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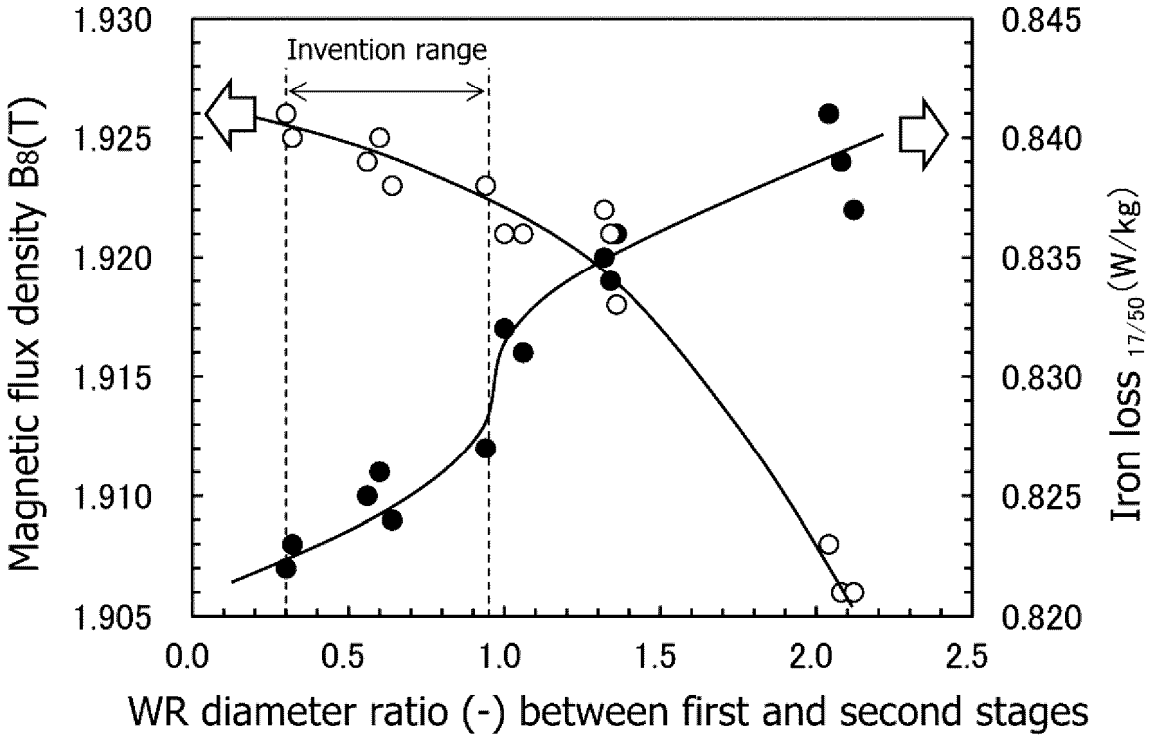
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(54) METHOD FOR COLD ROLLING GRAIN-ORIENTED ELECTROMAGNETIC STEEL SHEET, METHOD FOR MANUFACTURING SAME, AND COLD ROLLING EQUIPMENT TRAIN

(57) Provided is a method capable of stably and productively producing a grain-oriented electrical steel sheet with excellent magnetic properties when performing cold rolling using a single-stand rolling mill. Specifically, provided is a cold rolling method for a grain-oriented electrical steel sheet, including, in forming a cold-rolled sheet with a final thickness by performing cold rolling with the total rolling reduction rate set to 80% or higher, dividing the cold rolling into first-stage cold rolling and second-stage cold rolling; performing, during the first-stage cold rolling, cold rolling using a tandem rolling mill to obtain an intermediate thickness; and performing, during the second-stage cold rolling, cold rolling through one to three passes using a single-stand rolling mill, with the ratio of the work roll diameter of the single-stand rolling mill to the work roll diameter of the final stand of the tandem rolling mill used in the first-stage cold rolling set in the range of 0.30 to 0.95, to obtain a final thickness following the intermediate thickness, thereby achieving the best value of the magnetic flux density B_8 of the resulting product sheet in the sheet width direction of 1.920 T or higher. Also provided are a method for producing a grain-oriented electrical steel sheet using the cold rolling method, and a cold rolling equipment line used for the cold rolling.

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[Fig. 1]


Invention range
Magnetic flux density B8(T)
Iron loss W17/50(W/kg)
WR diameter ratio (-) between first and second stages
1.930
1.925
1.920
1.915
1.910
1.905
0.845
0.840
0.835
0.830
0.825
0.820
0.0
0.5
1.0
1.5
2.0
2.5

Description

Technical Field

[0001] The present invention relates to a cold rolling method for a grain-oriented electrical steel sheet, a method for producing a grain-oriented electrical steel sheet with excellent magnetic properties using the cold rolling method, and a cold rolling equipment line suitable for the cold rolling method. In this specification, the numerical range "x to y" represents x or more and y or less, including the boundary values.

Background Art

[0002] Grain-oriented electrical steel sheets are steel sheets with excellent magnetic properties, having a crystal structure in which the <001> orientation, which corresponds to the magnetic easy axis of iron, is highly aligned with the rolling direction of the steel sheets (known as "Goss orientation"). Such grain-oriented electrical steel sheets are typically produced using a steel material having a Si content of about 4.5 mass% or less. Many of such grain-oriented electrical steel sheets further contain components for forming inhibitors, such as MnS, MnSe, and AlN, to induce secondary recrystallization.

[0003] Meanwhile, Patent Literature 1 proposes a method for inducing secondary recrystallization without using inhibitor-forming components, known as the "inhibitor-free method." This inhibitor-free method is advantageous in that it enables low-cost production of grain-oriented electrical steel sheets, as it eliminates the need for high-temperature slab heating required when inhibitors are used. However, such a method relies on texture control performed with a highly purified steel material (hereinafter also referred to as "texture inhibition") to induce secondary recrystallization. Therefore, delicate control is required to form a favorable texture.

[0004] In the production of a grain-oriented electrical steel sheet, the cold rolling conditions are important from the viewpoint of appropriately controlling a texture. In particular, in the production of a grain-oriented electrical steel sheet using a steel material free of inhibitor-forming components, the cold rolling conditions are critical as the quality of a texture greatly affects the quality of magnetic properties.

[0005] As a method for forming a favorable texture, for example, Patent Literature 2 proposes a method of performing heat treatment (i.e., aging treatment) on a steel sheet at a low temperature during cold rolling. In addition, Patent Literature 3 proposes a method for setting the cooling rate to 30°C/s or higher during hot-rolled sheet annealing or annealing performed before finishing cold rolling (i.e., final cold rolling), and further performing, during the finishing cold rolling, aging between rolling passes at a sheet temperature of 150 to 300°C for 2 minutes or longer two or more times. Furthermore, Patent Literature 4 proposes a method for performing warm rolling on a steel sheet by increasing its temperature during rolling to utilize the dynamic aging effect, in which dislocations introduced during rolling are immediately pinned by C (carbon) and N (nitrogen).

[0006] These methods involve diffusing C (carbon) and N (nitrogen), which are solid solution elements, at a low temperature to pin dislocations introduced during rolling. By inhibiting dislocation motions in such a manner, it is intended to induce shear deformation during the following cold rolling, thereby improving the rolled texture. Applying this method can reduce the (111) fiber texture called Υ-fibers in a primary recrystallization texture obtained after the cold rolling. Therefore, it is possible to obtain the effect of increasing the occurrence frequency of the {110}<001> orientation, known as the Goss orientation, that is advantageous for magnetic properties.

[0007] As a rolling mill used for the aforementioned cold rolling, a single-stand reverse rolling mill (for example, refer to Patent Literature 5) or a tandem rolling mill including a plurality of stands (for example, refer to Patent Literature 6) is typically used. However, from the viewpoint of applying the aforementioned methods, it is considered advantageous to use a reverse rolling mill capable of performing so-called "aging treatment" by holding a rolled steel sheet, which has been coiled at a high temperature, for a long time.

