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(54) Fe-based amorphous alloy ribbon and magnetic core formed thereby

(57) A magnetic core provided with a shape for a transformer by a cut-lap or step-lap method, which is constituted by an Fe-based amorphous alloy ribbon having excellent magnetic characteristics, which is represented by the general formula: $Fe_aSi_bB_cM_x$ or $Fe_aSi_bB_cC_dM_x$ wherein M is Cr and/or Ni, *a* is 78 to 86 atomic %, *b* is 0.001 to 5 atomic %, *c* is 7 to 20 atomic %, *x* is 0.01 to 5 atomic %, and *d* is 0.001 to 4 atomic %, $(a + b + c + x)$ or $(a + b + c + d + x)$ being 100.

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Description

FIELD OF THE INVENTION

[0001] The present invention relates to an Fe-based amorphous alloy ribbon having excellent magnetic properties, and a magnetic core constituted by such an Fe-based amorphous alloy ribbon, and particularly to an Fe-based amorphous alloy ribbon and its magnetic core usable for various transformers, reactors, noise reduction parts such as choke coils for active filters, smoothing choke coils, common-mode choke coils, etc., laser power supplies, magnetic pulse power parts of accelerators, motors, generators, etc.

BACKGROUND OF THE INVENTION

[0002] Known as magnetic alloys having high saturation magnetic flux densities and low core losses used for various transformers and reactors, noise reduction parts such as choke coils for active filters, smoothing choke coils, common-mode choke coils and electromagnetic shields, laser power supplies, magnetic pulse power parts of accelerators, motors, generators, etc. are silicon steel and Fe-based amorphous alloys. Though silicon steel has a high magnetic flux density with low cost, it disadvantageously suffers from a core loss in high-frequency applications. The Fe-based amorphous alloys have lower saturation magnetic flux densities than silicon steel, resulting in a larger magnetic core size. They also have large magnetostriction, vulnerable to the deterioration of characteristics due to stress.

[0003] As magnetic core materials for transformers, JP 9-31610 A discloses a method for producing an amorphous Fe-Si-B-M alloy ribbon, wherein M represents an inevitable impurity, at least one selected from the group consisting of Al, Ti, S, Mn and Zr. This amorphous alloy has a magnetic flux density of 1.4 T or more in a magnetic field of 80 A/m.

[0004] As a method for improving the core loss of an Fe-based amorphous alloy, JP 10-324961 A discloses a method for producing an Fe-Si-B-M amorphous alloy ribbon, wherein M is at least one selected from the group consisting of Mn, Co, Ni and Cr. In this method, a heat treatment at a relatively low temperature is carried out for at least 6 hours or more before a conventional heat treatment at an intermediate or high temperature in a magnetic field.

[0005] However, the above conventional Fe-based amorphous alloy ribbons are not suitable as magnetic core materials for transformers because of low magnetic flux densities. Because a low magnetic flux density necessitates a low maximum operation magnetic flux density, the magnetic core having a low magnetic flux density inevitably has large volume or weight.

[0006] Though core loss has been investigated on plates obtained from the above conventional Fe-based amorphous alloy ribbons, no investigation has been conducted with respect to stress generated when worked to magnetic cores. Further, because a heat treatment needs a long period of time in the production method proposed by JP 10-324961, it is extremely poor in mass producibility.

[0007] Because amorphous Fe-Si-B or Fe-Si-B-C alloys have low crystallization temperatures in compositions suitable for high saturation magnetic flux densities, they should be heat-treated at low temperatures. In this case, because stress generated in the Fe-based amorphous alloys worked to magnetic cores for transformers is not sufficiently relaxed, the magnetic characteristics of the Fe-based amorphous alloys are extremely deteriorated.

OBJECT OF THE INVENTION

[0008] Accordingly, an object of the present invention is to provide an Fe-based amorphous alloy ribbon having improved saturation magnetic flux density and soft magnetic characteristics, whose stress is sufficiently relaxed by a heat treatment for a relatively short period of time.

[0009] Another object of the present invention is to provide a magnetic core constituted by such an Fe-based amorphous alloy ribbon.

SUMMARY OF THE INVENTION

[0010] The first Fe-based amorphous alloy ribbon having excellent magnetic characteristics according to the present invention is represented by the general formula: $Fe_aSi_bB_cM_x$, wherein M is Cr and/or Ni, a is 78 to 86 atomic %, b is 0.001 to 5 atomic %, c is 7 to 20 atomic %, and x is 0.01 to 5 atomic %, $(a + b + c + x)$ being 100. x is preferably 0.01 to 1 atomic % when M is Cr, and 0.1 to 5 atomic % when M is Ni. A heat treatment under predetermined conditions can provide this Fe-based amorphous alloy ribbon with an improved magnetic flux density and sufficiently relaxed stress. This Fe-based amorphous alloy ribbon preferably has a thickness of 25 to 40 μm, a saturation magnetic flux density of 1.6 T or more, and a magnetic flux density of 1.5 T or more in a magnetic field of 80 A/m.

[0011] More preferably, a is 78 to 85 atomic %, b is 0.001 to 3 atomic %, c is 10 to 20 atomic %, and x is 0.02 to 4 atomic %, to provide an Fe-based amorphous alloy ribbon with a further improved magnetic flux density and sufficiently

relaxed stress. This Fe-based amorphous alloy ribbon has a saturation magnetic flux density of 1.65 T or more, and a magnetic flux density of 1.6 T or more in a magnetic field of 80 A/m.

