

DESCRIPTION

TITLE OF INVENTION: NON-ORIENTED ELECTRICAL STEEL SHEET, MOTOR CORE, AND MOTOR

TECHNICAL FIELD

[0001] The present invention relates to a non-oriented electrical steel sheet, a motor core, and a motor.

This application is based upon and claims the benefit of priority of the prior Japanese Patent Application No. 2023-023379, filed on February 17, 2023, the entire contents of which are incorporated herein by reference.

BACKGROUND ART

[0002] Electrical steel sheets are used as a raw material for cores (iron cores) of electrical devices. Examples of electrical devices include drive motors mounted in automobiles, various compressor motors such as those used in air conditioners and refrigerators, household or industrial generators, and so on. These electrical devices are required to achieve high energy efficiency, miniaturization, and high output.

Therefore, the electrical steel sheets used as the cores of the electrical devices are required to be low in core loss and high in magnetic flux density. One solution is texture control, and there has been proposed so far a technique to develop a structure (α -fiber) that has an easy magnetization axis within a sheet surface of a steel sheet, is advantageous for improving magnetic properties, and is capable of relatively easily increasing accumulation by rolling processes in hot rolling and cold rolling, which are

essential steps for steel sheet manufacture.

Specifically, a structure whose $\langle 110 \rangle$ direction is substantially parallel to a rolling direction (RD) is formed.

[0003] Patent Literatures 1 to 3 all have disclosed a method of developing the $\{100\}\langle 011 \rangle$ orientation, and have described that the transformation temperature is lowered and rapid cooling is performed after hot rolling to refine a structure.

[0004] Specifically, Patent Literature 1 has described that within 3 seconds after hot rolling, cooling is performed down to 250°C or lower at a cooling rate of $200^{\circ}\text{C}/\text{second}$ or more and that without performing annealing between hot rolling and cold rolling, a cumulative reduction ratio in cold rolling is set to 88% or more. This makes it possible to manufacture an electrical steel sheet accumulated in the $\{100\}\langle 011 \rangle$ orientation in the steel sheet surface.

[0005] Further, Patent Literature 2 has disclosed a method of manufacturing an electrical steel sheet containing 0.6 mass% or more and 3.0 mass% or less of Al, and has described that an electrical steel sheet whose $\{100\}\langle 011 \rangle$ orientation is accumulated in the steel sheet surface can be manufactured by the same steps as the method described in Patent Literature 1.

[0006] Meanwhile, Patent Literature 3 has described that the finish rolling temperature in hot rolling is set to be equal to or higher than the Ac3 transformation point and cooling is performed down to a

steel sheet temperature of 250°C within 3 seconds after hot rolling, or that the finish rolling temperature is set to be equal to or lower than the Ac3 transformation point - 50°C and cooling is performed at a cooling rate equal to or more than that of standing-to-cool.

Further, in the manufacturing method described in Patent Literature 3, cold rolling is performed two times with intermediate annealing performed therebetween, annealing is not performed between hot rolling and the first cold rolling, and a cumulative reduction ratio is 5 to 15% in the second cold rolling. This makes it possible to manufacture an electrical steel sheet accumulated in the {100}<011> orientation in the steel sheet surface.

[0007] In any of the methods described in Patent Literatures 1 to 3, in the case where the finish rolling temperature in hot rolling is set to the Ac3 point or higher when manufacturing the electrical steel sheet accumulated in the {100}<011> orientation in the steel sheet surface, rapid cooling immediately thereafter is required. When the rapid cooling is performed, a cooling load after hot rolling increases. When considering operational stability, it is preferable to be able to reduce the load on a rolling mill where cold rolling is performed.

[0008] Meanwhile, in order to improve magnetic properties, a technique has also been proposed to develop the {411} orientation rotated by 20° from the {100} orientation. As a method of developing the {411}

orientation, Patent Literatures 4 to 7 all have disclosed a technique to develop the {411} orientation, and have described that the grain diameter in a hot-rolled sheet is optimized and the α -fiber in a texture of the hot-rolled sheet is strengthened.

[0009] Specifically, Patent Literature 4 has described that cold rolling is performed on a hot-rolled sheet whose degree of accumulation of the {211} orientation is higher than that of the {411} orientation and the cumulative reduction ratio in the cold rolling is set to 80% or more. This makes it possible to manufacture an electrical steel sheet accumulated in the {411} orientation in the steel sheet surface.

[0010] Further, Patent Literatures 5 and 6 have described that the slab heating temperature is set to 700°C or higher and 1150°C or lower, the starting temperature of finish rolling is set to 650°C or higher and 850°C or lower, the finishing temperature of the finish rolling is set to 550°C or higher and 800°C or lower, and further, the cumulative reduction ratio in cold rolling is set to 85 to 95%. This makes it possible to manufacture an electrical steel sheet accumulated in the {100} orientation and the {411} orientation in the steel sheet surface.

[0011] Meanwhile, Patent Literature 7 has described that when the α -fiber is developed to the vicinity of a steel sheet surface layer in a hot-rolled coil steel sheet by strip casting or the like, the {h11}<1/h12> orientation, particularly, the {100}<012> to {411}<148>

orientations are recrystallized by subsequent annealing of a hot-rolled sheet.

[0012] As a result of the examination of the above-described techniques, the present inventors found out that when the $\{100\}\langle 011\rangle$ orientation is strengthened to improve the magnetic properties in accordance with Patent Literatures 1 to 3, rapid cooling immediately after hot rolling is required, which causes a problem of a high manufacturing load. Further, they recognized that when the steel sheet in which the $\{100\}\langle 011\rangle$ orientation has been strengthened is used as a material for an interlocking core, core properties as expected from the raw material are not obtained in some cases. As a result of examining the cause of this, it was considered that the $\{100\}\langle 011\rangle$ orientation is responsible for a large change in magnetic properties in response to stress, specifically a large deterioration of magnetic properties (stress sensitivity) when compressive stress is applied.

[0013] In addition, they found out that in the techniques of Patent Literatures 4 to 7, although the $\{411\}$ orientation is developed, the accumulation of an in-plane orientation in the $\langle 011\rangle$ orientation is weak, and the magnetic properties in the 45° direction relative to the rolling direction of the steel sheet, which are characteristics of the α -fiber, are not sufficiently high. The fact that the in-plane orientation is not aligned with the $\langle 011\rangle$ orientation, namely, there is a large deviation from the α -fiber,

was a factor that inhibits accumulation in the {411} orientation as a plane orientation, and it was considered that this may be the reason why the magnetic properties are not sufficiently improved.

[0014] Further, the non-oriented electrical steel sheets for automobiles have been strongly required not only to achieve high magnetic flux density, but also to reduce core loss in particular, and have achieved low core loss by reducing the sheet thicknesses. However, reducing the sheet thickness leads to a decrease in motor manufacturing efficiency, and thus there has been a demand for a method of reducing the core loss while maintaining the sheet thickness.

CITATION LIST

PATENT LITERATURE

[0015] Patent Literature 1: Japanese Laid-open Patent Publication No. 2017-145462

Patent Literature 2: Japanese Laid-open Patent Publication No. 2017-193731

Patent Literature 3: Japanese Laid-open Patent Publication No. 2019-178380

Patent Literature 4: Japanese Patent No. 4218077

Patent Literature 5: Japanese Patent No. 5256916

Patent Literature 6: Japanese Laid-open Patent Publication No. 2011-111658

Patent Literature 7: Japanese Laid-open Patent Publication No. 2019-183185

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0016] In consideration of the above-described problems, an object of the present invention is to provide a non-oriented electrical steel sheet that has achieved both low core loss and high magnetic flux density without increasing a manufacturing load and with no need to reduce a sheet thickness.

SOLUTION TO PROBLEM

[0017] The present inventors conducted intensive research to solve the above-described problems. As a result, it became clear that it is important to optimize the chemical composition, the grain diameter after hot rolling, and the reduction ratio in cold rolling. Specifically, it is important to facilitate the development of crystal grains in the {411}<011> orientation, which do not easily develop normally, by, based on the α - γ transformation system chemical composition, optimizing the grain diameter by performing cooling under predetermined conditions after hot rolling, and further performing cold rolling at a predetermined reduction ratio, controlling the temperature of intermediate annealing within a predetermined range, and further performing a second cold rolling at an appropriate reduction ratio and then performing annealing. As a result of having conducted further intensive research based on these findings, the present inventors have reached the following aspects of the invention.

