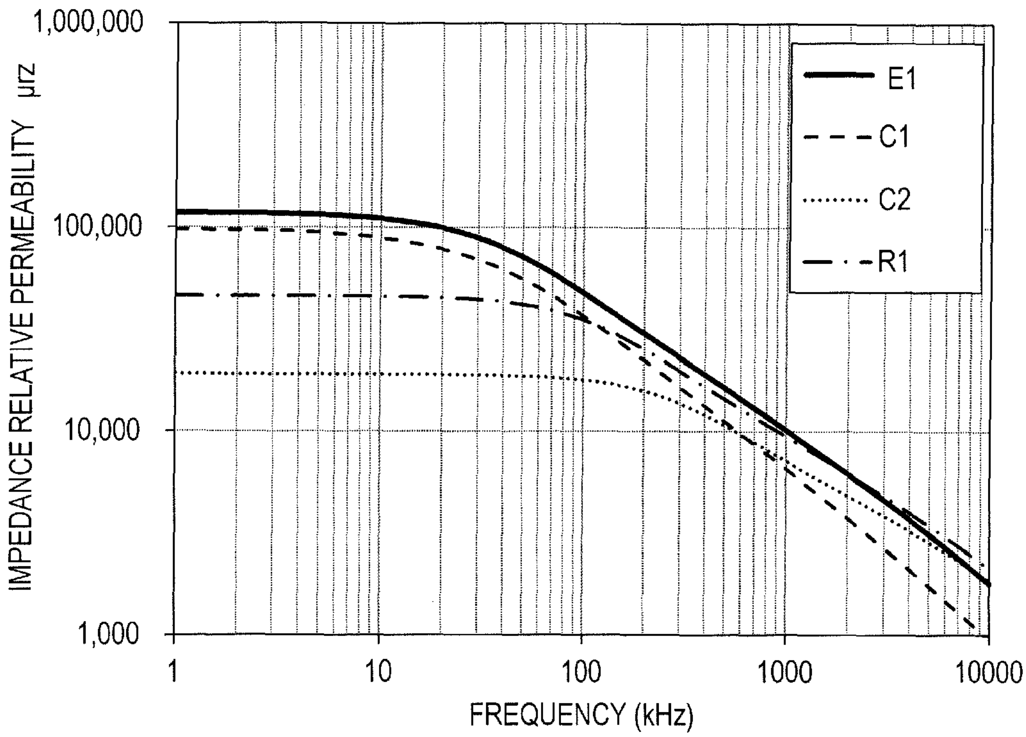

ENDOTHERM ← → EXOTHERM
0
100
200
300
400
500
600
700
800
TEMPERATURE (°C)

FIG.6


1,000,000
100,000
10,000
1,000
IMPEDANCE RELATIVE PERMEABILITY μrz
1
10
100
1000
10000
FREQUENCY (kHz)
E1
C1
C2
R1

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EUROPEAN SEARCH REPORT

Application Number
EP 20 16 0649

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	JP 3 719449 B2 (HITACHI METALS LTD) 24 November 2005 (2005-11-24) * paragraphs [0017], [0028] * * figure 2 * -----	1-4	INV. H01F1/153 H01F3/04 H01F41/02
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X	EP 0 625 786 A2 (HITACHI) 23 November 1994 (1994-11-23) * example 1 * -----	1-4	
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H01F

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	29 April 2020	Subke, Kai-Olaf

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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