[0012] The second Fe-based amorphous alloy ribbon having excellent magnetic characteristics according to the present invention is represented by the general formula: $Fe_aSi_bB_cC_dM_x$, wherein M is Cr and/or Ni, *a* is 78 to 86 atomic *%, b* is 0.001 to 5 atomic %, *c* is 7 to 20 atomic %, *d* is 0.001 to 4 atomic %, and *x* is 0.01 to 5 atomic %, (*a + b + c + d + x*) being 100. *x* is preferably 0.01 to 1 atomic % when M is Cr, and 0.1 to 5 atomic % when M is Ni. A heat treatment under predetermined conditions can provide this Fe-based amorphous alloy ribbon with an improved magnetic flux density and sufficiently relaxed stress. This Fe-based amorphous alloy ribbon preferably has a thickness of 25 to 40 μm, a saturation magnetic flux density of 1.6 T or more, and a magnetic flux density of 1.5 T or more in a magnetic field of 80 A/m.

[0013] More preferably, a is 78 to 85 atomic %, *b* is 0.001 to 3 atomic %, c is 10 to 20 atomic %, *d* is 0.01 to 3 atomic %, and x is 0.02 to 4 atomic %, to provide an Fe-based amorphous alloy ribbon with a further improved magnetic flux density and sufficiently relaxed stress. This Fe-based amorphous alloy ribbon has a saturation magnetic flux density of 1.65 T or more, and a magnetic flux density of 1.6 T or more in a magnetic field of 80 A/m.

[0014] The magnetic core of the present invention is constituted by either one of the above Fe-based amorphous alloy ribbons by a cut-lap or step-lap method to have a shape for a transformer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015]

Fig. 1(a) is a plan view showing one example of a ring-shaped magnetic core constituted by the Fe-based amorphous alloy ribbon of the present invention;
Fig. 1(b) is a cross-sectional view taken along the line A-A in Fig. 1(a);
Fig. 2(a) is a plan view showing another example of a ring-shaped magnetic core constituted by the Fe-based amorphous alloy ribbon of the present invention;
Fig. 2(b) is a cross-sectional view taken along the line B-B in Fig. 2(a);
Fig. 3(a) is a partially enlarged plan view showing a ring-shaped magnetic core produced by a cut-lap or step-lap method; and
Fig. 3(b) is a cross-sectional view taken along the line C-C in Fig. 3 (a); and
Fig. 4 is a schematic view showing the method of measuring a stress relaxation rate.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[1] Composition

[0016] The first Fe-based amorphous alloy of the present invention is represented by the general formula: $Fe_aSi_bB_cM_x$, wherein M is Cr and/or Ni, *a* is 78 to 86 atomic *%, b* is 0.001 to 5 atomic %, *c* is 7 to 20 atomic %, and *x* is 0.01 to 5 atomic %, (*a + b + c + x*) being 100.

[0017] The second Fe-based amorphous alloy of the present invention is represented by the general formula: $Fe_aSi_bB_cC_dM_x$, wherein M is Cr and/or Ni, *a* is 78 to 86 atomic %, *b* is 0.001 to 5 atomic %, c is 7 to 20 atomic %, *d* is 0.001 to 4 atomic %, and *x* is 0.01 to 5 atomic %, (*a + b + c + d* + x) being 100.

[0018] When the Fe-based amorphous alloy of the present invention containing Cr and/or Ni is used, stress generated at the time of producing a magnetic core is sufficiently relaxed by a heat treatment. Cr functions to provide the alloy with a reduced melt viscosity, and improved wettability with a roll and surface conditions. Cr and Ni also have an effect of accelerating the relaxation of stress in the Fe-based amorphous alloy at the time of a heat treatment, thereby improving its soft magnetic characteristics. However, sufficient effects cannot be obtained when too small amounts of Cr and/or Ni are contained, and there is remarkable deterioration in a Curie temperature and a saturation magnetic flux density when their amounts are excessive. Accordingly, the amount of Cr and/or Ni is 0.01 to 5 atomic %, preferably 0.02 to 4 atomic %, more preferably 0.1 to 4 atomic %, based on 100 atomic % of the main composition (*a + b + c + x or a + b + c + d + x) of the* alloy.

[0019] When M is Cr, the range of x is preferably 0.01 to 1 atomic %, more preferably 0.02 to 0.5 atomic %. When M is Ni, the range of x is preferably 0.1 to 5 atomic %, more preferably 0.3 to 4 atomic %. There is thus difference between Cr and Ni in a necessary amount. Cr is effective in a small amount to relax stress generated during working to a magnetic core, while Ni is effective in a larger amount than that of Cr to relax stress generated during working to a magnetic core. Cr and Ni may be properly selected depending on the required magnetic properties and stress relaxation rate.

[0020] Si is an element important to make the alloy amorphous and necessary to keep the Curie temperature of the alloy high to some extent. When the amount of Si is too small, the Curie temperature of the alloy is too low for practical

applications. On the other hand, when its amount is too much, the core loss of the alloy is increased, and the percentages of Fe and/or B in the alloy are reduced, resulting in lowered magnetic flux density and thermal stability. Accordingly, the amount of Si is 0.001 to 5 atomic %, preferably 0.001 to 3 atomic %, based on 100 atomic % of the main composition of the alloy.