Citation List

Patent Literature

[0008]

Patent Literature 1: JP-A-2000-129356
Patent Literature 2: JP-A-S50-16610
Patent Literature 3: JP-A-H08-253816
Patent Literature 4: JP-A-H01-215925
Patent Literature 5: JP-A-S54-013846

Patent Literature 6: JP-A-S54-029182

Summary of Invention

Technical Problem

[0009] As described above, each of the conventional methods disclosed in Patent Literatures 2 to 4 involves holding a steel sheet, during or after rolling, at a high temperature to promote the diffusion of C and N in steel, thereby utilizing the effect of the aging treatment, where dislocations introduced during rolling are pinned. Therefore, regarding a case where a tandem rolling mill is used, various studies have been conducted based, naturally, on the premise that extremely short aging treatment is performed between adjacent stands. Meanwhile, regarding a case where a reverse rolling mill is used, various studies have been conducted based on the premise that relatively long aging treatment is performed after coiling. However, such aging treatment involves significant equipment constraints, and thus is problematic. For example, to secure 1-hour aging treatment, it is necessary to interrupt rolling for 1 hour during reverse rolling, which significantly impairs productivity.

[0010] The present invention has been made in view of the aforementioned problems of the conventional methods, and an object of the present invention is to provide a method capable of stably and productively producing a grain-oriented electrical steel sheet with excellent magnetic properties when performing cold rolling using a single-stand rolling mill. Specifically, an object of the present invention is to propose a cold rolling method for a grain-oriented electrical steel sheet, and a method for producing a grain-oriented electrical steel sheet using the cold rolling method, and also provide a cold rolling equipment line suitable for such methods.

Solution to Problem

[0011] To solve the aforementioned problems, the inventors have conducted extensive studies by focusing on the conditions for cold rolling performed on a hot-rolled steel sheet. Consequently, the inventors have arrived at the present invention by finding that it is possible to productively and stably produce a grain-oriented electrical steel sheet with excellent magnetic properties by dividing the cold rolling into first-stage cold rolling and second-stage cold rolling, and performing the first-stage cold rolling using a tandem rolling mill and performing the second-stage cold rolling using a single-stand rolling mill, and also controlling the rolling reduction ratio as well as the work roll diameter ratio between the first-stage cold rolling and the second-stage cold rolling to be in an appropriate range.

[0012] The present invention based on the aforementioned findings proposes (i) a cold rolling method for a grain-oriented electrical steel sheet including performing cold rolling with a total rolling reduction rate of 80% or higher to form a cold-rolled sheet with a final thickness, wherein

the cold rolling is divided into first-stage cold rolling and second-stage cold rolling;
optionally, intermediate annealing is performed between the first-stage cold rolling and the second-stage cold rolling;
after the first-stage cold rolling, the steel sheet is coiled at a temperature of 80°C or higher, and the second-stage cold rolling is performed after at least 30 minutes have elapsed from the completion of the coiling;
an annealing temperature is set to 700°C or lower when performing the intermediate annealing;
during the first-stage cold rolling, the steel sheet is cold rolled using a tandem rolling mill, with a ratio of rolling reduction during the first-stage cold rolling to a total rolling reduction over the course of the cold rolling being set in a range of 0.50 to 0.95, to obtain an intermediate thickness;
during the second-stage cold rolling, the steel sheet is cold rolled through one to three passes using a single-stand rolling mill to obtain a final thickness from the intermediate thickness; and
a ratio of a work roll diameter of the single-stand rolling mill to a work roll diameter of a final stand of the tandem rolling mill is set in a range of 0.30 to 0.95, thereby achieving a best value of magnetic flux density B_8 of a resulting product sheet in a sheet width direction of 1.920 T or higher.

[0013] The cold rolling method for a grain-oriented electrical steel sheet according to the present invention may include the following feature as more preferable means: (ii) the second-stage cold rolling is performed by using a single-stand rolling mill with the work roll diameter changed, or using a plurality of single-stand rolling mills with different work roll diameters.

[0014] The present invention also provides a method for producing a grain-oriented electrical steel sheet, including forming a hot-rolled sheet by performing hot rolling on a steel slab having a chemical composition including C: 0.01 to 0.10 mass%, Si: 2.0 to 4.5 mass%, and Mn: 0.01 to 0.5 mass%, and further including, as an inhibitor-forming component, at least one group of components selected from among Group A: sol. Al: 0.010 to 0.05 mass% and N: 0.004 to 0.012 mass%, Group B: at least one of S and Se: a total of 0.01 to 0.05 mass%, and Group C: sol. Al: 0.010 to 0.05 mass%, N: 0.004 to

0.012 mass%, and at least one of S and Se: a total of 0.01 to 0.05 mass%, and further optionally including at least one component selected from the group consisting of Ni: 0.005 to 1.50 mass%, Cr: 0.005 to 0.3 mass%, Cu: 0.005 to 0.3 mass%, Sn: 0.005 to 0.3 mass%, Sb: 0.005 to 0.3 mass%, Mo: 0.005 to 0.3 mass%, Te: 0.005 to 0.3 mass%, Bi: 0.005 to 0.3 mass%, and P: 0.005 to 0.3 mass%, with a balance being Fe and unavoidable impurities; performing cold rolling on the hot-rolled sheet with a total rolling reduction rate of 80% or higher to obtain a cold-rolled sheet with a final thickness; performing primary recrystallization annealing, which also serves as decarburization annealing, on the cold-rolled sheet; applying an annealing separator to a surface of the steel sheet; and performing finishing annealing including inducing secondary recrystallization and subsequent purification, wherein the cold rolling is performed by applying any of the aforementioned cold rolling methods, thereby achieving a best value of magnetic flux density B_8 in a sheet width direction of 1.920 T or higher.

[0015] The present invention also provides a method for producing a grain-oriented electrical steel sheet, including forming a hot-rolled sheet by performing hot rolling on a steel slab having a chemical composition including C: 0.01 to 0.10 mass%, Si: 2.0 to 4.5 mass%, and Mn: 0.01 to 0.5 mass%, and further including sol. Al: less than 0.010 mass%, S: 0.0050 mass% or less, Se: 0.0050 mass% or less, and N: 0.0050 mass% or less, and further optionally including at least one component selected from the group consisting of Ni: 0.005 to 1.50 mass%, Cr: 0.005 to 0.3 mass%, Cu: 0.005 to 0.3 mass%, Sn: 0.005 to 0.3 mass%, Sb: 0.005 to 0.3 mass%, Mo: 0.005 to 0.3 mass%, Te: 0.005 to 0.3 mass%, Bi: 0.005 to 0.3 mass%, and P: 0.005 to 0.3 mass%, with a balance being Fe and unavoidable impurities; performing cold rolling on the hot-rolled sheet with a total rolling reduction rate of 80% or higher to obtain a cold-rolled sheet with a final thickness; performing primary recrystallization annealing, which also serves as decarburization annealing, on the cold-rolled sheet; applying an annealing separator to a surface of the steel sheet; and performing finishing annealing including inducing secondary recrystallization and subsequent purification, wherein the cold rolling is performed by applying any of the aforementioned cold rolling methods, thereby achieving a best value of magnetic flux density B_8 in a sheet width direction of 1.920 T or higher.

[0016] In addition, the present invention provides a cold rolling equipment line including a first-stage cold rolling mill and a second-stage cold rolling mill for use in the cold rolling method according to (i) above, wherein the first-stage cold rolling mill is a tandem rolling mill, and the second-stage cold rolling mill is a single-stand rolling mill, and a ratio of a work roll diameter of the second-stage cold rolling mill to a work roll diameter of a final stand of the tandem rolling mill is in a range of 0.30 to 0.95.

[0017] The cold rolling equipment line according to the present invention may be a cold rolling equipment line including a first-stage cold rolling mill and a second-stage cold rolling mill for use in the cold rolling method according to (ii) above, and may include the following feature as more preferable means: the first-stage cold rolling mill is a tandem rolling mill, and the second-stage cold rolling mill is a single-stand rolling mill, and the second-stage cold rolling mill includes a single-stand rolling mill with an adjustable work roll diameter, or a plurality of single-stand rolling mills with different work roll diameters.

[0018] The cold rolling equipment line according to the present invention may include, as more preferable means, at least one of the following configurations: (1) the tandem rolling mill has a function of controlling a coiling temperature by adjusting at least one of a temperature and a flow rate of a coolant to be sprayed onto at least one of a steel sheet surface and a work roll surface on an exit side of the final stand; and (2) a heat retention device is provided between the tandem rolling mill and the second-stage rolling mill, the heat retention device being adapted to maintain a steel sheet temperature at 50°C or higher after the first-stage cold rolling.

Advantageous Effects of Invention

[0019] According to the present invention, it is possible to stably produce a grain-oriented electrical steel sheet with excellent magnetic properties.

Brief Description of Drawings

[0020]

[Fig. 1] is a graph illustrating the influence of the work roll diameter ratio (i.e., WR diameter ratio) between a first-stage cold rolling mill and a second-stage cold rolling mill on magnetic flux density and iron losses.