[0018] (1) A non-oriented electrical steel sheet, includes a chemical composition containing:

in mass%,

C: 0.010% or less;

Si: 1.50% ~ 4.00%;

sol. Al: 0.3% ~ 0.7%;

S: 0.010% or less;

N: 0.010% or less;

Ti: 0.0005% ~ 0.0020%;

one or more selected from the group consisting of
Mn, Ni, and Cu: 2.50% ~ 5.00% in total;

Co: 0.000% ~ 1.000%;

Sn: 0.000% ~ 0.400%;

Sb: 0.000% ~ 0.400%; and

P: 0.000% ~ 0.400%, and

satisfying (1) Expression and (2) Expression below
when the Mn content (mass%) is set to [Mn], the Ni
content (mass%) is set to [Ni], the Cu content (mass%)
is set to [Cu], the Si content (mass%) is set to [Si],
the sol. Al content (mass%) is set to [sol. Al], and
the P content (mass%) is set to [P], and

having a balance consisting of Fe and impurities,
in which

when an area ratio of crystal grains in a
{hkl}<uvw> orientation (within a tolerance of 10°) to
the entire visual field when a steel sheet surface is
measured by a scanning electron microscope equipped
with electron back scattering diffraction (SEM-EBSD) is
represented as Ahkl-uvw, A411-011 is 15% or more, and

the number density of precipitates is 0.0001
pieces/ μm^2 ~ 0.3000 pieces/ μm^2 .

$(2 \times [\text{Mn}] + 2.5 \times [\text{Ni}] + [\text{Cu}]) - ([\text{Si}] + 2 \times [\text{sol. Al}] + 4 \times [\text{P}]) \geq 3.0\% \quad \dots(1)$

$10.5 \leq ([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}] \leq 12.5 \quad \dots(2)$

(2) A motor core, in which the non-oriented electrical steel sheets according to (1) are stacked.

(3) A motor, includes:

the motor core according to (2).

ADVANTAGEOUS EFFECTS OF INVENTION

[0019] According to the present invention, it is possible to provide a non-oriented electrical steel sheet that has achieved both low core loss and high magnetic flux density without increasing a manufacturing load and with no need to reduce a sheet thickness, a motor core, and a motor.

DESCRIPTION OF EMBODIMENTS

[0020] There will be explained an embodiment of the present invention in detail below.

[0021] First, there is explained a chemical composition of a non-oriented electrical steel sheet according to the embodiment of the present invention and a steel material used in its manufacturing method and a cold-rolled steel sheet used for manufacturing the non-oriented electrical steel sheet. In the following explanation, "%", which is the unit of content of each element contained in the non-oriented electrical steel sheet or steel material, means "mass %" unless otherwise specified. Furthermore, a numerical value range expressed using "~" means the range that includes numerical values described before

and after "~" as the lower limit value and the upper limit value.

[0022] The non-oriented electrical steel sheet according to this embodiment, the cold-rolled steel sheet, and the steel material include a chemical composition in which ferrite-austenite transformation (hereinafter, α - γ transformation) can occur, the chemical composition containing C: 0.010% or less, Si: 1.50% ~ 4.00%, sol. Al: 0.3% ~ 0.7%, S: 0.010% or less, N: 0.010% or less, Ti: 0.0005% ~ 0.0020%, one or more selected from the group consisting of Mn, Ni, and Cu: 2.50% ~ 5.00% in total, Co: 0.000% ~ 1.000%, Sn: 0.000% ~ 0.400%, Sb: 0.000% ~ 0.400%, and P: 0.000% ~ 0.400%, with a balance consisting of Fe and impurities. Further, the contents of Mn, Ni, Cu, Si, sol. Al, and P satisfy later-described predetermined conditions. Examples of the impurities include those contained in raw materials such as ores and scrap, and those contained in the manufacturing process.

[0023] (C: 0.010% or less)

C increases core loss and causes magnetic aging due to precipitation of fine carbides to cause inhibition of grain growth. Therefore, a lower C content is better. Such a phenomenon is significant when the C content is greater than 0.010%. Therefore, the C content is set to 0.010% or less. Incidentally, the lower limit of the C content is not limited in particular, but in consideration of the cost of a decarburization treatment during smelting, it is

preferably set to 0.0005% or more.

[0024] (Si: 1.50% ~ 4.00%)

Si increases electrical resistance, reduces eddy current loss, reduces core loss, and increases a yield ratio to improve punchability of an iron core. When the Si content is less than 1.50%, these effects cannot be fully obtained. Therefore, the Si content is set to 1.50% or more. On the other hand, when the Si content is greater than 4.00%, the magnetic flux density decreases, the punchability decreases due to an excessive increase in hardness, and performing cold rolling becomes difficult. Therefore, the Si content is set to 4.00% or less.

[0025] (sol. Al: 0.3% ~ 0.7%)

sol. Al increases electrical resistance, reduces eddy current loss, and reduces core loss. sol. Al also contributes to improvement in relative magnitude of a magnetic flux density B₅₀ relative to a saturation magnetic flux density. Here, the magnetic flux density B₅₀ is a magnetic flux density in a magnetic field of 5000 A/m. Further, in order to reduce TiN, which is a fine precipitate that inhibits the grain growth of {411}<110> grains due to bulging, it is necessary to facilitate the precipitation of AlN, which is relatively coarse compared to TiN, thereby reducing the number density of precipitates. When the sol. Al content is less than 0.3%, these effects cannot be fully obtained. In addition, sol. Al also has a desulfurization-promoting effect in steelmaking.

Therefore, the sol. Al content is set to 0.3% or more. On the other hand, when the sol. Al content is greater than 1.0%, the magnetic flux density decreases, the yield ratio decreases, and the punchability decreases. Therefore, the sol. Al content is set to 0.7% or less. The sol. Al content is preferably 0.5% ~ 0.6%.

[0026] (S: 0.010% or less)

S is not an essential element and is contained, for example, in steel as an impurity. S inhibits recrystallization and crystal grain growth during annealing due to precipitation of fine MnS. Therefore, a lower S content is better. The increase in core loss and the decrease in magnetic flux density due to such inhibition of recrystallization and crystal grain growth are significant when the S content is greater than 0.010%. Therefore, the S content is set to 0.010% or less. Incidentally, the lower limit of the S content is not limited in particular, but in consideration of the cost of a decarburization treatment during smelting, it is preferably set to 0.0003% or more.

[0027] (N: 0.010% or less)

N deteriorates magnetic properties through formation of fine precipitates such as TiN, and thus a lower N content is better. Therefore, the N content is set to 0.010% or less. Incidentally, the lower limit of the N content is not limited in particular, but in consideration of the cost of a denitrification treatment during smelting, the N content is preferably

set to 0.001% or more.

[0028] (Ti: 0.0005% ~ 0.0020%)

Ti is an element that is normally contained in molten steel at the stage of steelmaking, and from the viewpoint of smelting costs, the Ti content is set to 0.0005% or more. Further, when the Ti content exceeds 0.0020%, a large amount of TiN being a fine precipitate is formed to deteriorate magnetic properties.

Therefore, the Ti content is set to 0.0020% or less.

The Ti content is preferably 0.0010% ~ 0.0015%.

[0029] (One or more selected from the group consisting of Mn, Ni, and Cu: 2.50% ~ 5.00% in total)

These elements are elements necessary for causing α - γ transformation, and further, as will be described below, they are elements that contribute to the formation of AlN, and thus it is necessary to contain at least one of these elements in a total amount of 2.50% or more. On the other hand, when the total content exceeds 5.00%, the cost increases and the magnetic flux density decreases in some cases.

Therefore, the total content of at least one of these elements is set to 5.00% or less.

[0030] Further, the following additional conditions are set to be satisfied as the condition under which the α - γ transformation can occur. That is, when the Mn content (mass%) is set to [Mn], the Ni content (mass%) is set to [Ni], the Cu content (mass%) is set to [Cu], the Si content (mass%) is set to [Si], the sol. Al content (mass%) is set to [sol. Al], and the P content

(mass%) is set to [P], Expression (1) below is satisfied in mass%.

$$(2 \times [\text{Mn}] + 2.5 \times [\text{Ni}] + [\text{Cu}]) - ([\text{Si}] + 2 \times [\text{sol. Al}] + 4 \times [\text{P}]) \geq 3.0\% \quad \dots(1)$$

When Expression (1) described previously is not satisfied, either the α - γ transformation does not occur, or even if the α - γ transformation does occur, rolling can no longer be performed at a temperature in the γ region or the γ - α mixed region (Arl point or higher) in a later-described rolling step, resulting in a low magnetic flux density.

[0031] Further, it was found out that when a component balance of specific components is adjusted in order to reduce the number density of fine precipitates of TiN and the like, AlN, which is relatively coarse compared to TiN, is more likely to be formed, thereby making it possible to reduce the number density of fine precipitates.