[0021] B is an important element for making the alloy amorphous. When the amount of B is too small, the alloy is not easily made amorphous, resulting in reduced soft magnetic characteristics and increased core loss. On the other hand, when the amount of B is too much, the percentages of Fe and/or Si in the alloy are reduced, resulting in lowered magnetic flux density and thermal stability. Accordingly, the amount of B is 7 to 20 atomic %, preferably 10 to 20 atomic %, based on 100 atomic % of the main composition of the alloy.

[0022] C is effective to lower the melt viscosity of the alloy and improve wettability with a roll. However, too much C leads to the deterioration of magnetic characteristics by aging. Thus, the amount of C is 0.001 to 4 atomic %, preferably 0.01 to 3 atomic %, more preferably 0.1 to 3 atomic %, based on 100 atomic % of the main composition of the alloy.

[0023] The balance is substantially Fe, which is an important element to obtain a high magnetic flux density. However, too much Fe leads to an increased core loss and deteriorated thermal stability. Thus, the amount of Fe is 78 to 86 atomic %, preferably 78 to 85 atomic %, based on 100 atomic % of the main composition of the alloy.

[0024] The Fe-based amorphous alloy of the present invention may contain at least one of Mn, P, S, Cu, Al, Sn, Pb, Ca, Ti and Zr as an inevitable impurity in an amount of about 0.0002 to 0.2 atomic % based on 100 atomic % of the main composition of the above alloy.

[2] Production method

[0025] The Fe-based amorphous alloy of the present invention is obtained by rapidly quenching a melt of the above composition by single roll method, etc. and heat-treating the resultant Fe-based amorphous alloy at a predetermined temperature to relax stress in the alloy. Though the rapid quenching by a single roll method, etc. is usually carried out in the air, in an atmosphere of Ar or He, or in a reduced-pressure atmosphere, it may be carried out in an atmosphere containing nitrogen, carbon monoxide or carbon dioxide. Though the heat treatment is usually carried out in an inert gas atmosphere of Ar, He, N_2, etc. or in vacuum, it may be carried out in the air.

[0026] The heat treatment is carried out desirably in an inert gas atmosphere usually having a dew point of -30°C or lower. The heat treatment in an inert gas atmosphere having a dew point of -60°C or lower is more preferable because of small unevenness in the heat-treated ribbon. In the case of a heat treatment at a constant temperature, the temperature-holding time is usually 24 hours or less, preferably 4 hours or less, from the aspect of mass producibility. During the heat treatment, an average temperature-elevating speed is preferably 0.1-200°C/min, more preferably 0.1-100°C/min, and the average cooling speed is preferably 0.1-3000°C/min, more preferably 0.1-100°C/min. The heat treatment in this range can provide the alloy with a low magnetic core loss. The heat treatment may be carried out by a single step or multiple steps, or may be repeated plural times. Further, DC, AC or pulse current may be supplied to the alloy to generate heat for a heat treatment.

[0027] The Fe-based amorphous alloy ribbon of the present invention may be coated with (1) a powder or film of SiO_2, MgO, Al_2O_3, etc., (2) an insulating layer formed by a chemical conversion treatment, or (3) an insulating oxide layer formed by an anodic oxidation treatment, for interlayer insulation, if necessary. These treatments decrease the influence of eddy current flowing particularly between layers at high frequencies, thereby reducing a magnetic core loss at high frequencies. These treatments are particularly effective for magnetic cores constituted by as wide ribbons as 50 mm or more having good surface conditions. Further, impregnation, coating, etc. may be conducted in the production of magnetic cores.

[0028] The Fe-based amorphous alloy ribbon of the present invention can be worked to rings for magnetic cores 1 for transformers, motors and generators, etc. as shown in Figs. 1 and 2. The Fe-based amorphous alloy ribbon 10 of the present invention is suitably formed to transformer shapes by a cut-lap or a step-lap method to provide magnetic cores.

[0029] The present invention will be described referring to Examples below without intention of limiting the present invention thereto.

Example 1

[0030] Alloy melts having compositions represented by $Fe_aSi_bB_cM_x$ ($a + b + c + x = 100$) as shown in Table 1 were rapidly quenched by a single roll method to produce amorphous alloy ribbons of 5 mm in width and 25 μm in thickness.

[0031] Each Fe-based amorphous alloy ribbon was wound to form a toroidal magnetic core of 19 mm in outer diameter and 15 mm in inner diameter, which was heat-treated in an Ar gas atmosphere. During the heat treatment, a magnetic field of 1 kA/m was applied in a direction aligned with the magnetic path of the core, and the temperature was elevated to an optimum heat-treating temperature between 320°C and 370°C, at which the highest saturation magnetic flux density and other soft magnetic properties were obtained, over 2 hours, kept at each heat-treating temperature for 1 hour, and

then cooled to 200°C over 1 hour. The heat-treated ribbons were mostly amorphous. The resultant toroidal magnetic cores were measured with respect to a saturation magnetic flux density Bs, a magnetic flux density B_{80} in a magnetic field of 80 A/m, a core loss $W_{13/50}$ in a magnetic flux density of 1.3 T at a frequency of 50 Hz, and core loss $W_{14/50}$ in a magnetic flux density of 1.4 T at a frequency of 50 Hz.