[Fig. 2] is a graph illustrating the influence of the work roll diameter ratio (i.e., WR diameter ratio) between a first-stage cold rolling mill and a second-stage cold rolling mill on magnetic flux density and iron losses and also on their variation in the sheet width direction.

Description of Embodiments

[0021] First, the inventors have conducted the following experiments for producing grain-oriented electrical steel sheets

using steel materials free of inhibitor-forming components, where texture control is particularly important, and studied the conditions necessary to improve magnetic properties.

(Experiment 1)

[0022] Steel materials (i.e., slabs), each containing C: 0.050 mass%, Si: 3.3 mass%, and Mn: 0.04 mass%, and further containing S, Se, and O: less than 0.0050 mass% each and N: less than 0.0025 mass%, with the balance being Fe and unavoidable impurities, were produced by melting and casting. Each steel slab, which is free of inhibitor-forming components, was heated to a temperature of 1100°C, and then hot-rolled to obtain a hot-rolled sheet with a thickness of 3.0 mm. Next, the hot-rolled sheet was subjected to hot-rolled sheet annealing at 1000°C for 70 seconds to obtain a hot-rolled-sheet-annealed sheet. Next, the hot-rolled-sheet-annealed sheet was subjected to first-stage cold rolling that includes cold-rolling the steel sheet by using a 5-stand tandem rolling mill with a final stand work roll diameter of 250 mm and by setting the steel sheet temperature between adjacent stands, from the third stand to the final stand, to 120°C or higher so as to obtain an intermediate thickness shown in Table 1. Then, the resulting steel sheet was coiled. During the coiling, the sheet temperature (i.e., coiling temperature) was measured. The steel sheet with the intermediate thickness was then conveyed to a single-stand rolling mill with a work roll diameter of 200 mm and subjected to cold rolling through one to four passes shown in Table 1 to obtain a cold-rolled sheet with a final thickness of 0.22 mm. During the process, the time interval (i.e., elapsed time) between the end of the first-stage cold rolling and the start of the second-stage cold rolling was varied. The cold-rolled sheet with the final thickness was subjected to primary recrystallization annealing also serving as decarburization annealing. After an annealing separator was applied to the steel sheet surface, the cold-rolled sheet was subjected to finishing annealing, which included secondary recrystallization and subsequent purification, thereby obtaining a product sheet.

[0023] Test specimens for magnetic measurement were taken from the center of the thus-obtained product sheet coil in the longitudinal direction. The magnetic flux density B_8 (magnetic flux density when a magnetic field of 800 A/m is applied) of each test specimen was measured through an Epstein test defined in JIS C 2550. The results are also shown in Table 1. Table 1 also shows the ratio of the rolling reduction during the first-stage cold rolling to the total rolling reduction in the entire cold rolling (i.e., the rolling reduction during the first stage/the total rolling reduction; hereinafter referred to simply as the "rolling reduction ratio"). Herein, the "rolling reduction" refers to the "reduction (mm) in sheet thickness due to rolling."

[0024] From the results in Table 1, it is found that relatively favorable magnetic properties are obtained when the rolling reduction ratio is in the range of 0.50 to 0.95. It is also found that, among the conditions that yield such relatively favorable magnetic properties, the magnetic properties are even more favorable when the coiling temperature after the first-stage cold rolling is 80°C or higher and the time interval (i.e., elapsed time) between the first-stage cold rolling and the second-stage cold rolling is 30 minutes or longer.

[Table 1]

Condition No.	First-stage cold rolling			Time interval (min) between first-stage cold rolling and second-stage cold rolling	The number (times) of passes of second-stage cold rolling	Magnetic flux density B_8 (T)	Remarks
	Sheet thickness (mm) (intermediate thickness) after rolling	Rolling reduction ratio (-)	Coiling temperature (°C)				
1	1.7	0.47	100	60	4	1.903	Comparative Example
2	1.5	0.54	110	40	3	1.924	Invention Example
3	1.0	0.72	110	50	2	1.922	Invention Example
4	0.6	0.86	120	35	2	1.923	Invention Example

(continued)

Condition No.	First-stage cold rolling			Time interval (min) between first-stage cold rolling and second-stage cold rolling	The number (times) of passes of second-stage cold rolling	Magnetic flux density B_8 (T)	Remarks
	Sheet thickness (mm) (intermediate thickness) after rolling	Rolling reduction ratio (-)	Coiling temperature (°C)				
5	0.4	0.94	120	50	1	1.921	Invention Example
6	0.3	0.97	120	55	1	1.902	Comparative Example
7	0.6	0.86	100	50	2	1.922	Invention Example
8	0.6	0.86	80	30	2	1.920	Invention Example
9	0.6	0.86	80	25	2	1.913	Comparative Example
10	0.6	0.86	40	50	2	1.912	Comparative Example

(Experiment 2)

[0025] Steel materials (i.e., slabs), each containing C: 0.03 mass%, Si: 3.2 mass%, and Mn: 0.06 mass%, and further containing S, Se, and O: less than 0.0050 mass% each and N: less than 0.0025 mass%, with the balance being Fe and unavoidable impurities, were produced by melting and casting. Each steel slab, which was free of inhibitor-forming components, was heated to a temperature of 1100°C, and was then hot-rolled to obtain a hot-rolled sheet with a thickness of 3.0 mm and a width of 1000 mm. Next, the hot-rolled sheet was subjected to hot-rolled sheet annealing at 1000°C for 70 seconds to obtain a hot-rolled-sheet-annealed sheet. Next, the hot-rolled-sheet-annealed sheet was subjected to first-stage cold rolling that includes cold-rolling the steel sheet by using a 5-stand tandem rolling mill with a final stand work roll diameter of 250 mm and by setting the steel sheet temperature between adjacent stands, from the third stand to the final stand, to 120°C or higher so as to obtain an intermediate thickness of 0.6 mm. Then, the resulting steel sheet was coiled at a temperature of 100°C. Next, after 40 minutes had elapsed since the completion of the first-stage cold rolling, second-stage cold rolling was performed through two passes using various single-stand rolling mills with different work roll diameters so that a cold-rolled sheet with a final thickness of 0.22 mm was obtained. The work roll diameters for the second-stage cold rolling came in 14 types: 75 mm, 80 mm, 140 mm, 150 mm, 160 mm, 235 mm, 250 mm, 265 mm, 330 mm, 335 mm, 340 mm, 510 mm, 520 mm, and 530 mm. The cold-rolled sheet with the final thickness was subjected to primary recrystallization annealing, which also served as decarburization annealing. Then, an annealing separator was applied to the steel sheet surface, followed by finishing annealing, which included inducing secondary recrystallization and subsequent purification, thereby obtaining a product sheet.

[0026] A sample material having a total width of 1000 mm was taken from the center of the product sheet coil thus obtained in the longitudinal direction. From the sample material, 10 test specimens, each measuring 100 mm in width × 300 mm in length and having the longitudinal direction coinciding with the rolling direction, were taken. For each test specimen, the magnetic flux density B_8 (i.e., magnetic flux density when a magnetic field of 800 A/m is applied) and the iron loss $W_{17/50}$ (i.e., iron losses per kg of a steel sheet when magnetized up to a magnetic flux density of 1.7 T in an AC magnetic field with an excitation frequency of 50 Hz) were measured using a single-sheet magnetic measurement device, and their best values in the sheet width direction were determined. The reason for determining the best values in the sheet width direction is to identify the best possible magnetic properties that can be obtained.

[0027] Fig. 1 illustrates, regarding the aforementioned measurement results, the relationship between the work roll diameter ratio between the first-stage cold rolling and the second-stage cold rolling (i.e., the second-stage WR diameter/the first-stage WR diameter; hereinafter referred to simply as a "WR diameter ratio") and the best values of the magnetic properties (i.e., the magnetic flux density B_8 and the iron loss $W_{17/50}$) in the sheet width direction. Fig. 1 demonstrates that the iron loss properties significantly improve when the WR diameter ratio is 0.95 or less. In addition, the magnetic flux density also improves as the WR diameter ratio decreases. Specifically, it has been found that by setting the ratio (i.e., WR diameter ratio) of the work roll diameter for the second-stage cold rolling to the work roll diameter (250 mm) for the first-stage cold rolling to 0.95 or less, the best value of the magnetic flux density B_8 in the sheet width direction can be stably maintained at 1.920 T or higher.

[0028] The method according to this embodiment has been completed by further improving the aforementioned experimental results.