[0032] When the concentration of Si is increased, the α -phase is stabilized during a slab heating step, resulting in that it is possible to reduce MnS, which is derived from S that is easily dissolved in the α -phase, and increase AlN, which is derived from N that is easily dissolved in the γ -phase. However, when the concentration of Si is increased, the amount of C dissolved in steel decreases during cold rolling, resulting in that TiC is more likely to be formed. In addition, when the concentration of Mn is increased, MnS is more likely to be formed, and when the

concentration of Al is increased, AlN is more likely to be formed. The present inventors conducted various studies focusing on the formation balance of these precipitates, and found out a correlation between the Si content, the Mn content, and the Al content in order to reduce the number density of fine precipitates. Specifically, the relationship between the Si content, the sol. Al content, and the Mn content satisfies the following (2) Expression.

$$10.5 \leq ([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}] \leq 12.5 \quad \dots(2)$$

[0033] Incidentally, the upper limit and the lower limit of (2) Expression are set to 10.5 and 12.5, respectively, but when they fall outside these ranges, it becomes difficult to control the formation of AlN. When $([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}]$ is less than 10.5 in (2) Expression, the formation of AlN is excessive and the grain growth is inhibited by AlN. On the other hand, when $([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}]$ exceeds 12.5, the formation of AlN is insufficient and precipitates such as TiC and MnS increase, failing to reduce the number density of fine precipitates.

[0034] (Co: 0.000% ~ 1.000%)

Co is an element effective for causing α - γ transformation, and thus it may be contained as necessary, but when it is contained excessively, the cost increases and the magnetic flux density decreases in some cases. Therefore, the Co content is set to 1.000% or less.

[0035] (Sn: 0.000% ~ 0.400%, Sb: 0.000% ~ 0.400%)

Sn and Sb improve a texture after cold rolling and recrystallization, and increase the magnetic flux density. Therefore, these elements may be contained as necessary, but when they are contained excessively, they embrittle steel. Therefore, the Sn content and the Sb content are both set to 0.400% or less. When further effects such as magnetic properties are given as described above, it is preferable to contain one or more selected from the group consisting of Sn: 0.020% ~ 0.400% and Sb: 0.020% ~ 0.400%.

[0036] (P: 0.000% ~ 0.400%)

P may be contained in order to ensure hardness of the steel sheet after recrystallization, but when it is contained excessively, embrittlement of steel is caused. Therefore, the P content is set to 0.400% or less. When further effects such as magnetic properties are given, it is preferable to contain 0.020% ~ 0.400% of P.

[0037] Next, there is explained a method of measuring the area ratio of specific oriented grains in the non-oriented electrical steel sheet according to this embodiment. The area ratio of specific oriented grains is measured by extracting a target specific orientation (a tolerance is set to 10° , hereafter referred to as within a tolerance of 10°) from a measurement region observed by a scanning electron microscope (SEM: Scanning Electron Microscope) equipped with electron back scattering diffraction (EBSD: Electron Back Scattering Diffraction) under the following measurement

conditions using OMI Analysis 7.3 (manufactured by TSL). An extracted area is divided by the area of the measurement region to find a percentage. This percentage is set to the area ratio of the specific oriented grains. Hereinafter, the "area ratio of crystal grains having a crystal orientation in a $\{hkl\}\langle uvw \rangle$ orientation (within a tolerance of 10°) to the measurement region" and the "area ratio of crystal grains having a crystal orientation in a $\{hkl\}$ orientation (within a tolerance of 10°) to the measurement region" may be simply referred to as a " $\{hkl\}\langle uvw \rangle$ ratio" and a " $\{hkl\}$ ratio" respectively. Hereinafter, in the description of crystal orientations, it is assumed that the tolerance is within 10° .

[0038] In the non-oriented electrical steel sheet according to this embodiment, the $\{411\}\langle 011 \rangle$ ratio is set to 15% or more when the steel sheet surface is measured by the SEM-EBSD. When the $\{411\}\langle 011 \rangle$ ratio is less than 15%, it is impossible to obtain excellent magnetic properties. Therefore, the $\{411\}\langle 011 \rangle$ ratio is set to 15% or more, and preferably set to 25% or more.

[0039] Incidentally, details of the measurement conditions for finding the area ratio of each oriented grain are as follows.

- Measuring device: SEM model number "JSM-6400 (manufactured by JEOL Ltd.)" and EBSD detector model number "HIKARI (manufactured by TSL)" are used

- Step interval: 0.3 μm (after intermediate annealing, after skin pass rolling), or 5.0 μm (after finish annealing)
- Magnification: 1000 times (after intermediate annealing, after skin pass rolling), or 100 times (after finish annealing)
- Measurement object: Center layer (sheet thickness 1/2 portion) of a Z surface in the center in the C direction of the steel sheet (cut surface of the steel sheet cut in the sheet thickness direction)
- Measurement region: Region having 1000 μm or more in the L direction and having 1000 μm or more in the C direction

[0040] Further, when the steel sheet surface is measured by the SEM-EBSD, it is preferable that the steel sheet should have a maximum intensity at $\phi_1 = 0 \sim 10^\circ$ among $\phi_1 = 0 \sim 90^\circ$ and $\Phi = 20^\circ$, and should have a maximum intensity at $\Phi = 5$ to 35° among $\phi_1 = 0^\circ$ and $\Phi = 0 \sim 90^\circ$. Having a maximum intensity at $\phi_1 = 0 \sim 10^\circ$ among $\phi_1 = 0 \sim 90^\circ$ and $\Phi = 20^\circ$ is synonymous with having a maximum intensity near the $\{411\}\langle 011 \rangle$ orientation among the $\{411\}\langle uvw \rangle$ orientations. The $\{411\}\langle 011 \rangle$ orientation has excellent magnetic properties in the 45° direction, compared to $\{411\}\langle 148 \rangle$, and so on. It is more preferable to have a maximum intensity at $\phi_1 = 0 \sim 5^\circ$ among $\phi_1 = 0 \sim 90^\circ$ and $\Phi = 20^\circ$.

[0041] On the other hand, having a maximum intensity at $\Phi = 5 \sim 35^\circ$ among $\phi_1 = 0^\circ$ and $\Phi = 0^\circ \sim 90^\circ$ when the

steel sheet surface is measured by the SEM-EBSD is synonymous with having a maximum intensity near the $\{411\}\langle 011\rangle$ orientation among the $\{hkl\}\langle 011\rangle$ orientations. Since the $\{411\}\langle 011\rangle$ orientation has excellent magnetic properties and lower stress sensitivity than the $\{100\}\langle 011\rangle$ orientation, there is little magnetic deterioration in an interlocking core or the like. It is more preferable to have a maximum intensity at $\Phi = 20^\circ \sim 30^\circ$ among $\phi_1 = 0^\circ$ and $\Phi = 0 \sim 90^\circ$.

[0042] There is explained a method of determining the maximum intensity in a specific orientation range of the steel sheet here. In the measurement region by the SEM-EBSD, an orientation distribution function (ODF: Orientation Distribution Function) is created under the following conditions using OIM Analysis 7.3. Then, data of the created ODF are output, and the point having a maximum ODF value within a specific orientation range (defining a range by angles of ϕ_1 and Φ) is set as the maximum intensity.

[0043] Further, there is explained a method of determining the ODF intensity of a specific orientation in the steel sheet. In the measurement region by the SEM-EBSD, an ODF is created under the following conditions using OIM Analysis 7.3. Then, data of the created ODF are output, and the ODF value in a specific orientation (defining an orientation by angles of ϕ_1 and Φ) is set as the ODF intensity.

[0044] Incidentally, the details of ODF creation

conditions are as follows.

- Series Rank [L]: 16
- Gaussian Half-Width [degrees]: 5
- Sample Symmetry: Triclinic (None)
- Bunge Euler Angles: $\phi_1 = 0^\circ \sim 90^\circ$, $\phi_2 = 45^\circ$, $\Phi = 0^\circ \sim 90^\circ$

[0045] Further, the area ratio of crystal grains having a specific orientation (within a tolerance of 10°) to the entire visual field when measurement is performed by the SEM-EBSD is represented as follows. When the area ratio of crystal grains having a crystal orientation in the $\{hkl\}\langle uvw \rangle$ orientation (within a tolerance of 10°) to the entire visual field is represented by $A_{hkl-uvw}$, and the area ratio of crystal grains having a crystal orientation in the $\{hkl\}$ orientation (within a tolerance of 10°) to the entire visual field is represented by A_{hkl} , Expressions (3) and (4) below are both satisfied.

$$A_{411-011}/A_{411} - 148 \geq 1.1 \quad \dots(3)$$

$$A_{411-011}/A_{100} - 011 \geq 2.0 \quad \dots(4)$$

[0046] Further, the magnetic properties are superior when there are many crystal grains having a crystal orientation in the $\{411\}$ orientation, but the magnetic properties are inferior when there are many crystal grains having a crystal orientation in the $\{111\}$ orientation. Therefore, it is preferable that the $\{411\}$ ratio should exceed the $\{111\}$ ratio, and more preferably, the $\{411\}$ ratio is set to equal to or more than twice the $\{111\}$ ratio.