[0032] As shown in Fig. 4, each Fe-based amorphous alloy ribbon 10 cut to a length of 10.5 ($\pi \cdot R_0$) cm was wound around a quartz pipe 11 having a diameter of R_0 cm to form a single-plate sample and heat-treated under the same conditions as above to relax stress during working to a ring. A diameter R_1 of a circle corresponding to the C-shaped sample 10' freed from the quartz pipe 11 was measured to determine a stress relaxation rate Rs expressed by the formula: $Rs = (R_0/R_1) \times 100$ [%], as a parameter expressing to which extent stress is relaxed by the annealing (heat treatment). The stress relaxation rate Rs of 100% means that the stress is completely relaxed.

[0033] The results are shown in Table 1.

Table 1

Sample No.	Composition	Bs [T]	B_{80} [T]	$W_{13/50}$ [W/kg]	$W_{14/50}$ [W/kg]	Rs [%]
1-1	$Fe_{82}Si_2B_{15.95}Cr_{0.05}$	1.64	1.62	0.27	0.35	92.5
1-2	$Fe_{82}Si_2B_{15.9}Cr_{0.1}$	1.64	1.63	0.20	0.26	95.7
1-3	$Fe_{82}Si_2B_{15.5}Cr_{0.5}$	1.62	1.51	0.20	0.24	98.8
1-4	$Fe_{82}Si_2B_{15}Cr_1$	1.60	1.50	0.24	0.30	99.0
1-5	$Fe_{82}Si_2B_{15.98}Ni_{0.02}$	1.64	1.60	0.28	0.36	92.3
1-6	$Fe_{82}Si_2B_{15.9}Ni_{0.1}$	1.64	1.57	0.21	0.28	95.1
1-7	$Fe_{82}Si_2B_{15.5}Ni_{0.5}$	1.63	1.57	0.21	0.29	97.0
1-8	$Fe_{82}Si_2B_{15}Ni_1$	1.60	1.54	0.25	0.33	97.2
1-9	$Fe_{82}Si_2B_{15.8}Cr_{0.1}Ni_{0.1}$	1.62	1.58	0.27	0.37	93.1
1-10	$Fe_{82}Si_2B_{15.5}Cr_{0.3}Ni_{0.2}$	1.61	1.56	0.23	0.31	95.2
1-11	$Fe_{82}Si_2B_{15}Cr_{0.5}Ni_{0.5}$	1.60	1.52	0.25	0.33	97.3
1-12	$Fe_{83.9}Si_{0.1}B_{15.9}Cr_{0.1}$	1.63	1.61	0.31	0.44	94.4
1-13	$Fe_{83}Si_1B_{15.9}Cr_{0.1}$	1.64	1.62	0.22	0.29	94.7
1-14	$Fe_{81}Si_3B_{15.9}Cr_{0.1}$	1.62	1.60	0.22	0.27	95.1
1-15	$Fe_{83.9}Si_2B_{14}Cr_{0.1}$	1.64	1.63	0.21	0.26	96.0
1-16	$Fe_{80.9}Si_2B_{17}Cr_{0.1}$	1.61	1.56	0.22	0.29	95.6
1-17	$Fe_{81.5}Si_{0.01}B_{17.99}Ni_{0.5}$	1.68	1.65	0.28	0.37	92.1
1-18	$Fe_{80}Si_{0.01}B_{17.99}Ni_2$	1.68	1.66	0.30	0.35	92.5
1-19	$Fe_{77}Si_{0.01}B_{17.99}Ni_5$	1.65	1.63	0.32	0.35	93.3
1-20	$Fe_{81.5}Si_1B_{17}Ni_{0.5}$	1.67	1.65	0.29	0.35	93.4
1-21	$Fe_{80}Si_1B_{17}Ni_2$	1.67	1.65	0.29	0.36	93.3
1-22	$Fe_{77}Si_1B_{17}Ni_5$	1.65	1.63	0.31	0.38	95.6
1-23	$Fe_{81.5}Si_2B_{16}Ni_{0.5}$	1.68	1.65	0.25	0.31	93.0
1-24	$Fe_{80}Si_2B_{16}Ni_2$	1.67	1.65	0.24	0.29	93.2
1-25	$Fe_{77}Si_2B_{16}Ni_5$	1.65	1.62	0.28	0.37	93.1
1-26*	$Fe_{82}Si_{0.01}B_{17.99}$	1.64	1.63	0.38	0.49	90.2
1-27*	$Fe_{82}Si_1B_{17}$	1.64	1.63	0.35	0.48	91.3
1-28*	$Fe_{82}Si_2B_{16}$	1.64	1.62	0.30	0.41	92.2
1-29*	$Fe_{72}Si_{0.01}B_{17.99}Ni_{10}$	1.58	1.57	-	-	-
1-30*	$Fe_{72}Si_1B_{17}Ni_{10}$	1.58	1.55	-	-	-

Table continued

Sample No.	Composition	Bs [T]	B_{80} [T]	$W_{13/50}$ [W/kg]	$W_{14/50}$ [W/kg]	Rs [%]
1-31*	$Fe_{72}Si_2B_{16}Ni_{10}$	1.64	1.61	0.35	0.51	89.9
1-32*	$Fe_{82}Si_2B_{10}Cr_6$	1.55	1.49	-	-	-
1-33*	$Fe_{82}Si_2B_{10}Ni_6$	1.58	1.48	-	-	-
1-34*	$Fe_{82}Si_2B_6Cr_5Ni_5$	1.51	1.45	-	-	-
1-35* *	$Fe_{79}Si_6B_{15.95}Cr_{0.05}$	1.58	1.55	-	-	-
1-36*	$Fe_{76}Si_8B_{15.95}Cr_{0.05}$	1.52	1.45	-	-	-
1-37*	$Fe_{84.9}Si_{10}B_5Cr_{0.1}$	1.61	1.57	0.39	0.59	92.4
1-38*	$Fe_{75.9}Si_2B_{22}Cr_{0.1}$	1.50	1.45	-	-	-
Note: * A sample outside the present invention.						