[0029] Next, the chemical composition that the steel material (i.e., slab) used to produce the grain-oriented electrical steel sheet of this embodiment should have will be described. In the following description, the unit "%" of the content of each component represents "mass%" unless otherwise stated.

C: 0.01 to 0.10%

[0030] C is an element effective in improving the primary recrystallization texture. From the viewpoint of obtaining such an effect, the C content is set to 0.01% or more. However, if the C content exceeds 0.10%, the primary recrystallization texture deteriorates. Furthermore, an excessive C content makes it difficult to reduce the C content to levels, such as 0.003% or less, where magnetic aging does not occur during decarburization annealing. Therefore, the C content is set in the range of 0.01 to 0.10%. Preferably, the C content is set to 0.02% or more, and preferably, the C content is set to 0.08% or less.

Si: 2.0 to 4.5%

[0031] Si is an element effective in increasing the specific resistance of steel and thus improving the iron loss properties. From the viewpoint of obtaining such an effect, the Si content is set to 2.0% or more. However, if the Si content exceeds 4.5%, cold rollability significantly decreases. Therefore, the upper limit is set at 4.5%. Preferably, the Si content is set to 2.5% or more, and preferably, the Si content is set to 4.0% or less.

Mn: 0.01 to 0.5%

[0032] Mn is a useful element as it has the effect of improving workability during hot rolling, and also from the viewpoint of controlling the formation of an oxide film during primary recrystallization annealing. Therefore, the Mn is set to 0.01% or more. However, if the Mn content exceeds 0.5%, the primary recrystallization texture deteriorates, leading to deteriorated magnetic properties. Therefore, the upper limit is set to 0.5%. Preferably, the Mn content is set to 0.03% or more, and more preferably, the Mn content is set to 0.2% or less.

[0033] The components other than C, Si, and Mn differ depending on whether or not precipitation-type inhibitors, such as AlN, MnS, and MnSe, are used to induce secondary recrystallization.

[0034] First, a case in which precipitation-type inhibitors are used to induce secondary recrystallization is described.

[0035] When AlN is used as an inhibitor, it is preferable that the Al content, in terms of sol. Al (i.e., acid-soluble Al), be set in the range of 0.010 to 0.05%, and the N content be set in the range of 0.004 to 0.012%. If sol. Al is less than 0.010%, the amount of AlN that precipitates becomes too small, making it difficult to obtain a sufficient inhibitor effect. This results in poor secondary recrystallization, and reduced magnetic flux density. Meanwhile, if sol. Al content exceeds 0.05%, secondary recrystallization tends to become unstable. In addition, if the N content is less than 0.004%, AlN does not precipitate appropriately during the hot-rolling step, the hot-rolled sheet annealing step, or the like, making it difficult to control the crystal grain size during the hot-rolled sheet annealing and the intermediate annealing, and even during the primary recrystallization annealing. Meanwhile, if the N content exceeds 0.012%, surface defects called blisters frequently occur. Accordingly, each of the Al content and the N content is preferably set in the aforementioned range. From the viewpoint of stabilizing the inhibitor during the secondary recrystallization, sol. Al is more preferably set to 0.010% or more, and sol. Al is more preferably set to 0.035% or less. The N content is more preferably set to 0.008% or more, and the N content is more preferably set to 0.012% or less.

[0036] Note that the N content in the steel sheet can be increased by applying nitriding treatment during a step prior to the finishing annealing. Therefore, the N content at the raw-material stage, such as in a steel slab, may be 0.008% or less as long as it is 0.004% or more. In addition, if N is added, the N content may be increased to approximately 0.05% from the viewpoint of appropriately controlling the primary recrystallization grain size and obtaining the inhibitor strength necessary for secondary recrystallization.

[0037] Meanwhile, if sulfide such as MnS, or selenide such as MnSe is used as an inhibitor, it is preferable that the total content of at least one of S and Se be set in the range of 0.01 to 0.05%. If the total content of S and Se is less than 0.01%, the absolute amount of the inhibitor becomes insufficient. Meanwhile, if the total content of S and Se exceeds 0.05%, it becomes difficult to achieve purification during the finishing annealing. Note that S or Se may be added alone, and in such a case also, the content of S or Se is preferably set in the range of 0.01 to 0.05%. More preferably, the total content of S and Se is set to 0.015% or more, and more preferably, the total content of S and Se is set to 0.040% or less.

[0038] When inhibitors are used to induce secondary recrystallization, the aforementioned AlN-based inhibitor may be used in combination with the MnS-based inhibitor or the MnSe-based inhibitor.

[0039] Meanwhile, to develop secondary recrystallization grains without using precipitation-type inhibitors, as disclosed in Patent Literature 1, it is preferable to minimize the content of Al, N, S, and Se, which are inhibitor-forming components. Specifically, it is preferable to reduce the Al content, in terms of sol. Al, to less than 0.010%, the S content to 0.0050% or less, the Se content to 0.0050% or less, and the N content to 0.0050% or less. If the content of any of these elements exceeds the aforementioned value, it becomes difficult to obtain a secondary recrystallization texture based on the texture inhibition effect. In addition, the N content is preferably set in the aforementioned range to prevent the formation of Si nitride during the purification of the finishing annealing.

[0040] In addition, when precipitation-type inhibitors are not used, it is also preferable to reduce the content of each of Ti, Nb, B, Ta, and V, which are nitride-forming elements, to 0.0050% or less from the viewpoint of preventing interference with the texture inhibition effect, thereby suppressing deterioration of the iron loss properties.

[0041] The steel material used to produce the grain-oriented electrical steel sheet of this embodiment contains the aforementioned components, with the balance basically being Fe and unavoidable impurities. Note that the steel material may further contain Ni in the range of 0.005 to 1.50% in addition to the aforementioned components from the viewpoint of improving the texture of the hot-rolled sheet and thereby improving the magnetic properties. In addition, the steel material may also contain at least one element selected from the group consisting of Cr, Cu, Sn, Sb, Mo, Te, Bi, and P, which are grain-boundary-segregation-type elements, in the range of 0.005 to 0.3% each, for the purpose of improving the magnetic properties.

[0042] Next, a method for producing the grain-oriented electrical steel sheet according to this embodiment is described.

[0043] First, a steel material (i.e., slab) used as the raw material for the grain-oriented electrical steel sheet can be produced by melting steel that satisfies the aforementioned chemical composition, using a commonly known refining process, and then performing an ordinary continuous casting process or ingot making-blooming process on the steel.

[0044] The steel material (i.e., slab) is then heated to an appropriate temperature and then subjected to hot rolling. When the steel slab contains precipitation-type inhibitor-forming components, the heating temperature for the steel slab is preferably set in the range of 1350 to 1450°C to completely dissolve Al, Se, S, and the like as a solid solution. Meanwhile, when the steel slab does not contain precipitation-type inhibitor-forming components, the heating temperature for the steel slab is preferably set to 1250°C or below. This is because when the heating temperature for the steel slab is too high, the inhibitor-forming components, which have dissolved as a solid solution during heating, become precipitated non-uniformly as fine particles during hot rolling. This may locally inhibit grain boundary migration, leading to an uneven grain size distribution and thus hindering the development of secondary recrystallization grains.

[0045] The conditions for the hot rolling performed following the steel slab heating may be determined in accordance with an ordinary method used to produce grain-oriented electrical steel sheets. In addition, the steel sheet that has been subjected to the aforementioned hot rolling, i.e., the hot-rolled sheet, may be subjected to hot-rolled sheet annealing for the purpose of improving the magnetic properties, or may not be subjected to hot-rolled sheet annealing if lower production cost is prioritized.

[0046] Next, the hot-rolled sheet that has been subjected to the aforementioned hot rolling or hot-rolled sheet annealing is subjected to cold rolling. The cold rolling is the most important step in this embodiment and needs to be performed by satisfying the following conditions. First, the cold rolling in this embodiment needs to be divided into first-stage cold rolling and second-stage cold rolling, and the total rolling reduction rate of the first-stage and second-stage cold rolling needs to be set to 80% or higher. If the total rolling reduction rate is less than 80%, it becomes difficult to sufficiently increase the density of dislocations introduced during rolling to promote pinning of the dislocations via strain aging and thus improve the texture. The total rolling reduction rate is preferably set to 84% or higher, and the total rolling reduction rate is preferably set to 96% or less. Herein, the "total rolling reduction rate" refers to the percentage of a value obtained by dividing the total reduction in sheet thickness over the course of the cold rolling, that is, the total rolling reduction by the sheet thickness before the cold rolling.