[0047] Next, the number density of precipitates in the non-oriented electrical steel sheet according to this embodiment is explained. The precipitates here are mainly fine precipitates such as TiN, and further include fine precipitates such as AlN and MnS. Since Ti and Al are contained as the chemical composition, it is practically difficult to reduce the number density of these precipitates to smaller than 0.0001 pieces/ μm^2 . On the other hand, when the number of precipitates increases and the number density of the precipitates is greater than 0.3000 pieces/ μm^2 , TiN (or AlN) being a precipitate becomes excessive and the magnetic properties deteriorate. Therefore, the number density of precipitates in the non-oriented electrical steel sheet is set to 0.0001 pieces/ μm^2 ~ 0.3000 pieces/ μm^2 .

[0048] The number density of precipitates is measured, for example, by observing a sample by an extraction replica method using a transmission electron microscope (TEM) and calculating the number density.

Specifically, a transmission electron microscope is used to observe a surface at a depth position of 1/2 of a sheet thickness t from the steel sheet surface by an extraction replica method, and the number of fine precipitates having a circle-equivalent diameter of 20 ~ 500 nm in a visual field of $5\ \mu\text{m} \times 5\ \mu\text{m}$ is counted in the same sample. However, during observation, it is set not to include in the visual field, coarse precipitates (circle-equivalent diameter of 1 μm or

more) that are not included in the calculation of the number density. Then, the number of precipitates is counted in 10 or more visual fields in the same sample, and the average value of counted numbers is calculated as the number density of precipitates. Incidentally, image analysis software may be used when counting the number of precipitates.

[0049] Next, the thickness of the non-oriented electrical steel sheet according to this embodiment is explained. The sheet thickness of the non-oriented electrical steel sheet according to this embodiment is not limited in particular. A preferable sheet thickness of the non-oriented electrical steel sheet according to this embodiment is 0.25 ~ 0.5 mm.

Normally, as the sheet thickness decreases, the core loss decreases, but the magnetic flux density also decreases. In this regard, as long as the sheet thickness is 0.25 mm or more, the core loss is lower and the magnetic flux density is higher. Further, as long as the sheet thickness is 0.50 mm or less, a low core loss can be maintained. A more preferable lower limit value of the sheet thickness is 0.30 mm.

[0050] Further, as excellent magnetic properties in the non-oriented electrical steel sheet according to this embodiment, it is preferable that the magnetic flux density B₅₀ in the 45° direction relative to the rolling direction should be 1.70 T or more and a core loss W_{10/400} in the 45° direction relative to the rolling direction should be 14 W/kg or less. Further,

as for strength, a tensile strength is preferably 600 MPa or more.

[0051] Incidentally, the tensile strength is found by taking a JIS No. 5 test piece with the rolling direction of the non-oriented electrical steel sheet set as the longitudinal direction and conducting a tensile test in accordance with JIS Z2241: 2011.

[0052] The above-described non-oriented electrical steel sheet has characteristics of a non-oriented electrical steel sheet manufactured by performing finish annealing. Hereinafter, the characteristics of a non-oriented electrical steel sheet before performing finish annealing (after performing skin pass rolling) will be explained.

[0053] The non-oriented electrical steel sheet after skin pass rolling (before finish annealing) according to this embodiment has the following GOS (Grain Orientation Spread) value (G_s). Here, the GOS value is an average of orientation differences among all measurement points (pixels) in the same grain, and the GOS value is high when a crystal grain has many strains. After skin pass rolling, when the GOS value G_s is small, that is, it is in a low strain state, grain growth due to bulging easily occurs during finish annealing of the next step. Thus, the upper limit of the GOS value G_s after skin pass rolling is set to 3.0. On the other hand, when the GOS value G_s is less than 0.8, the amount of strain becomes too small, and the finish annealing time required for the grain growth due

to bulging becomes long. Therefore, the GOS value G_s after skin pass rolling is set to 0.8 or more and 3.0 or less.

[0054] Here, there is explained a method of calculating G_s in the steel sheet. Analysis is performed with OIM Analysis 7.3 using the SEM-EBSD data used when the above-described crystal orientation is defined, to thereby find the number average value of the GOS value, and the value is set as G_s .

[0055] Further, in the non-oriented electrical steel sheet after skin pass rolling (before finish annealing), as an α -fiber ratio is higher, the magnetic properties after finish annealing become more advantageous. Here, there is explained a method of measuring the α -fiber ratio. In this embodiment, the α -fiber is set to be in the $\{hkl\}\langle 011 \rangle$ orientation. In the measurement region by the SEM-EBSD, the $\{hkl\}\langle 011 \rangle$ orientation is extracted (within a tolerance of 10°) using OMI Analysis 7.3. An extracted area is divided by the area of the measurement region to find a percentage. This percentage is set as the α -fiber ratio.

[0056] In the non-oriented electrical steel sheet after skin pass rolling (before finish annealing), the α -fiber ratio is set to 20.0% or more, and is preferably 25.0% or more.

[0057] Further, in the non-oriented electrical steel sheet after skin pass rolling (before finish annealing), the ODF intensity in the $\{100\}\langle 011 \rangle$

orientation is set to 15.0 or less. Here, the ODF intensity in the $\{100\}\langle 011 \rangle$ orientation is an ODF value at $\phi_1 = 0^\circ$ and $\Phi = 0^\circ$ of the ODF created using the SEM-EBSD data used when the above-described crystal orientation is defined. Since the $\{411\}\langle 011 \rangle$ orientation has excellent magnetic properties and lower stress sensitivity than the $\{100\}\langle 011 \rangle$ orientation, there is little magnetic deterioration in an interlocking core or the like. By setting the ODF intensity in the $\{100\}\langle 011 \rangle$ orientation after skin pass rolling (before finish annealing) to 15.0 or less, the $\{411\}\langle 011 \rangle$ orientation after subsequent finish annealing can be strengthened.

[0058] The non-oriented electrical steel sheet according to this embodiment can be widely applied to applications in which magnetic properties (high magnetic flux density and low core loss) are required by forming a core, and can also be applied to applications in which particularly high strength is also required, such as rotors. Specifically, a motor core is formed by stacking the non-oriented electrical steel sheets according to this embodiment, and the non-oriented electrical steel sheet according to this embodiment can be widely applied to applications such as a motor including the formed motor core, and can also be applied to a rotor that forms the motor.

[0059] Next, there is explained an example of a method of manufacturing the non-oriented electrical steel sheet according to this embodiment. In this

embodiment, hot rolling, cold rolling, intermediate annealing, a second soft reduction cold rolling (hereinafter to be referred to as skin pass rolling), and finish annealing are performed.

[0060] In the hot rolling, hot rolling is performed on the steel material that satisfies the above-described chemical composition to manufacture a hot-rolled sheet. The hot rolling step includes a heating step and a rolling step.

[0061] The steel material is, for example, a slab manufactured by normal continuous casting, and the steel material having the above-described composition is manufactured by a well-known method. For example, a molten steel is manufactured in a converter, an electric furnace, or the like. The manufactured molten steel is secondarily smelted in a degassing facility or the like to obtain a molten steel having the above-described chemical composition. The molten steel is used to cast the slab by a continuous casting method or an ingot-making method. The cast slab may be bloom-rolled.

[0062] In the heating step, it is preferable to heat the steel material having the above-described chemical composition to 1000 ~ 1080°C in order to prevent Ti from being solid-dissolved and precipitating as TiN. Specifically, the steel material is charged into a heating furnace or a soaking furnace, and heated in the furnace. A retention time at the above-described heating temperature in the heating furnace or the

soaking furnace is not particularly limited, but is, for example, 30 ~ 200 hours. Further, when heating the slab, the temperature rising rate from 600°C ~ the heating temperature is set to 0.02°C/sec or less in order to prevent Ti from being solid-dissolved.

[0063] In the rolling step, multiple passes of rolling are performed on the steel material heated in the heating step to manufacture a hot-rolled sheet. Here, the "pass" means that the steel sheet passes through one rolling stand having a pair of work rolls and is subjected to rolling. As the hot rolling, for example, tandem rolling may be performed using a tandem rolling mill including a plurality of rolling stands arranged in a row (each rolling stand has a pair of work rolls) to perform multiple passes of rolling, or reverse rolling having a pair of work rolls may be performed to perform multiple passes of rolling. In terms of productivity, it is preferable to perform multiple passes of rolling using the tandem rolling mill.