[0034] It is clear from Table 1 that Samples 1-1 to 1-25 have larger stress relaxation rates Rs than those of Samples 1-26 to 1-28, 1-31 and 1-37, so that their stress generated when worked to rings was sufficiently relaxed. More improvement was obtained in Samples 1-1 to 1-25 than in Samples 1-26 to 1-38 with respect to the core losses $W_{13/50}$ and $W_{14/50}$.

[0035] When an alloy having a low magnetic flux density is used at an operating magnetic flux density of 1.3 T or more, it suffers from an extremely large core loss, for instance, $W_{14/50}$, unsuitable as a magnetic core material. However, because the Fe-based amorphous alloy ribbon of the present invention has as high a saturation magnetic flux density as 1.6 T or more, its operating magnetic flux density can be increased to 1.4 T, so that its core loss $W_{14/50}$ is so small that the magnetic core can withstand practical applications. Accordingly, the Fe-based amorphous alloy ribbon of the present invention can provide smaller and higher-performance magnetic cores than conventional ones.

Example 2

[0036] Samples 2-1 to 2-11 and 2-12 to 2-16 of various compositions were produced and heat-treated in the same manner as in Example 1. The core loss increase ratio Wr of each resultant Fe-based amorphous alloy ribbon is shown in Table 2 together with a composition, a heat treatment temperature, a saturation magnetic flux density Bs, a stress relaxation rate Rs, an average surface roughness Ra, and a space factor. The saturation magnetic flux density Bs and the stress relaxation rate Rs were measured in the same manner as in Example 1.

[0037] The core loss increase ratio Wr is a parameter expressing an increase ratio of the core loss when the operating magnetic flux density increases from 1.3 T to 1.4 T, which is represented by the following equation:

$$Wr = (W_{14/50} - W_{13/50}) / W_{13/50} \times 100\ [\%] \quad \ldots (2),$$

wherein $W_{13/50}$ represents a core loss at a magnetic flux density of 1.3 T and a frequency of 50 Hz, and $W_{14/50}$ represents a core loss at a magnetic flux density of 1.4 T and a frequency of 50 Hz. In Sample 2-12, stress generated when worked to a toroidal magnetic core was not sufficiently relaxed, and its saturation magnetic flux density was small. Accordingly, it had drastically increased core loss with large Wr at an operating magnetic flux density of 1.4T. Though Sample 2-13 had a high saturation magnetic flux density, it had large Wr because of a low relaxation rate of stress generated when worked to a toroidal magnetic core. Because Samples 2-1 to 2-11 containing proper amounts of Cr or Ni had stress sufficiently relaxed by a heat treatment, and high saturation magnetic flux density, their core loss increase ratios Wr were smaller than those of Samples 2-12 and 2-13.

[0038] To measure surface roughness, each Fe-based amorphous alloy ribbon was cut to a rectangular shape of 5 mm in width, 25 μm in thickness and 12 cm in length, and heat-treated in the same manner as above. The measured surface roughness was arithmetically averaged in a width direction of the ribbon. The space factor of a magnetic core constituted by each Fe-based amorphous alloy ribbon was further measured. In general, the smaller the surface roughness Ra, the larger the space factor of the magnetic core. The addition of Cr and/or Ni in proper amounts serves to reduce the melt viscosity of the alloy, thereby making a roll well wettable by the alloy melt. Accordingly, the resultant amorphous alloy ribbon has a smoother surface than those of conventional amorphous alloy ribbons containing no Cr or Ni. The Fe-based amorphous alloy ribbon with a smoother surface provides a magnetic core with a larger space factor, thereby making the magnetic core smaller and lighter in weight.

Table 2

Sample No.	Composition	Bs [T]	Wr [%]	Rs [%]	Ra(1) [μm]	Space Factor [%]
2-1	$Fe_{82}Si_2B_{15.95}Cr_{0.05}$	1.64	29.6	92.5	0.28	87
2-2	$Fe_{82}Si_2B_{15.9}Cr_{0.1}$	1.64	30.0	95.7	0.28	88
2-3	$Fe_{82}Si_2B_{15.5}Cr_{0.5}$	1.62	20.0	98.8	0.26	87
2-4	$Fe_{83.9}Si_2B_{14}Cr_{0.1}$	1.64	28.3	96.0	0.31	88
2-5	$Fe_{80.9}Si_2B_{17}Cr_{0.1}$	1.61	31.8	95.6	0.33	87
2-6	$Fe_{81.5}Si_1B_{17}Ni_{0.5}$	1.67	20.7	93.4	0.25	91
2-7	$Fe_{80}Si_1B_{17}Ni_2$	1.67	24.1	93.3	0.26	90
2-8	$Fe_{77}Si_1B_{17}Ni_5$	1.65	22.6	95.6	0.41	86
2-9	$Fe_{81.5}Si_2B_{16}Ni_{0.5}$	1.68	24.0	93.0	0.29	93
2-10	$Fe_{80}Si_2B_{16}Ni_2$	1.67	20.8	93.2	0.23	92
2-11	$Fe_{77}Si_2B_{16}Ni_5$	1.65	32.1	93.1	0.36	89
2-12*	$Fe_{79}Si_9B_{12}$	1.58	32.5	90.1	0.44	86
2-13*	$Fe_{82}Si_2B_{16}$	1.64	36.7	92.2	0.45	85
2-14*	$Fe_{81.5}Si_2B_{16}Co_{0.5}$	1.68	25.1	94.2	0.25	86
2-15*	$Fe_{80}Si_2B_{16}Co_2$	1.69	23.3	94.3	0.25	87
2-16*	$Fe_{77}Si_2B_{16}Co_5$	1.71	31.2	93.1	0.28	90

Note: * A sample outside the present invention.