[0047] Intermediate annealing may be optionally performed between the first-stage cold rolling and the second-stage cold rolling. If intermediate annealing is performed, the annealing temperature needs to be set to 700°C or below. If annealing is performed at a temperature above 700°C during the cold rolling process, the rolled texture will recover or recrystallize, thereby eliminating the dislocations introduced during the cold rolling. This results in deterioration of the magnetic properties of the resulting grain-oriented electrical steel sheet. Therefore, the annealing temperature of the intermediate annealing is restricted.

[0048] In addition, the transition from the first-stage cold rolling to the second-stage cold rolling needs to be controlled such that the ratio of the rolling reduction during the first-stage cold rolling to the total rolling reduction over the course of the cold rolling, that is, the rolling reduction ratio falls within the range of 0.50 to 0.95. Herein, the total rolling reduction over the course of the cold rolling refers to the difference between the thickness of the hot-rolled sheet and the final thickness of the cold-rolled sheet, and the rolling reduction during the first-stage cold rolling refers to the reduction in sheet thickness during the first-stage cold rolling. Setting the rolling reduction ratio of the first-stage cold rolling to be in the aforementioned range allows sufficient dislocation density to be accumulated in the steel sheet. If the rolling reduction ratio is less than 0.50, sufficient dislocation density will not be accumulated. Meanwhile, if the rolling reduction ratio exceeds 0.95, it becomes difficult to obtain a sufficient effect of improving the texture through the second-stage cold rolling, which is a feature of this embodiment. Note that the rolling reduction ratio is preferably set to 0.60 or higher, and the rolling reduction ratio is preferably set to 0.80 or less.

[0049] It is important that the aforementioned first-stage cold rolling be performed using a tandem rolling mill including a plurality of rolling mills to obtain an intermediate thickness, and that the second-stage cold rolling be performed through one to three passes using a single-stand rolling mill to obtain a final thickness from the intermediate thickness. Setting the number of passes of the second-stage cold rolling to three or less can increase the rolling reduction rate per pass in a state where dislocations are pinned, thereby further promoting the formation of deformation bands.

[0050] It is also important that the ratio of the work roll diameter of the rolling mill used in the second-stage cold rolling to the work roll diameter of the final stand of the tandem rolling mill used in the first-stage cold rolling (i.e., WR diameter ratio) be in the range of 0.30 to 0.95. Using a smaller-diameter roll in the second-stage cold rolling compared to the first-stage cold rolling will increase the frictional force on the steel sheet surface during rolling, thereby imparting significant shear deformation to the surface layer of the steel sheet. Specifically, the second-stage cold rolling is performed under high pressure using a small-diameter roll, thereby applying shear stress to the {111}<112> texture obtained through the first-stage cold rolling. This induces crystal rotation to form a {110}<001> texture. Consequently, the crystal grain size after secondary recrystallization can be made finer along with the formation of the {110}<001> texture and an increase in the {110}<001> texture, so that the iron loss properties can be improved. In this embodiment, therefore, the work roll used in the second-stage cold rolling is a small-diameter roll having a work roll diameter ratio, that is, a WR diameter ratio of 0.95 or less relative to the work roll diameter of the final stand of the tandem rolling mill used in the first-stage cold rolling. However, if the WR diameter ratio is below 0.30, deformation resistance during the second-stage cold rolling may increase, potentially impairing threadability and rollability. Therefore, the lower limit of the WR diameter ratio is set to 0.30. The WR diameter ratio is preferably set to 0.35 or higher, and the WR diameter ratio is preferably set to 0.90 or less.

[0051] If the second-stage cold rolling is performed through two or three passes, it is possible to, as long as the work roll diameter satisfies the aforementioned conditions, perform the passes by using a single rolling mill and using work rolls having different diameters, or perform the passes by using a plurality of rolling mills with different work roll diameters.

[0052] The steel sheet subjected to the first-stage cold rolling is required to be coiled at a temperature of 80°C or higher and then subjected to the second-stage cold rolling after at least 30 minutes have elapsed from the completion of coiling. Satisfying these conditions promotes pinning of dislocations via strain aging, thereby further enhancing the effect of improving the texture. The coiling temperature is preferably 100°C or higher, and the elapsed time is preferably 60 minutes or longer.

[0053] The tandem rolling mill used in the first-stage cold rolling according to this embodiment preferably has the following function from the viewpoint of maintaining the steel sheet temperature at 80°C or higher after the completion of the first-stage cold rolling. Such a function is to control the coiling temperature by adjusting at least one of the temperature and the flow rate of coolant to be sprayed onto at least one of the steel sheet surface and the work roll surface on the exit side of the final stand of the tandem rolling mill.

[0054] Typically, cold rolling is performed while rolling oil at 70°C or below is supplied to a roll. Therefore, to maintain the coiling temperature for the steel sheet at 80°C or higher, it is preferable to provide a function of wiping off the rolling oil to prevent contact between the oil and the steel sheet that has been subjected to the cold rolling, or perform control to blow away the rolling oil using high-pressure gas or air. From the viewpoint of productivity, it is more efficient to perform the first-stage cold rolling and the second-stage cold rolling consecutively, but deliberately providing a time interval of 30 minutes or longer between the two stages is also an important factor.

[0055] In addition, for the rolling mills used in the cold rolling for the grain-oriented electrical steel sheet according to this embodiment, it is preferable to provide a heat retention device between the first-stage tandem rolling mill and the second-stage rolling mill to maintain the steel sheet temperature at 50°C or higher after the first-stage cold rolling, from the viewpoint of promoting aging.

[0056] Note that the steel sheet temperature at the start of the cold rolling is not limited to a particular value, and so-called warm rolling may also be performed. However, if the steel sheet temperature at the start of the cold rolling is too high, rolling oil may be baked onto the steel sheet surface, which is problematic. Therefore, the temperature is preferably 280°C or below.

[0057] Next, the cold-rolled sheet having the final thickness is subjected to primary recrystallization annealing, which

also serves as decarburization annealing. The purpose of the primary recrystallization annealing is to recrystallize the cold-rolled sheet having a rolled texture and to adjust it to a primary recrystallization texture best suited for secondary recrystallization, as well as to reduce the carbon content in the steel to a level where magnetic aging does not occur. Another purpose is to form an oxide film necessary for forming a forsterite coating on the steel sheet surface. Therefore, the primary recrystallization annealing is preferably performed at a temperature of 750 to 900°C under an oxidizing wet hydrogen-nitrogen atmosphere or wet hydrogen-argon atmosphere. In addition, the heating rate of the primary recrystallization annealing is preferably set high, for example, 50°C/s or higher (i.e., rapid heating), to improve the texture.

[0058] After the primary recrystallization annealing, an annealing separator is applied to the steel sheet surface. It is preferable to use an annealing separator composed primarily of magnesia (MgO) to form a forsterite coating on the steel sheet surface after finishing annealing. Note that it is preferable to add an appropriate amount of an auxiliary agent, such as Ti oxide or a Sr compound, to the annealing separator to form a uniform forsterite coating and improve stripping resistance.

[0059] The steel sheet coated with the annealing separator is subjected to finishing annealing in a coiled state for inducing secondary recrystallization and for, after the completion of the secondary recrystallization, forming a forsterite coating and also removing impurities, such as inhibitor-forming components, from the steel sheet (i.e., purification) at a temperature of 1100°C or higher. The finishing annealing is preferably performed under an H_2 atmosphere during the purification, and under an atmosphere of N_2, Ar, or H_2, or a mixed gas thereof during other processes. Through the purification, the content of each of Al, N, S, and Se, which are the inhibitor-forming components, in the steel sheet is reduced to impurity levels, specifically, Al: 0.008 mass% or less, N: 0.003 mass% or less, S: 0.003 mass% or less, and Se: 0.005 mass% or less. Note that to induce secondary recrystallization more effectively during the finishing annealing, the steel sheet may be isothermally held at a temperature around the secondary recrystallization temperature for a long time, or the steel sheet may be heated at a slow rate in the aforementioned temperature range.