[0064] Rolling in the rolling step (rough rolling and finish rolling) is performed at a temperature in the γ region or the γ - α mixed region (Ar1 point or higher). That is, hot rolling is performed so that the temperature when the steel sheet passes through the final pass of finish rolling (a finish rolling temperature FT (°C)) is the Ar1 point or higher.

[0065] Here, the finish rolling temperature FT means a surface temperature (°C) of the steel sheet on the exit side of a rolling stand where final pass reduction is

performed in the above-described rolling step during the hot rolling step. The finish rolling temperature FT can be measured by, for example, a thermometer installed on the exit side of the rolling stand where final pass reduction is performed. Incidentally, the finish rolling temperature FT means an average value of temperature measurement results of 10 sections obtained by the steel sheet entire length being divided into 10 equal sections in the rolling direction, excluding one section at the leading end and one section at the trailing end, for example.

[0066] Thereafter, by transformation from austenite to ferrite due to cooling after the rolling step, high strain and moderately fine crystal grains are obtained. Cooling conditions are that the cooling is started 0.1 seconds after the steel sheet has passed through the final pass of finish rolling, and the cooling is performed so that a surface temperature of the hot-rolled sheet is 300°C or higher and the Ar1 point or lower after 3 seconds. In this way, immediate rapid cooling is not performed. By avoiding the immediate rapid cooling as described above, no special rapid cooling device is required, which is also advantageous in terms of manufacture (cost). When cold rolling is then performed at a suitable grain diameter that does not allow excessive refinement, the α -fiber develops after intermediate annealing, and after the subsequent skin pass and finish annealing, the {411}<011> orientation, which does not easily develop normally,

can be developed.

[0067] In addition, it is presumed that the texture of the hot-rolled sheet becomes a structure in which unrecrystallized austenite has been transformed if immediate rapid cooling is performed and becomes a structure in which partially recrystallized austenite has been transformed if immediate rapid cooling is omitted. In the case where immediate rapid cooling is performed after finish rolling, the texture is accumulated in the $\{100\}\langle 011 \rangle$ orientation in the structure after finish annealing thereafter, and in the case where immediate rapid cooling is omitted after finish rolling, the texture is accumulated in the $\{411\}\langle 011 \rangle$ orientation in the structure after finish annealing thereafter. Thus, transforming partially recrystallized austenite is considered important to strengthen the $\{411\}\langle 011 \rangle$ orientation.

[0068] Here, the cooling conditions are preferably such that the average crystal grain diameter in the hot-rolled sheet before cold rolling is 3 to 10 μm . If the crystal grains are coarsened excessively, it becomes difficult for the α -fiber to develop after cold rolling and intermediate annealing, and a desired $\{411\}\langle 011 \rangle$ ratio is not obtained in some cases. Further, if the crystal grains are refined excessively, a desired $\{411\}\langle 011 \rangle$ ratio is not obtained. Therefore, in order to achieve an average crystal grain diameter of 3 ~ 10 μm in the hot-rolled sheet before cold rolling, the temperature is set to a temperature of the

Ar1 point or lower within 3 seconds after the steel sheet has passed through the final pass of finish rolling. As for the method of measuring the grain diameter, the grain diameter is measured by an intercept method, for example.

[0069] Further, the surface temperature of the hot-rolled sheet 3 seconds after the steel sheet has passed through the final pass of finish rolling is measured by the following method. At a hot-rolling facility line of electrical steel sheets, a cooling device and a transfer line (for example, a transfer roller) are arranged downstream of a hot rolling mill. A thermometer that measures the surface temperature of the hot-rolled sheet is arranged on the exit side of the rolling stand where the final pass in the hot rolling mill is performed. Further, a plurality of thermometers are also arranged along the transfer line at the transfer roller arranged downstream of the rolling stand. The cooling device is arranged downstream of the rolling stand where the final pass is performed. On the entry side of a water-cooling device, a thermometer is arranged. The cooling device may be, for example, a well-known water-cooling device or a well-known forced air cooling device. Preferably, the cooling device is the water-cooling device. The coolant of the water-cooling device may be water or a mixed fluid of water and air.

[0070] The temperature of the hot-rolled sheet is measured using the thermometer arranged at the hot-

rolling facility line. Then, the temperature 3 seconds after the steel sheet has passed through the final pass of finish rolling is found.

[0071] Thereafter, coiling is performed without performing hot-rolled sheet annealing, and cold rolling is performed on the hot-rolled sheet. Incidentally, the hot-rolled sheet annealing mentioned here means, for example, a heat treatment with a temperature rising temperature of the A_{c1} point or lower and 300°C or higher.

[0072] Without performing the hot-rolled sheet annealing on the hot-rolled sheet, cold rolling is performed on the hot-rolled sheet. As the cold rolling, for example, tandem rolling may be performed using a tandem rolling mill including a plurality of rolling stands arranged in a row (each rolling stand has a pair of work rolls) to perform multiple passes of rolling. Further, reverse rolling may be performed using a Sendzimir rolling mill or the like including a pair of work rolls to perform one pass or multiple passes of rolling. In terms of productivity, it is preferable to perform multiple passes of rolling using the tandem rolling mill.

[0073] In the cold rolling, cold rolling is performed without performing an annealing treatment in the middle of the cold rolling. For example, in the case where reverse rolling is performed and multiple passes of cold rolling are performed, the multiple passes of cold rolling are performed without performing an annealing

treatment between the passes of cold rolling.

Incidentally, only one pass of cold rolling may be performed using a reverse-type rolling mill. Further, in the case where cold rolling is performed using a tandem-type rolling mill, cold rolling is performed continuously in multiple passes (passes of respective rolling stands).

[0074] In this embodiment, a reduction ratio RR1 (%) in the cold rolling is preferably set to 75 ~ 95%. Here, the reduction ratio RR1 is defined as follows.

Reduction ratio RR1 (%) = (1 - sheet thickness after final pass rolling in cold rolling / sheet thickness before first pass rolling in cold rolling) × 100

[0075] When the cold rolling is finished, intermediate annealing is subsequently performed. In this embodiment, it is preferable to control an intermediate annealing temperature T1 (°C) to the Acl point or lower. When the intermediate annealing temperature exceeds the Acl point, a part of the structure of the steel sheet is transformed to austenite and the strain in the steel sheet decreases excessively.

Incidentally, if the intermediate annealing temperature is too low, recrystallization does not occur, and the grains in the {411}<011> orientation do not grow sufficiently during the subsequent skin pass rolling and finish annealing, and the magnetic flux density does not increase in some cases. Therefore, it is preferable to set the intermediate annealing

temperature T1 (°C) to 600°C or higher.

[0076] Here, the intermediate annealing temperature T1 (°C) is the sheet temperature (the temperature of the steel sheet surface) near an extraction port of an annealing furnace. The sheet temperature at the annealing furnace can be measured by a thermometer arranged at the extraction port of the annealing furnace.

[0077] Incidentally, the retention time at the intermediate annealing temperature T1 in the intermediate annealing step may be any time well known to those skilled in the art. The retention time at the intermediate annealing temperature T1 is, for example, 5 ~ 60 seconds, but the retention time at the intermediate annealing temperature T1 is not limited to this. Further, a temperature rising rate up to the intermediate annealing temperature T1 may also be a well-known condition. The temperature rising rate up to the intermediate annealing temperature T1 is, for example, 10.0 ~ 20.0°C/second, but the temperature rising rate up to the intermediate annealing temperature T1 is not limited to this.

[0078] The atmosphere during the intermediate annealing is not particularly limited, but for the atmosphere during the intermediate annealing, for example, an atmosphere gas (dry) containing 20% H₂ with a balance consisting of N₂ is used. The cooling rate of the steel sheet after the intermediate annealing is not particularly limited, and is, for example, 5.0 ~

60.0°C/second.

[0079] When up to the intermediate annealing is finished under the conditions described above, a cold-rolled steel sheet obtained has an α -fiber ratio (within a tolerance of 10°) of 15% or more when measured by the SEM-EBSD. As above, in order to achieve 15.0% or more of the α -fiber ratio (within a tolerance of 10°) at a stage before the skin pass rolling, it is necessary to have the α - γ transformation system composition (high concentration of γ former elements of Mn, Ni, and Cu, hereinafter referred to as high Mn, and the like) and perform the steps from hot rolling to intermediate annealing under the conditions described previously, and particularly, the cooling conditions after the finish rolling are important. The α -fiber, which easily produces the $\{411\}\langle 011\rangle$ orientation, is developed by transformation from partially recrystallized austenite to ferrite, cold rolling the hot-rolled sheet having an average grain diameter of 3 to 10 μm after hot rolling, and then intermediate annealing the steel sheet. As described previously, when the immediate rapid cooling is performed, the structure becomes the structure in which unrecrystallized austenite has been transformed, and does not become the structure in which partially recrystallized austenite has been transformed. The cold-rolled steel sheet manufactured in this manner is subjected to skin pass rolling under later-described conditions, and further subjected to finish annealing,

and thereby the non-oriented electrical steel sheet of the present invention is obtained.