(1) Arithmetically averaged surface roughness.

[0039] Toroidal magnetic cores produced by ribbons of Samples 2-12 and 2-13 had smaller saturation magnetic flux densities Bs than those of the single-plate samples of the same composition because of stress generated when worked to the magnetic cores. On the other hand, because stress was sufficiently relaxed by a heat treatment in the toroidal magnetic cores produced by the ribbons of Samples 2-1 to 2-11 within the scope of the present invention, there was only small decrease in the saturation magnetic flux density, and their decrease ratios were extremely smaller than those of Samples 2-12 and 2-13.

[0040] When elements for improving core loss and corrosion resistance are added to the Fe-based amorphous alloy, the magnetic characteristics of the alloy are generally likely to be deteriorated. However, the Fe-based amorphous alloy ribbons of the present invention containing proper amounts of Cr and/or Ni effective for stress relaxation have comparable saturation magnetic flux densities to those of the alloys containing neither Cr nor Ni. Accordingly, the Fe-based amorphous alloy ribbons of the present invention have excellent magnetic characteristics, suitable for magnetic cores for transformers, because stress generated during producing magnetic cores is sufficiently relaxed.

[0041] As well known, the addition of Co increases the saturation magnetic flux density of the Fe-based amorphous alloy. Samples 2-14 to 2-16 containing Co had large saturation magnetic flux density and space factor. However, the addition of Co increases the cost of the Fe-based amorphous alloy because Co is a rare metal. On the other hand, Ni and Cr are less expensive than Co. If Ni or Cr is added in a proper amount, the Fe-based amorphous alloy is provided with improved magnetic flux density and space factor as in the addition of Co. Accordingly, the addition of Ni and/or Cr in proper amounts is effective to provide the Fe-based amorphous alloy ribbon with sufficiently relaxed stress and excellent magnetic properties, which enables the production of small, lightweight magnetic cores.

Example 3

[0042] Alloy melts having compositions represented by $Fe_aSi_bB_cC_dM_x$ ($a + b + c + d + x = 100$) as shown in Table 3 were rapidly quenched by a single roll method, to form Fe-based amorphous alloy ribbons of 5 mm in width and 25 μm in thickness. Each of the resultant Fe-based amorphous alloy ribbons was wound to form a toroidal magnetic core of 19 mm in outer diameter and 15 mm in inner diameter, and heat-treated in the same manner as in Example 1. The heat-treated alloys were mostly amorphous.

[0043] Each Sample was measured in the same manner as in Example 1 with respect to a saturation magnetic flux density Bs, a magnetic flux density B80 in a magnetic field of 80 A/m, a core loss $W_{13/50}$ at a magnetic flux density of 1.3 T and a frequency of 50 Hz, a core loss $W_{14/50}$ at a magnetic flux density of 1.4 T and a frequency of 50 Hz, and a stress relaxation rate Rs. The results are shown in Table 3.