[0060] After the finishing annealing, the steel sheet is preferably subjected to flattening annealing for shape correction. Furthermore, during the flattening annealing, an insulation coating may be applied to and baked onto the steel sheet surface. The type of the insulation coating is not particularly defined, but from the viewpoint of reducing iron losses, the method disclosed in JP-A-S50-79442 or JP-A-S48-39338 can be applied, for example. These methods involve applying a coating solution containing phosphate, chromate, and colloidal silica to the steel sheet surface, and baking the coating solution at a temperature of about 800°C to form a tension-imparting insulation coating. Furthermore, from the viewpoint of reducing iron losses even more, magnetic domain subdividing treatment may be performed by, for example, forming a groove in the steel sheet surface during any one of the steps following the cold rolling, or introducing heat strain into the steel sheet surface by irradiating it with an electron beam or a laser beam after the finishing annealing.

[0061] The grain-oriented electrical steel sheet according to this embodiment, produced as described above, exhibits excellent magnetic properties. Specifically, the best value of the magnetic flux density B_8 in the sheet width direction is 1.920 T or higher.

Examples

(Example 1)

[0062] Steel slabs, each having a chemical composition including C: 0.040 mass%, Si: 3.3 mass%, and Mn: 0.05 mass%, and also including other components shown in Table 2, with the balance being Fe and unavoidable impurities, were produced by melting. Each steel slab was heated to a temperature of 1200°C and then hot-rolled to obtain a hot-rolled sheet with a thickness of 2.5 mm. Next, the hot-rolled sheet was subjected to hot-rolled sheet annealing at 1000°C for 60 seconds. The resulting hot-rolled-sheet-annealed steel sheet was subjected to first-stage cold rolling that includes cold-rolling the steel sheet by using a 4-stand tandem rolling mill with a final stand work roll diameter of 400 mm and by setting the steel sheet temperature between adjacent stands, from the third pass to the final pass, to 150°C or higher so as to obtain an intermediate thickness shown in Table 2, and coiling the steel sheet at a temperature of 100°C. Some of the coils were then subjected to intermediate annealing at 1000°C for 30 seconds after the first-stage cold rolling.

[0063] After 30 minutes or more had elapsed since the completion of the first-stage cold rolling, the cold-rolled sheet with the intermediate thickness was subjected to cold rolling through the number of passes shown in Table 2, using a single-stand rolling mill with a work roll diameter of 300 mm so as to obtain a cold-rolled sheet with a final thickness of 0.27 mm.

[0064] The cold-rolled sheet with the final thickness was rapidly heated at a heating rate of 80°C/s in the temperature range of 400°C to 700°C, and was then subjected to primary recrystallization annealing, which also serves as decarburization annealing, at 850°C for 40 seconds under a wet hydrogen atmosphere. Then, after the primary recrystallization annealing, an annealing separator composed primarily of MgO was applied to the steel sheet surface and was then dried, followed by finishing annealing including inducing secondary recrystallization and subsequent purification.

[0065] After the finishing annealing, a coating solution for the formation of an insulation coating, containing phosphate, chromate, and colloidal silica at a weight ratio of 3:1:2, was applied to the steel sheet surface. Then, flattening annealing was performed at 850°C for 30 seconds to bake the insulation coating and correct its shape, thereby obtaining a product

sheet.

[0066] From the center of the thus obtained product sheet coil in the longitudinal direction, test specimens, each measuring 30 mm in width × 280 mm in length and having the longitudinal direction coinciding with the rolling direction, were cut out at a plurality of positions so as to obtain a total weight of 500 g or more. Then, the magnetic flux density B_8 of each test specimen was measured through an Epstein test defined in JIS C 2550, and the best value of the magnetic flux density B_8 was evaluated.

[0067] Table 2 also shows the measurement results. Table 2 demonstrates that all of the steel sheets that satisfy the conditions of the present embodiment exhibit excellent magnetic properties, specifically, a best value of the magnetic flux density B_8 of 1.920 T or higher.

[Table 2]

Steel sheet No.	Chemical composition (mass%) of slab				Cold rolling conditions				Best value (T) of magnetic flux density B_8	Remarks
	Al	N	S	Other components	Sheet thickness (mm) (intermediate thickness) after first-stage cold rolling	Rolling reduction ratio of first-stage cold rolling * ()	Intermediate annealing performed or not?	The number (times) of passes of second-stage cold rolling		
1	0.005	0.002	0.001	-	0.60	0.85	Not performed	2	1.921	Invention Example
2	0.005	0.002	0.001	-	0.60	0.85	Performed	2	1.902	Comparative Example
3	0.008	0.003	0.001	-	0.80	0.76	Not performed	2	1.922	Invention Example
4	0.008	0.003	0.001	-	1.50	0.45	Not performed	4	1.899	Comparative Example
5	0.004	0.002	0.001	Ni:0.02, Sn:0.01, Cu:0.05, Cr:0.05	0.40	0.94	Not performed	1	1.923	Invention Example
6	0.004	0.002	0.001	Ni:0.02, Sn:0.01, Cu:0.05, Cr:0.05	0.35	0.96	Not performed	1	1.905	Comparative Example
7	0.002	0.004	0.001	Sn:0.02, Sb:0.02, Cu:0.05, P:0.08, Ti:0.001	0.45	0.92	Not performed	1	1.924	Invention Example
8	0.005	0.002	0.001	Sb:0.02, Mo:0.01, Bi:0.001	0.45	0.92	Not performed	1	1.925	Invention Example

(continued)

Steel sheet No.	Chemical composition (mass%) of slab				Cold rolling conditions				Best value (T) of magnetic flux density B_8	Remarks
	Al	N	S	Other components	Sheet thickness (mm) (intermediate thickness) after first-stage cold rolling	Rolling reduction ratio of first-stage cold rolling * ()	Intermediate annealing performed or not?	The number (times) of passes of second-stage cold rolling		
9	0.008	0.004	0.001	Sb:0.02, Te:0.001, Cr:0.05, Nb:0.001	0.45	0.92	Not performed	1	1.925	Invention Example
* Note: Rolling reduction ratio of first-stage cold rolling: (reduction in sheet thickness during first-stage cold rolling)/(total reduction in sheet thickness over the course of cold rolling)										

(Example 2)

[0068] Steel slabs, each having a chemical composition including C: 0.05 mass%, Si: 3.4 mass%, Mn: 0.08 mass%, Al: 0.015 mass%, N: 0.006 mass%, S: 0.003 mass%, and Se: 0.012 mass%, with the balance being Fe and unavoidable impurities, were produced by melting. Each steel slab was heated to a temperature of 1400°C and then hot-rolled to obtain a hot-rolled sheet with a thickness of 2.0 mm. Next, the hot-rolled sheet was subjected to hot-rolled sheet annealing at 1080°C for 60 seconds. The resulting steel sheet was subjected to first-stage cold rolling that includes cold-rolling the steel sheet by using a 4-stand tandem rolling mill with a final stand work roll diameter of 400 mm and by setting the steel sheet temperature between adjacent stands, from the third pass to the final pass, to 150°C or higher so as to obtain an intermediate thickness of 0.7 mm, and coiling the steel sheet at a temperature of 100°C.

[0069] Next, after 40 minutes or more had elapsed from the completion of the first-stage cold rolling, the cold-rolled sheet with the intermediate thickness was subjected to rolling through two passes, using different single-stand rolling mills with six types of roll diameters: 80 mm, 160 mm, 250 mm, 330 mm, 400 mm, and 550 mm so as to obtain a cold-rolled sheet with a final thickness of 0.25 mm.

[0070] The cold-rolled sheet with the final thickness was subjected to primary recrystallization annealing, which also serves as decarburization annealing, at 850°C for 120 seconds under a wet hydrogen atmosphere. After the primary recrystallization annealing, an annealing separator composed primarily of MgO and containing 5 mass% TiO_2 was applied to the steel sheet surface, followed by finishing annealing including inducing secondary recrystallization and subsequent purification by holding the steel sheet at 1200°C for 10 hours.

[0071] After the finishing annealing, a coating solution for the formation of an insulation coating, containing phosphate, chromate, and colloidal silica at a weight ratio of 3:1:2, was applied to the steel sheet surface. Flattening annealing was then performed at 850°C for 30 seconds to bake the insulation coating and correct the sheet shape, thereby obtaining a product sheet.

[0072] A sample material was taken from the center of the thus obtained product sheet coil in the longitudinal direction. From the sample material, 10 test specimens, each measuring 30 mm in width $\times$ 280 mm in length and having the longitudinal direction coinciding with the rolling direction, were taken along the sheet width direction. Then, the magnetic flux density B_8 (i.e., magnetic flux density when a magnetic field of 800 A/m is applied) and the iron loss $W_{17/50}$ (i.e., iron losses per kg of a steel sheet when magnetized up to a magnetic flux density of 1.7 T in an AC magnetic field with an excitation frequency of 50 Hz) were measured with a single-sheet magnetic measurement device. In addition, their mean values and standard deviations σ were determined.