[0080] When the intermediate annealing is finished, skin pass rolling is next performed. Specifically, rolling (cold rolling) is performed on the cold-rolled steel sheet after the intermediate annealing step at normal temperature in the atmosphere. Here, for the skin pass rolling, for example, the reverse rolling mill such as the above-described Sendzimir rolling mill or the tandem rolling mill is used.

[0081] In the skin pass rolling, rolling is performed without performing an annealing treatment in the middle. For example, in the case where the reverse rolling is performed and the skin pass rolling is performed in multiple passes, multiple passes of rolling are performed without performing an annealing treatment between the passes. Incidentally, only one pass of skin pass rolling may be performed using the reverse-type rolling mill. Further, when the skin pass rolling is performed using the tandem-type rolling mill, rolling is performed continuously in multiple passes (passes of respective rolling stands).

[0082] As described above, in this embodiment, after strain is introduced into the steel sheet by the hot rolling and the cold rolling, the strain introduced into the steel sheet is temporarily reduced by the intermediate annealing. Then, the skin pass rolling is performed. Thereby, the intermediate annealing is performed while reducing the strain introduced

excessively by the cold rolling in the intermediate annealing, thereby inhibiting preferential recrystallization of {111} grains in the steel sheet surface and allowing the {411}<011> oriented crystal grains to remain. Then, in the skin pass rolling, an appropriate amount of strain is introduced into each crystal grain in the steel sheet, to bring the steel sheet into a state in which grain growth due to bulging is likely to occur in the finish annealing of the next step.

[0083] In this embodiment, a reduction ratio RR2 in the skin pass rolling is set to 5 ~ 20%. Here, the reduction ratio RR2 is defined as follows.

Reduction ratio RR2 (%) = (1 - sheet thickness after final pass rolling in skin pass rolling / sheet thickness before first pass rolling in skin pass rolling) × 100

[0084] Here, when the reduction ratio RR2 is less than 5%, the amount of strain becomes too small, and the finish annealing time required for the grain growth due to bulging becomes long. Further, when the reduction ratio RR2 exceeds 20%, the amount of strain becomes too large, and normal grain growth occurs in place of bulging and {411}<148> and {111}<011> grow during the finish annealing. Therefore, the reduction ratio RR2 is set to 5 ~ 20%.

[0085] The number of passes in the skin pass rolling may be only one pass (that is, only one rolling), or may be multiple passes of rolling.

[0086] As described previously, the GOS value and the α -fiber ratio described previously can be obtained by causing recrystallization in the steel sheet having the α - γ transformation system composition (high Mn, and the like) by the intermediate annealing and performing the skin pass rolling under the conditions described above.

[0087] After the skin pass rolling, finish annealing is performed at 750°C or higher and the Acl point or lower for 2 hours or longer. When a finish annealing temperature T2 (°C) is set to less than 750°C, the grain growth due to bulging does not occur sufficiently. In this case, the degree of accumulation of the {411}<011> orientation decreases. Further, when the finish annealing temperature T2 is higher than the Acl point, a part of the structure of the steel sheet is transformed to austenite, the grain growth due to bulging does not occur, and a desired {411}<011> ratio is not obtained. Further, when the annealing time is less than 2 hours, even if the finish annealing temperature T2 is 750°C or higher and the Acl point or lower, the grain growth due to bulging does not occur sufficiently, and the degree of accumulation of the {411}<011> orientation decreases. Incidentally, the upper limit of the annealing time for the finish annealing is not particularly limited, but a preferable upper limit is 10 hours because the effect is saturated if the annealing time exceeds 10 hours.

[0088] Here, the finish annealing temperature T2 is set to the sheet temperature (the temperature of the

steel sheet surface) near an extraction port of an annealing furnace. The furnace temperature of the annealing furnace can be measured by a thermometer arranged at the extraction port of the annealing furnace.

[0089] Incidentally, a temperature rising rate TR2 up to the finish annealing temperature T2 in the finish annealing step may be any temperature rising rate well known to those skilled in the art, and a retention time Δt_2 (sec) at the finish annealing temperature T2 may also be any time well known to those skilled in the art. Here, the retention time Δt_2 means the retention time after the surface temperature of the steel sheet reaches the finish annealing temperature T2.

[0090] A preferable temperature rising rate TR2 up to the finish annealing temperature T2 in the finish annealing step is set to 0.1°C/second or more and less than 10.0°C/second. As long as the temperature rising rate TR2 is 0.1°C/second or more and less than 10.0°C/second, the grain growth due to bulging occurs sufficiently. In this case, the degree of accumulation of the {411}<011> crystal orientation further increases, and the crystal grains in the ND plane at the center position of the sheet thickness are also further less likely to vary.

[0091] The temperature rising rate TR2 is found by the following method. A thermocouple is attached to the steel sheet having the above-described chemical composition and obtained by performing the steps from

the hot rolling to the skin pass, thereby obtaining a sample steel sheet. Temperature rises in the sample steel sheet with the thermocouple attached thereto, and the time from when the temperature rising starts until the temperature reaches the finish annealing temperature T2 is measured. The temperature rising rate TR2 is found based on the measured time.

[0092] The retention time Δt_2 at the finish annealing temperature T2 in the finish annealing step is 2 hours or longer. As long as the retention time Δt_2 is 2 hours or longer, the grain growth of the {411}<110> grains occurs due to bulging, and the strength is increased by grain refining strengthening. In this case, the degree of accumulation of the {411}<011> crystal orientation further increases, and the crystal grains in the ND plane at the center position of the sheet thickness are also further less likely to vary. The lower limit of the retention time Δt_2 is 2 hours, and preferably 3 hours. As described previously, a preferable upper limit of the retention time Δt_2 is 10 hours, and more preferably 5 hours.

[0093] The atmosphere during the finish annealing step is not particularly limited. For example, an atmosphere gas (dry) containing 20% H₂ with a balance consisting of N₂ is used for the atmosphere during the finish annealing step. The cooling rate of the steel sheet after the finish annealing is not limited in particular. The cooling rate is 5 ~ 20°C/second, for example.

[0094] Incidentally, the non-oriented electrical steel sheet obtained after the skin pass rolling may be shipped without being subjected to the finish annealing. For example, the steps up to the skin pass rolling may be performed at a steel sheet manufacturer, and punching or stacking of the non-oriented electrical steel sheet may be performed at a core manufacturer, which is a shipping destination, and then strain relief annealing may be performed in place of the finish annealing under the conditions of the annealing temperature of 750°C or higher and the Acl point or lower and the annealing time of 2 hours or longer.

[0095] As described above, the non-oriented electrical steel sheet according to this embodiment can be manufactured.

[0096] The method of manufacturing the non-oriented electrical steel sheet according to this embodiment is not limited to the above-described manufacturing steps.

[0097] For example, in the above-described manufacturing steps, shot blasting and/or pickling may be performed after hot rolling and before cold rolling. In the shot blasting, shot blasting is performed on the steel sheet after hot rolling to destroy and remove scales formed on the surface of the steel sheet after hot rolling. In the pickling, a pickling treatment is performed on the steel sheet after hot rolling. For example, an aqueous hydrochloric acid solution is used as a pickling bath for the pickling treatment. Scales formed on the surface of the steel sheet are removed by

pickling. Shot blasting may be performed after hot rolling and before cold rolling, and then pickling may be performed. Further, after hot rolling and before cold rolling, pickling may be performed without performing shot blasting. After hot rolling and before cold rolling, shot blasting may be performed without performing pickling. Incidentally, the shot blasting and the pickling are optional steps. Therefore, it is not necessary to perform both the shot blasting step and the pickling step after hot rolling and before cold rolling.

[0098] The method of manufacturing the electrical steel sheet according to this embodiment may further include coating after finish annealing. In the coating, an insulating coating film is formed on the surface of the steel sheet after finish annealing.

[0099] The type of insulating coating film is not particularly limited. The insulating coating film may be an organic component or an inorganic component, and the insulating coating film may contain an organic component and an inorganic component. The inorganic component is, for example, dichromate-boric acid-based, phosphoric acid-based, silica-based, and so on. The organic component is, for example, general resins based on acrylic, acrylic styrene, acrylic silicon, silicon, polyester, epoxy, and fluorine. When coatability is considered, a preferable resin is an emulsion-type resin. Insulating coating that exhibits adhesive performance when heated and/or pressurized may be

applied. The insulating coating having adhesive performance is, for example, resins based on acrylic, phenol, epoxy, and melamine.

[0100] Incidentally, the coating is an optional step. Therefore, it is not necessary to perform the coating after finish annealing.