Table 3

Sample No.	Composition	Bs [T]	B_{80} [T]	$W_{13/50}$ [W/kg]	$W_{14/50}$ [W/kg]	Rs [%]
3-1	$Fe_{82}Si_2B_{13.95}C_2Cr_{0.05}$	1.64	1.61	0.28	0.38	95.2
3-2	$Fe_{82}Si_2B_{13.9}C_2Cr_{0.1}$	1.64	1.61	0.20	0.23	97.2
3-3	$Fe_{82}Si_2B_{13.5}C_2Cr_{0.5}$	1.63	1.60	0.21	0.25	99.5
3-4	$Fe_{82}Si_2B_{13}C_2Cr_1$	1.62	1.54	0.25	0.30	99.2
3-5	$Fe_{82}Si_2B_{13.98}C_2Ni_{0.02}$	1.64	1.61	0.28	0.38	95.0
3-6	$Fe_{82}Si_2B_{13.9}C_2Ni_{0.1}$	1.63	1.59	0.23	0.29	95.1
3-7	$Fe_{82}Si_2B_{13.5}C_2Ni_{0.5}$	1.63	1.57	0.26	0.30	98.3
3-8	$Fe_{82}Si_2B_{13}C_2Ni_1$	1.62	1.55	0.27	0.33	99.0
3-9	$Fe_{81.5}Si_2B_{14}C_2Ni_{0.5}$	1.67	1.63	0.28	0.31	94.9
3-10	$Fe_{80}Si_2B_{14}C_2Ni_2$	1.67	1.64	0.25	0.31	95.1
3-11	$Fe_{77}Si_2B_{14}C_2Ni_5$	1.66	1.63	0.27	0.35	95.0
3-12	$Fe_{82}Si_2B_{13.8}C_2Cr_{0.1}Ni_{0.1}$	1.63	1.61	0.23	0.28	93.0
3-13	$Fe_{82}Si_2B_{13.5}C_2Cr_{0.3}Ni_{0.2}$	1.63	1.60	0.25	0.30	96.3
3-14	$Fe_{82}Si_2B_{13}C_2Cr_{0.5}Ni_{0.5}$	1.60	1.57	0.28	0.35	97.3
3-15	$Fe_{83.9}Si_{0.1}B_{13.9}C_2Cr_{0.1}$	1.64	1.60	0.35	0.47	94.5
3-16	$Fe_{83}Si_1B_{13.9}C_2Cr_{0.1}$	1.63	1.61	0.23	0.28	96.8
3-17	$Fe_{81}Si_3B_{13.9}C_2Cr_{0.1}$	1.62	1.61	0.24	0.27	97.1
3-18	$Fe_{80.9}Si_2B_{15}C_2Cr_{0.1}$	1.61	1.53	0.25	0.31	96.8
3-19	$Fe_{78.9}Si_2B_{17}C_2Cr_{0.1}$	1.60	1.52	0.26	0.32	95.4
3-20*	$Fe_{82}Si_2B_{14}C_2$	1.65	1.63	0.29	0.39	94.9
3-21 *	$Fe_{79}Si_2B_{11}C_2Cr_6$	1.54	1.48	-	-	-
3-22*	$Fe_{79}Si_2B_{11}C_2Ni_6$	1.51	1.45	-	-	-
3-23*	$Fe_{76}Si_2B_{10}C_2Cr_5Ni_5$	1.50	1.39	-	-	-
3-24*	$Fe_{77}Si_5B_{17.87}C_{0.08}Cr_{0.05}$	1.57	1.45	-	-	-
3-25*	$Fe_{77}Si_5B_{14.95}C_3Cr_{0.05}$	1.58	1.46	-	-	-
3-26*	$Fe_{77}Si_5B_{11.95}C_6Cr_{0.05}$	1.52	1.45	-	-	-
3-27*	$Fe_{76}Si_8B_{13.9}C_2Cr_{0.1}$	1.52	1.44	-	-	-
3-28*	$Fe_{82.9}Si_{10}B_5C_2Cr_{0.1}$	1.62	1.60	0.29	0.42	94.6
3-29*	$Fe_{73.9}Si_2B_{22}C_2Cr_{0.1}$	1.51	1.44	-	-	-
Note: * A sample outside the present invention.						

[0044] It is clear from Table 3 that Samples 3-1 to 3-19 had improved core losses $W_{13/50}$ and $W_{14/50}$ than those of Samples 3-21 to 3-29.

Example 4

[0045] The same alloy melts as in Examples 1 to 3 were rapidly quenched by a single roll method, to obtain Fe-based amorphous alloy ribbons of 25 μm in thickness and 50 mm in width. Each ribbon was wound to a toroidal magnetic core of 19 mm in outer diameter and 15 mm in inner diameter for a transformer by a cut-lap or step-lap method, and heat-treated in the same manner as in Example 1. Because proper amounts of Cr and/or Ni were contained in the amorphous alloys, stress generated when worked to rings was sufficiently relaxed by the heat treatment, resulting in magnetic cores for transformers having narrow gaps and excellent magnetic characteristics.

[0046] The Fe-based amorphous alloy ribbons of the present invention having high saturation magnetic flux densities and low magnetic core losses are usable for power transformers and reactors, noise reduction parts such as choke coils for active filters, smoothing choke coils, common-mode choke coils, electromagnetic shields, etc., laser power supplies, parts for pulse power circuits of accelerators, motors, generators, etc. Because stress is sufficiently relaxed by a heat treatment for a relatively short period of time in the Fe-based amorphous alloy ribbons of the present invention, which contain proper amounts of Cr and/or Ni, they are suitable for mass production. Particularly in magnetic cores for power source transformers worked by a cut-lap or step-lap method as shown in Fig. 3, the deterioration of magnetic characteristics and magnetic core losses can be made extremely small.

[0047] The addition of Cr and/or Ni in proper amounts lowers the viscosity of the alloy melt, thereby making a roll well wettable by the alloy melt and thus improving the surface conditions of the resultant Fe-based amorphous alloy ribbon. The alloy ribbon with a smooth surface makes it possible to produce small, lightweight magnetic cores with high space factors.

Claims

1. An Fe-based amorphous alloy ribbon having excellent magnetic characteristics, which is represented by the general formula: $Fe_aSi_bB_cM_x$, wherein M is Cr and/or Ni, *a* is 78 to 86 atomic %, *b* is 0.001 to 5 atomic %, c is 7 to 20 atomic %, and x is 0.01 to 5 atomic %, $(a + b + c + x)$ being 100.

2. The alloy ribbon of claim 1, wherein
a is 78 to 85 atomic *%, b* is 0.001 to 3 atomic %, c is 10 to 20 atomic %, and x is 0.02 to 4 atomic %, and
said alloy ribbon (10) has a saturation magnetic flux density of 1.65 T or more, and a magnetic flux density of 1.6 T or more in a magnetic field of 80 A/m.

3. An Fe-based amorphous alloy ribbon having excellent magnetic characteristics, which is represented by the general formula: $Fe_aSi_bB_cC_dM_x$, wherein M is Cr and/or Ni, *a* is 78 to 86 atomic *%, b* is 0.001 to 5 atomic %, c is 7 to 20 atomic %, *d* is 0.001 to 4 atomic %, and x is 0.01 to 5 atomic %, $(a + b + c + d + x)$ being 100.