[0073] Fig. 2 illustrates the influence of the work roll diameter ratio (i.e., WR diameter ratio) between the first-stage and second-stage cold rolling mills on the mean values of the magnetic flux density and iron losses and also on their variation (3σ) in the sheet width direction. Fig. 2 demonstrates that, for each of the steel sheets whose cold rolling WR diameter ratio satisfies the conditions of the present invention, the magnetic flux density and the iron loss properties are favorable, and that their variation is relatively small.

(Example 3)

[0074] The steel sheet produced from Steel 1, which had been subjected to the first-stage cold rolling (to have an intermediate thickness of 0.6 mm) in Example 1, was subjected to the second-stage cold rolling through one pass using a single-stand rolling mill with a work roll diameter of 330 mm, and through another pass using a single-stand rolling mill with a work roll diameter of 250 mm (i.e., a total of two passes). The resulting steel sheet was formed into a product coil of a grain-oriented electrical steel sheet under conditions similar to those of Example 1. Then, a sample material was taken from the center of the product sheet coil in the longitudinal direction. Then, 10 test specimens, each measuring 30 mm in width $\times$ 280 mm in length and having the longitudinal direction coinciding with the rolling direction, were taken from the sample material along the sheet width direction. Then, the magnetic flux density B_8 was measured with a single-sheet magnetic measurement device. Consequently, the magnetic flux density B_8 of each test specimen in the sheet width direction was found to be in the range of 1.922 $\pm$ 0.002 T. The results can confirm that as long as the ratio of the WR diameter in each pass of the second-stage cold rolling to the WR diameter in the first-stage cold rolling satisfies the conditions of this embodiment, it is possible to obtain favorable magnetic properties even when the second-stage cold rolling is performed using a plurality of single-stand rolling mills with different work roll diameters.

Industrial Applicability

[0075] The method of the present invention is also applicable to other steel products whose texture is controlled by utilizing carbon in the steel.

Claims

1. A cold rolling method for a grain-oriented electrical steel sheet comprising performing cold rolling with a total rolling reduction rate of 80% or higher to form a cold-rolled sheet with a final thickness,
characterized in that

the cold rolling is divided into first-stage cold rolling and second-stage cold rolling;
optionally, intermediate annealing is performed between the first-stage cold rolling and the second-stage cold rolling;
after the first-stage cold rolling, the steel sheet is coiled at a temperature of 80°C or higher, and the second-stage cold rolling is performed after at least 30 minutes have elapsed from the completion of the coiling;
an annealing temperature is set to 700°C or lower when performing the intermediate annealing;
during the first-stage cold rolling, the steel sheet is cold rolled using a tandem rolling mill, with a ratio of rolling reduction during the first-stage cold rolling to a total rolling reduction over the course of the cold rolling being set to be in a range of 0.50 to 0.95, to obtain an intermediate thickness;
during the second-stage cold rolling, the steel sheet is cold rolled through one to three passes using a single-stand rolling mill to obtain a final thickness from the intermediate thickness; and
a ratio of a work roll diameter of the single-stand rolling mill to a work roll diameter of a final stand of the tandem rolling mill is set to be in a range of 0.30 to 0.95, thereby achieving a best value of magnetic flux density B_8 of a resulting product sheet in a sheet width direction of 1.920 T or higher.

2. The cold rolling method for a grain-oriented electrical steel sheet according to claim 1, wherein
the second-stage cold rolling is performed by using a single-stand rolling mill with the work roll diameter changed, or by using a plurality of single-stand rolling mills with different work roll diameters.

3. A method for producing a grain-oriented electrical steel sheet, comprising:

forming a hot-rolled sheet by performing hot rolling on a steel slab having a chemical composition including

C: 0.01 to 0.10 mass%, Si: 2.0 to 4.5 mass%, and Mn: 0.01 to 0.5 mass%, and
further including, as an inhibitor-forming component, at least one group of components selected from among Group A: sol. Al: 0.010 to 0.05 mass% and N: 0.004 to 0.012 mass%, Group B: at least one of S and Se: a total of 0.01 to 0.05 mass%, and Group C: sol. Al: 0.010 to 0.05 mass%, N: 0.004 to 0.012 mass%, and at least one of S and Se: a total of 0.01 to 0.05 mass%, and
further optionally including at least one component selected from the group consisting of Ni: 0.005 to 1.50 mass%, Cr: 0.005 to 0.3 mass%, Cu: 0.005 to 0.3 mass%, Sn: 0.005 to 0.3 mass%, Sb: 0.005 to 0.3 mass%, Mo: 0.005 to 0.3 mass%, Te: 0.005 to 0.3 mass%, Bi: 0.005 to 0.3 mass%, and P: 0.005 to 0.3 mass%, with a balance being Fe and unavoidable impurities;

performing cold rolling on the hot-rolled sheet with a total rolling reduction rate of 80% or higher to obtain a cold-rolled sheet with a final thickness;
performing primary recrystallization annealing, which also serves as decarburization annealing, on the cold-rolled sheet;
applying an annealing separator to a surface of the steel sheet; and
performing finishing annealing including inducing secondary recrystallization and subsequent purification, wherein:
the cold rolling is performed by applying the cold rolling method according to claim 1 or 2, thereby achieving a best value of magnetic flux density B_8 in a sheet width direction of 1.920 T or higher.

4. A method for producing a grain-oriented electrical steel sheet, comprising:

forming a hot-rolled sheet by performing hot rolling on a steel slab having a chemical composition including

C: 0.01 to 0.10 mass%, Si: 2.0 to 4.5 mass%, and Mn: 0.01 to 0.5 mass%, and
further including sol. Al: less than 0.010 mass%, S: 0.0050 mass% or less, Se: 0.0050 mass% or less, and N: 0.0050 mass% or less, and
further optionally including at least one component selected from the group consisting of Ni: 0.005 to 1.50 mass%, Cr: 0.005 to 0.3 mass%, Cu: 0.005 to 0.3 mass%, Sn: 0.005 to 0.3 mass%, Sb: 0.005 to 0.3 mass%,

Mo: 0.005 to 0.3 mass%, Te: 0.005 to 0.3 mass%, Bi: 0.005 to 0.3 mass%, and P: 0.005 to 0.3 mass%, with a balance being Fe and unavoidable impurities;

performing cold rolling on the hot-rolled sheet with a total rolling reduction rate of 80% or higher to obtain a cold-rolled sheet with a final thickness;
performing primary recrystallization annealing, which also serves as decarburization annealing, on the cold-rolled sheet;
applying an annealing separator to a surface of the steel sheet; and
performing finishing annealing including inducing secondary recrystallization and subsequent purification,
wherein:
the cold rolling is performed by applying the cold rolling method according to claim 1 or 2, thereby achieving a best value of magnetic flux density B_8 in a sheet width direction of 1.920 T or higher.

5. A cold rolling equipment line comprising a first-stage cold rolling mill and a second-stage cold rolling mill for use in the cold rolling method according to claim 1,
wherein:

the first-stage cold rolling mill is a tandem rolling mill, and the second-stage cold rolling mill is a single-stand rolling mill, and
a ratio of a work roll diameter of the second-stage cold rolling mill to a work roll diameter of a final stand of the tandem rolling mill falls within a range of 0.30 to 0.95.