[0101] Incidentally, the non-oriented electrical steel sheet according to this embodiment is not limited to the above-described manufacturing method. The manufacturing method is not limited to the above, as long as the composition is within the composition range described above, the area ratio of crystal grains having the $\{411\}<011>$ orientation (within a tolerance of 10°) to the entire visual field when the steel sheet surface is measured by electron back scattering diffraction (EBSD) is 15% or more, and the number density of precipitates is $0.0001 \text{ pieces}/\mu\text{m}^2 \sim 0.3000 \text{ pieces}/\mu\text{m}^2$.

EXAMPLE

[0102] Next, the non-oriented electrical steel sheet according to the embodiment of the present invention will be specifically explained with reference to examples. The examples to be explained below are merely examples of the non-oriented electrical steel sheet according to the embodiment of the present invention, and the non-oriented electrical steel sheet according to the present invention is not limited to the examples below.

[0103] (First example)

A molten steel was cast to fabricate an ingot containing components illustrated in Table 1 below. Here, "(1) Expression" in Table 1 represents the value of the left side of (1) Expression described previously, and "(2) Expression" in Table 1 represents the value of $([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}]$ in (2) Expression described previously. The fabricated ingot was then heated up to a slab heating temperature ST illustrated in Table 2 and hot rolled, and finish rolled at the finish rolling temperature FT illustrated in Table 2. Temperature rising rates from 600°C ~ the slab heating temperature ST are also illustrated in Table 2. Then, after passing through the final pass, cooling was performed under the cooling conditions illustrated in Table 2 (for the time from when the steel sheet passes through the final pass to when cooling is started, and at the temperature of the steel sheet 3 seconds after the steel sheet has passed through the final pass).

[0104] Then, on a hot-rolled steel sheet, hot-rolled sheet annealing was not performed, scales were removed by pickling, and cold rolling was performed at the reduction ratio $RR1$ illustrated in Table 2. Then, intermediate annealing was performed in an atmosphere of 20% hydrogen and 80% nitrogen, and the intermediate annealing temperature $T1$ was controlled to the temperature illustrated in Table 2, and the intermediate annealing was performed for 30 seconds.

[0105] Next, except for No. 9 and No. 10, skin pass

rolling was performed at the reduction ratio RR_2 illustrated in Table 2. Then, except for No. 9, finish annealing was performed in a 100% hydrogen atmosphere at the finish annealing temperature T_2 illustrated in Table 2. At this time, the retention time Δt_2 at the finish annealing temperature T_2 was set to the time illustrated in Table 2. Incidentally, before performing the finish annealing, the GOS value G_s was calculated under the measurement conditions described previously.

[0106] Further, in order to examine the texture obtained after the finish annealing, a part of the steel sheet was cut out, and the thickness of a cut-out test piece was reduced to $1/2$. The $\{411\}\langle 011 \rangle$ ratio was found by performing observation in a measurement region by the SEM-EBSD under the measurement conditions described previously. Further, the number density of precipitates was found by observing precipitates having a circle-equivalent diameter of 20 to 500 nm using a transmission electron microscope with an acceleration voltage of 200 kV by the extraction replica method under the measurement conditions described previously. The results are illustrated in Table 3.

[0107] Further, in order to examine the magnetic properties and the tensile strength obtained after the finish annealing, the magnetic flux density B_{50} and the core loss $W_{10/400}$ were measured, and at the same time, a core loss deterioration ratio of the core loss $W_{10/50}$ under compressive stress was found as an index of

stress sensitivity. As for the magnetic flux density B50, as a measurement sample, 55 mm square samples were taken in two directions of 0° and 45° relative to the rolling direction. Then, these two types of samples were measured, and the value in the 45° direction relative to the rolling direction was set as the magnetic flux density B50 in the 45° direction, and the average value of the values in the 0° direction, 45° direction, 90° direction, and 135° direction relative to the rolling direction was set as the all-around average of the magnetic flux density B50. As for the core loss W10/400, samples taken in the 45° direction relative to the rolling direction from the above-described measurement samples were used, and the average value in the 45° direction was found. Further, as for a core loss deterioration ratio W_x [%] of the core loss W10/50 under compressive stress, when the core loss W10/50 without stress was set to W10/50 (0) and the core loss W10/50 under a compressive stress of 10 MPa was set to W10/50 (10), the core loss deterioration ratio W_x was calculated by the following equation. The measurement results are illustrated in Table 3.

$$W_x = \{W10/50 (10) - W10/50 (0)\} / W10/50 (0)$$

[0108] [Table 1]

ITEM	CHEMICAL COMPOSITION (BALANCE IS Fe AND IMPURITIES)																	
No.	C	Si	sol.Al	S	N	Ti	Mn	Ni	Cu	Mn,Ni,Cu	Co	Sn	Sb	P	(1) EXPRESSION	(2) EXPRESSION	EVALUATION	
	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]	[MASS%]		
1	0.0020	2.5	0.6	0.0015	0.0015	0.0015	3.8	0.0	0.0	3.8	0.0	0.00	0.00	0.030	3.78	10.5	INVENTION EXAMPLE	
2	0.0018	2.5	0.1	0.0018	0.0011	0.0020	3.0	0.0	0.0	3.0	0.0	0.00	0.00	0.020	3.22	55.0	COMPARATIVE EXAMPLE	
3	0.0018	2.5	0.3	0.0018	0.0011	0.0005	1.2	0.0	0.0	1.2	0.0	0.00	0.00	0.020	-0.78	12.3	COMPARATIVE EXAMPLE	
4	0.0012	2.4	0.5	0.0015	0.0014	0.0020	3.2	0.2	0.0	3.4	0.0	0.03	0.01	0.000	3.50	11.2	INVENTION EXAMPLE	
5	0.0009	2.5	0.4	0.0008	0.0008	0.0015	3.5	0.0	0.2	3.7	0.2	0.00	0.11	0.080	3.58	15.0	COMPARATIVE EXAMPLE	
6	0.0018	2.5	0.6	0.0018	0.0011	0.0020	3.5	0.0	0.0	3.5	0.0	0.00	0.00	0.030	3.18	10.0	COMPARATIVE EXAMPLE	
7	0.0020	2.5	0.5	0.0015	0.0015	0.0015	3.6	0.0	0.2	3.8	0.1	0.05	0.00	0.030	3.78	12.2	INVENTION EXAMPLE	
8	0.0012	1.0	0.3	0.0015	0.0014	0.0050	3.0	0.0	0.0	3.0	0.0	0.15	0.00	0.010	4.36	13.3	COMPARATIVE EXAMPLE	
9	0.0012	3.5	0.8	0.0015	0.0014	0.0015	5.2	0.0	0.0	5.2	0.0	0.15	0.00	0.100	4.90	10.9	COMPARATIVE EXAMPLE	
10	0.0025	2.5	0.6	0.0012	0.0015	0.0010	3.8	0.0	0.0	3.8	0.0	0.02	0.00	0.030	3.78	10.5	COMPARATIVE EXAMPLE	
11	0.0015	2.5	0.6	0.0012	0.0015	0.0010	3.8	0.0	0.0	3.8	0.0	0.02	0.00	0.030	3.78	10.5	COMPARATIVE EXAMPLE	
12	0.0018	2.5	0.6	0.0023	0.0020	0.0020	3.8	0.0	0.0	3.8	0.0	0.03	0.00	0.020	3.82	10.5	COMPARATIVE EXAMPLE	
13	0.0009	2.0	0.5	0.0008	0.0008	0.0005	3.5	0.0	0.0	3.5	0.0	0.00	0.11	0.100	3.60	11.0	INVENTION EXAMPLE	

[0109] [Table 2]