4. The alloy ribbon of claim 3, wherein
a is 78 to 85 atomic %, *b* is 0.001 to 3 atomic %, c is 10 to 20 atomic %, *d* is 0.01 to 3 atomic %, and *x* is 0.02 to 4 atomic %, and
said alloy ribbon (10) has a saturation magnetic flux density of 1.65 T or more, and a magnetic flux density of 1.6 T or more in a magnetic field of 80 A/m.

5. The alloy ribbon of claim 1 or 3, having a saturation magnetic flux density of 1.6 T or more, and a magnetic flux density of 1.5 T or more in a magnetic field of 80 A/m.

6. The alloy ribbon of claim 1 or 3, wherein M is Cr, and *x* is 0.01 to 1 atomic %.

7. The alloy ribbon of claim 1 or 3, wherein M is Ni, and *x* is 0.1 to 5 atomic %.

8. A magnetic core (1) constituted by the Fe-based amorphous alloy ribbon (10) recited in any preceding claim, which is provided with a shape for a transformer by a cut-lap or step-lap method.

Fig. 1(a)

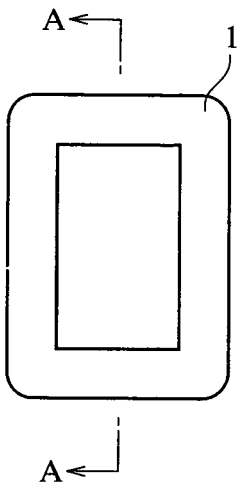

Fig. 1(b)

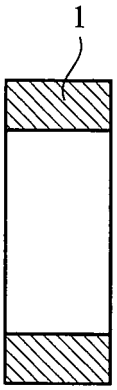

Fig. 2(a)

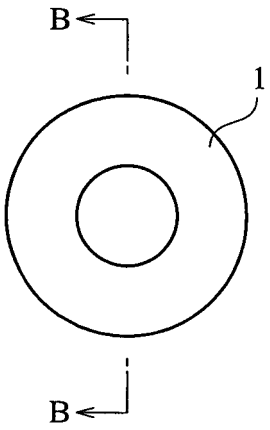

Fig. 2(b)

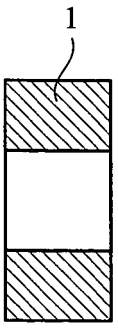

Fig. 3(a)

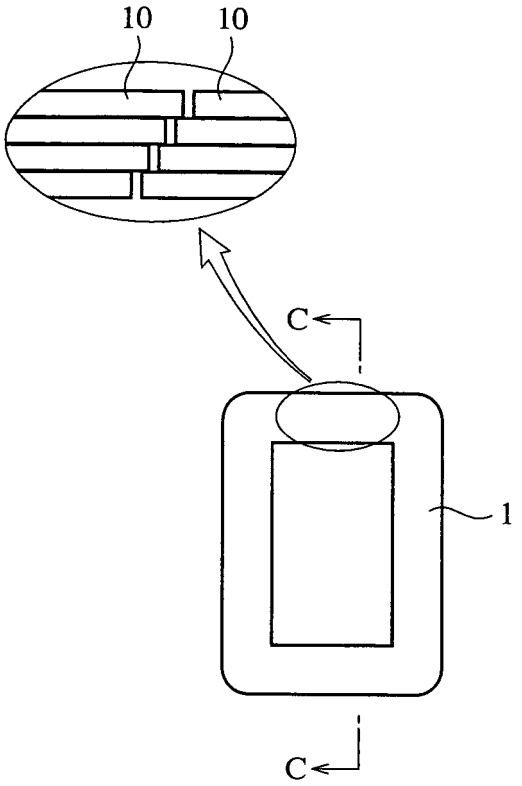

Fig. 3(b)

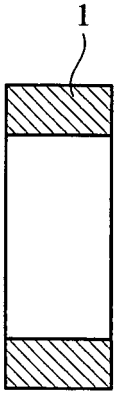
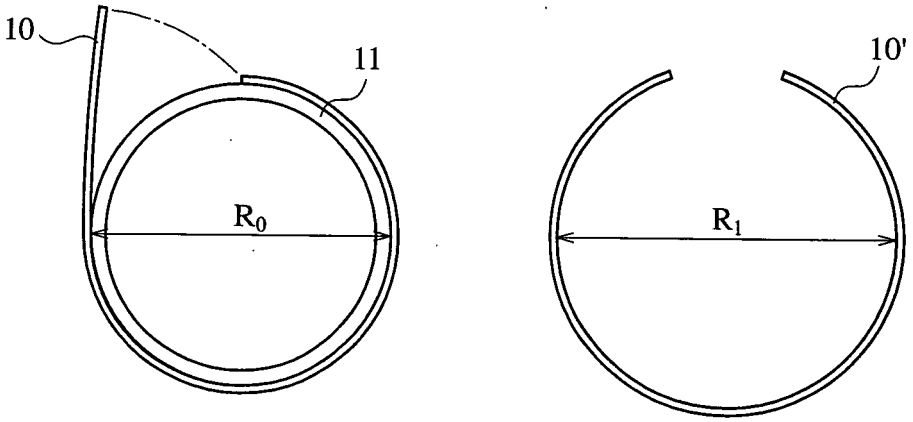
Fig. 4