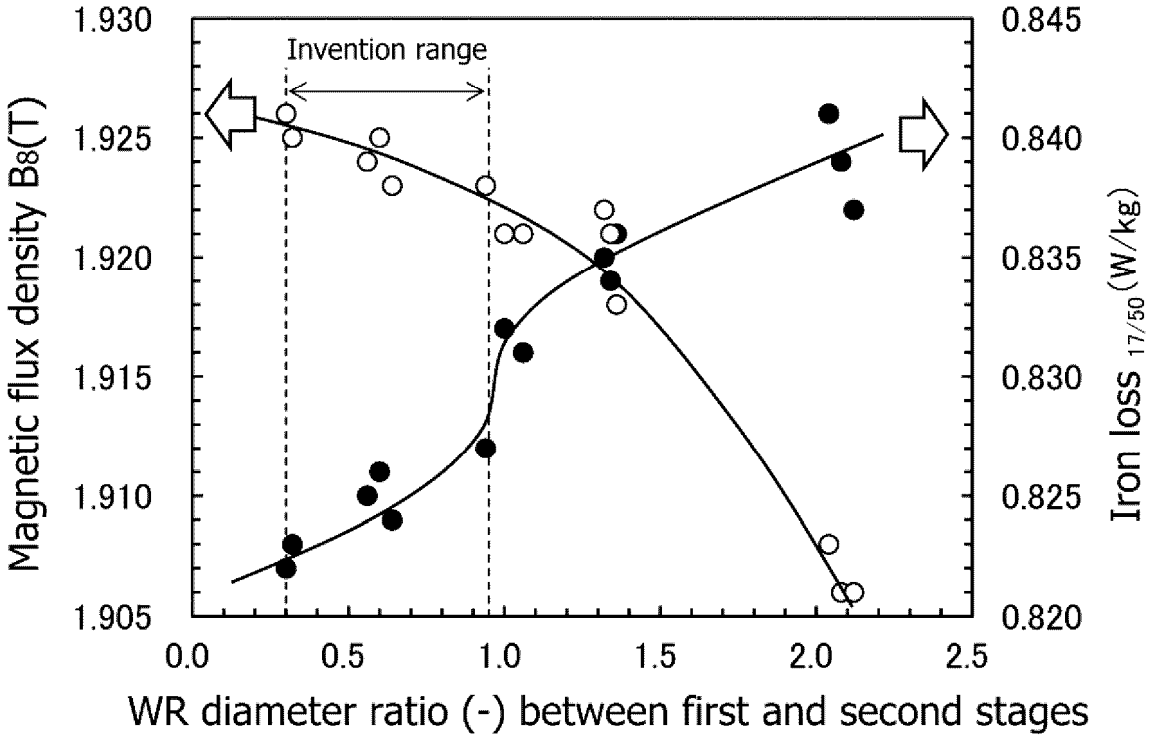
6. The cold rolling equipment line according to claim 5, comprising a first-stage cold rolling mill and a second-stage cold rolling mill for use in the cold rolling method according to claim 2,
wherein:

the first-stage cold rolling mill is a tandem rolling mill, and the second-stage cold rolling mill is a single-stand rolling mill, and
the second-stage cold rolling mill includes a single-stand rolling mill with an adjustable work roll diameter, or a plurality of single-stand rolling mills with different work roll diameters.

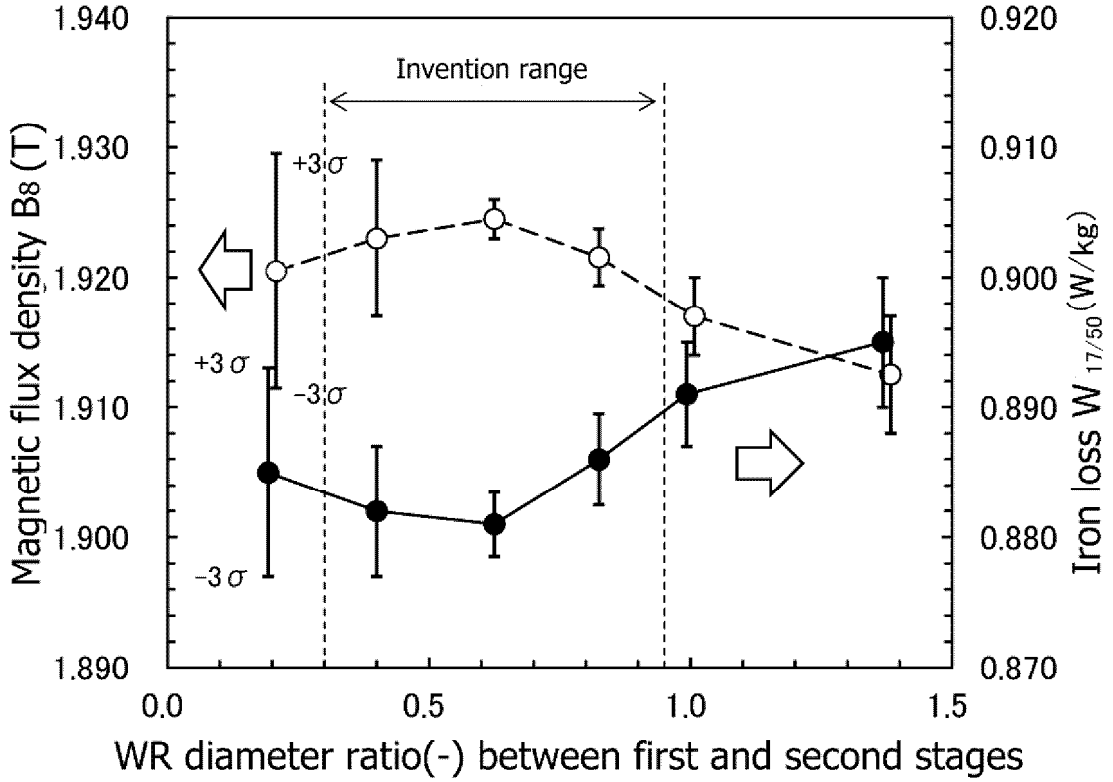
7. The cold rolling equipment line according to claim 5 or 6, further comprising at least one of the following configurations:

(1) the tandem rolling mill has a function of controlling a coiling temperature by adjusting at least one of a temperature and a flow rate of coolant to be sprayed onto at least one of a steel sheet surface and a work roll surface on an exit side of the final stand; and
(2) a heat retention device is provided between the tandem rolling mill and the second-stage rolling mill, the heat retention device being adapted to maintain a steel sheet temperature at 50°C or higher after the first-stage cold rolling.

[Fig. 1]


Invention range
Magnetic flux density B8(T)
Iron loss W17/50(W/kg)
1.930
1.925
1.920
1.915
1.910
1.905
0.845
0.840
0.835
0.830
0.825
0.820
0.0
0.5
1.0
1.5
2.0
2.5
WR diameter ratio (-) between first and second stages

[Fig. 2]


Invention range
+3σ
+3σ
-3σ
-3σ
Magnetic flux density B8 (T)
Iron loss W17/50(W/kg)
1.940
1.930
1.920
1.910
1.900
1.890
0.920
0.910
0.900
0.890
0.880
0.870
0.0
0.5
1.0
1.5
WR diameter ratio(-) between first and second stages

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2025/000157

A. CLASSIFICATION OF SUBJECT MATTER

C21D 8/12(2006.01)i; ***B21B 1/22***(2006.01)i; ***B21B 3/02***(2006.01)i; ***B21B 13/02***(2006.01)i; ***B21B 27/10***(2006.01)i; ***C22C 38/00***(2006.01)i; ***C22C 38/60***(2006.01)i; ***H01F 1/16***(2006.01)i; ***H01F 1/147***(2006.01)i
FI: C21D8/12 B; C21D8/12 C; C22C38/00 303U; C22C38/60; B21B13/02 A; B21B1/22 J; B21B3/02; B21B27/10 A; B21B27/10 C; H01F1/147 175; H01F1/16

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)

C21D8/12; B21B1/22; B21B3/02; B21B13/02; B21B27/10; C22C38/00-38/60; H01F1/16; H01F1/147

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 1971-2025
Registered utility model specifications of Japan 1996-2025
Published registered utility model applications of Japan 1994-2025

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.
A	WO 2008/133337 A1 (NIPPON STEEL CORPORATION) 06 November 2008 (2008-11-06) entire text, all drawings	1-7
A	JP 2005-272973 A (JFE STEEL CORPORATION) 06 October 2005 (2005-10-06) entire text	1-7
A	JP 2002-129234 A (NIPPON STEEL CORPORATION) 09 May 2002 (2002-05-09) entire text, all drawings	1-7

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 March 2025	**15 April 2025**
Name and mailing address of the ISA/JP **Japan Patent Office (ISA/JP)** **3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915** **Japan**	Authorized officer Telephone No.

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2025/000157

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
WO 2008/133337 A1	06 November 2008	US 2010/0084058 A1 entire text, all drawings EP 2140949 A1 KR 10-2009-0114413 A CN 101668596 A	
JP 2005-272973 A	06 October 2005	(Family: none)	
JP 2002-129234 A	09 May 2002	KR 10-2002-0033021 A entire text, all drawings CN 1349862 A	

Form PCT/ISA/210 (patent family annex) (July 2022)

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2000129356 A **[0008]**
- JP S5016610 A **[0008]**
- JP H08253816 A **[0008]**
- JP H01215925 A **[0008]**
- JP S54013846 A **[0008]**
- JP S54029182 A **[0008]**
- JP S5079442 A **[0060]**
- JP S4839338 A **[0060]**