ITEM No.	TRANSFORMATION POINT			HOT ROLLING STEP						COLD ROLLING STEP	INTERMEDIATE ANNEALING STEP	SKIN PASS ROLLING REDUCTION RATIO RR2	FINISH ANNEALING STEP		EVALUATION
	Ac1 POINT	Ac3 POINT	Ac1 POINT	SLAB HEATING TEMPERATURE ST	SLAB HEATING TEMPERATURE RISING RATE	FINISH ROLLING TEMPERATURE FT	COOLING START	TEMPERATURE AFTER 3 SECONDS	TEMPERATURE REDUCTION RATIO RR1				FINISH ANNEALING TEMPERATURE T2	FINISH ANNEALING TIME At2	
	[°C]	[°C]	[°C]	[°C]	[°C/SECOND]	[°C]	[SECOND]	[°C]	[%]	[°C]	[°C]	[%]	[°C]	[TIME]	
1	729	902	974	1050	0.01	850	0.10	700	86	700	700	15	800	3	INVENTION EXAMPLE
2	779	932	982	1050	1.00	950	0.10	200	86	700	700	15	800	3	COMPARATIVE EXAMPLE
3	-	-	-	1000	0.01	950	0.10	700	86	700	700	15	800	3	COMPARATIVE EXAMPLE
4	777	929	979	1050	0.02	950	0.20	400	86	700	700	15	800	3	INVENTION EXAMPLE
5	753	916	977	1050	0.02	850	0.20	600	86	700	700	15	750	3	COMPARATIVE EXAMPLE
6	789	941	988	1050	0.02	950	0.20	600	86	700	700	15	800	3	COMPARATIVE EXAMPLE
7	729	902	974	1050	0.02	950	0.10	700	86	700	700	15	800	3	INVENTION EXAMPLE
8	673	864	912	1050	0.50	900	0.50	400	86	700	700	15	800	3	COMPARATIVE EXAMPLE
9	646	803	861	1000	0.01	850	0.12	400	86	DISCONTINUED DUE TO LAMINATION					COMPARATIVE EXAMPLE
10	729	902	974	1050	0.01	850	0.10	700	86	700	700	0	800	3	COMPARATIVE EXAMPLE
11	729	902	974	1050	0.01	850	0.10	700	86	700	700	25	800	3	COMPARATIVE EXAMPLE
12	779	932	982	1200	0.01	850	0.10	400	86	700	700	15	800	3	COMPARATIVE EXAMPLE
13	759	908	957	1000	0.01	850	0.15	500	86	700	700	10	800	3	INVENTION EXAMPLE

[0110] [Table 3]

No.	AFTER SKIN PASS	TEXTURE AFTER FINISH ANNEALING	SHEET THICKNESS	PRECIPITATE	MAGNETIC PROPERTIES				EVALUATION
	Gs	{411}<011> RATIO		NUMBER DENSITY	B50 (ALL-AROUND)	B50 (45°)	W10/400 (45°)	CORE LOSS DETERIORATION RATIO Wx	
	[-]	[%]	[mm]	[PIECE/ μm^2]	[T]	[T]	[W/kg]	[%]	
1	2.1	23.9	0.3	0.0800	1.62	1.73	12.2	31.1	INVENTION EXAMPLE
2	1.7	<u>11.2</u>	0.3	<u>5.1000</u>	1.62	1.73	15.2	50.7	COMPARATIVE EXAMPLE
3	2.0	<u>8.1</u>	0.3	0.1500	1.66	1.60	14.9	53.8	COMPARATIVE EXAMPLE
4	2.3	22.7	0.3	0.2200	1.60	1.71	13.4	32.9	INVENTION EXAMPLE
5	2.6	18.4	0.3	<u>0.9100</u>	1.58	1.70	14.9	46.2	COMPARATIVE EXAMPLE
6	1.8	20.4	0.3	<u>0.7400</u>	1.62	1.71	14.6	44.7	COMPARATIVE EXAMPLE
7	2.0	23.1	0.3	0.1400	1.61	1.70	13.3	32.3	INVENTION EXAMPLE
8	2.0	27.5	0.3	<u>10.5000</u>	1.59	1.71	15.4	31.7	COMPARATIVE EXAMPLE
9	-	-	-	-	-	-	-	-	COMPARATIVE EXAMPLE
10	0.3	<u>9.5</u>	0.3	0.1100	1.63	1.61	14.5	53.3	COMPARATIVE EXAMPLE
11	3.2	<u>10.8</u>	0.3	0.0900	1.57	1.64	14.7	33.5	COMPARATIVE EXAMPLE
12	2.1	19.6	0.3	<u>1.3000</u>	1.61	1.72	14.8	34.4	COMPARATIVE EXAMPLE
13	1.9	28.6	0.3	0.0020	1.63	1.73	12.0	30.8	INVENTION EXAMPLE

[0111] The underlines in Table 1 and Table 3 indicate conditions that are outside the range of the present invention. No. 1, No. 4, No. 7, and No. 13 being an invention example all had good values for the magnetic flux density B50, the core loss W10/400, the core loss deterioration ratio, and the tensile strength.

[0112] On the other hand, in No. 2 being a comparative example, sol. Al was insufficient and the value of $([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}]$ exceeded the upper limit of (2) Expression, and thus AlN was insufficient as fine precipitates, and further, the temperature rising rate during slab heating was high, and thus Ti was solid-dissolved and a large amount of finer TiN was

precipitated instead. Further, rapid cooling was performed after finish rolling, and thus the {411}<011> ratio was small and the core loss W10/400 and the core loss deterioration ratio were poor. In No. 3 being a comparative example, the total amount of one or more selected from the group consisting of Mn, Ni, and Cu was insufficient, and the composition was a composition in which α - γ transformation did not occur, and thus the {411}<011> ratio was small, and the magnetic flux density B50 (45° direction), the core loss W10/400, and the core loss deterioration ratio were poor. In No. 5 being a comparative example, the value of $([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}]$ exceeded the upper limit of (2) Expression, and thus the formation of AlN was insufficient and a large amount of fine TiN was precipitated instead. As a result, the number density of precipitates was high, and the core loss W10/400 and the core loss deterioration ratio were poor. In No. 6 being a comparative example, the value of $([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}]$ was below the lower limit of (2) Expression, and thus the number density of precipitates was high due to excessive formation of AlN. As a result, the core loss W10/400 and the core loss deterioration ratio were poor.

[0113] In No. 8 being a comparative example, the value of $([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}]$ exceeded the upper limit of (2) Expression, Ti was contained excessively, and further, the temperature rising rate during slab heating was high, and thus a large amount of TiN was

formed, the number density was high, and further, Si was insufficient, resulting in that the core loss W10/400 was poor. In No. 9 being a comparative example, the total amount of one or more selected from the group consisting of Mn, Ni, and Cu was excessive, and thus due to segregation, lamination occurred during cold rolling and manufacture was then discontinued. In No. 10 being a comparative example, skin pass rolling was not performed, and thus the $\{411\}<011>$ ratio was small, and the magnetic flux density B50 (45° direction), the core loss W10/400, and the core loss deterioration ratio were poor. In No. 11 being a comparative example, the reduction ratio RR2 in skin pass rolling was too large, and thus the $\{411\}<011>$ ratio was small, and the magnetic flux density B50 (45° direction) and the core loss W10/400 were poor. In No. 12 being a comparative example, the slab heating temperature ST was too high, and thus a large amount of fine TiN was precipitated and the number density was high. As a result, the core loss W10/400 was poor.

INDUSTRIAL APPLICABILITY

[0114] According to the present invention, it is possible to provide a non-oriented electrical steel sheet that has achieved both low core loss and high magnetic flux density without increasing a manufacturing load and with no need to reduce a sheet thickness, a motor core, and a motor, and the present invention has a significant industrial value.

CLAIMS

[Claim 1] A non-oriented electrical steel sheet,
comprising a chemical composition containing:

in mass%,

C: 0.010% or less;

Si: 1.50% ~ 4.00%;

sol. Al: 0.3% ~ 0.7%;

S: 0.010% or less;

N: 0.010% or less;

Ti: 0.0005% ~ 0.0020%;

one or more selected from the group consisting of
Mn, Ni, and Cu: 2.50% ~ 5.00% in total;

Co: 0.000% ~ 1.000%;

Sn: 0.000% ~ 0.400%;

Sb: 0.000% ~ 0.400%; and

P: 0.000% ~ 0.400%, and

satisfying (1) Expression and (2) Expression below
when the Mn content (mass%) is set to [Mn], the Ni
content (mass%) is set to [Ni], the Cu content (mass%)
is set to [Cu], the Si content (mass%) is set to [Si],
the sol. Al content (mass%) is set to [sol. Al], and
the P content (mass%) is set to [P], and

having a balance consisting of Fe and impurities,
wherein

when an area ratio of crystal grains in a
{hkl}<uvw> orientation (within a tolerance of 10°) to
the entire visual field when a steel sheet surface is
measured by a scanning electron microscope equipped
with electron back scattering diffraction (SEM-EBSD) is

represented as Ahkl-uvw, A411-011 is 15% or more, and
the number density of precipitates is 0.0001
pieces/ $\mu\text{m}^2 \sim 0.3000$ pieces/ μm^2 .

$$(2 \times [\text{Mn}] + 2.5 \times [\text{Ni}] + [\text{Cu}]) - ([\text{Si}] + 2 \times [\text{sol. Al}] + 4 \times [\text{P}]) \geq 3.0\% \quad \dots(1)$$
$$10.5 \leq ([\text{Si}] + [\text{Mn}]) \div [\text{sol. Al}] \leq 12.5 \quad \dots(2)$$

[Claim 2] A motor core, wherein the non-oriented
electrical steel sheets according to claim 1 are
stacked.

[Claim 3] A motor, comprising:

the motor core according to claim 2.