

DESCRIPTION

TITLE

NON-ORIENTED ELECTRICAL STEEL SHEET

5

TECHNICAL FIELD

[0001] The present disclosure relates to a non-oriented electrical steel sheet, particularly a non-oriented electrical steel sheet having a Si concentration gradient in the thickness direction.

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BACKGROUND

[0002] For example, motors for drones and vacuum cleaners are increasingly driven in a very high frequency range of 1 kHz to 20 kHz from the viewpoint of size reduction, weight reduction, and efficiency enhancement. Non-oriented electrical steel sheets used as a core material of such motors are required to have low high-frequency iron loss and high magnetic flux density.

[0003] An effective way of reducing high-frequency iron loss is to increase specific resistance, and accordingly high Si steels are conventionally developed. However, since Si is a nonmagnetic element, there is a problem in that magnetic flux density and saturation magnetization decrease.

[0004] As a method of achieving both reduced high-frequency iron loss and high magnetic flux density, a Si-gradient magnetic material whose Si concentration gradient in the thickness direction is controlled is developed. For example, JP H11-293422 A (PTL 1) discloses an electrical steel sheet that has a Si concentration gradient in the thickness direction, wherein the Si concentration at the surface of the steel sheet is higher than the Si concentration at the center of the sheet thickness of the steel sheet, a part having a Si concentration of 5 % to 8 % occupies 10 % or more of the sheet thickness from both surfaces of the steel sheet in the thickness direction, and the Si concentration at the center of the sheet thickness of the steel sheet is 3.4 % or more.

CITATION LIST

Patent Literature

35 **[0005]** PTL 1: JP H11-293422 A

SUMMARY

(Technical Problem)

[0006] However, when a material merely having a Si concentration gradient in the thickness direction is used as an iron core material for motors of drones, vacuum cleaners, etc. (for example, frequency: 1 kHz to 20 kHz, magnetic flux density: 0.8 T to 2.0 T), hysteresis loss is high and magnetic flux density is low, so that iron loss and copper loss cannot be reduced sufficiently. It could therefore be helpful to achieve low iron loss and high magnetic flux density in a Si-gradient magnetic material.

(Solution to Problem)

[0007] In order to achieve both low iron loss and high magnetic flux density, we repeatedly studied the influences of components on the magnetic properties of a Si-gradient material. We consequently discovered that both low high-frequency iron loss and high magnetic flux density can be achieved by optimizing the difference in Si concentration between the surface layer and the inner layer of the Si-gradient material and further adding Co and one or two selected from Sn and Sb.

[0008] We provide the following.

1. A non-oriented electrical steel sheet that is a multilayer electrical steel sheet having a stacked structure of an inner layer and a surface layer located on each of both sides of the inner layer, wherein the surface layer has a chemical composition containing (consisting of), in mass%, Si: 4.0 % to 7.5 %, C: 0.0010 % to 0.0100 %, Co: 0.0010 % to 0.0100 %, and one or two selected from Sn: 0.010 % to 0.100 % and Sb: 0.010 % to 0.100 %, with a balance consisting of Fe and inevitable impurities, the inner layer has a chemical composition containing (consisting of), in mass%, Si: 3.0 % to 6.0 %, C: 0.0010 % to 0.0100 %, Co: 0.0010 % to 0.0100 %, and one or two selected from Sn: 0.010 % to 0.100 % and Sb: 0.010 % to 0.100 %, with a balance consisting of Fe and inevitable impurities, ΔSi defined as a difference $[\text{Si}]_1 - [\text{Si}]_0$ between a Si content $[\text{Si}]_1$ in the surface layer and a Si content $[\text{Si}]_0$ in the inner layer is 0.5 mass% to 3.3 mass%, a ratio t_1/t of a total thickness t_1 of the surface layers on both sides of the inner layer to a sheet thickness t of the electrical steel sheet is 0.08 to 0.73, and a ratio B_{50}/B_s of magnetic flux density B_{50} at a magnetic field strength of 5000 A/m to saturation magnetization B_s is 0.825 or more, and iron loss $W_{10/10k}$ at a frequency of 10 kHz and a maximum magnetic flux density of 1.0 T and the sheet thickness t satisfy the following

formula (1):

$$W_{10/10k} \leq 25 + 6900 \times t \quad \dots (1).$$

[0009] 2. The non-oriented electrical steel sheet according to 1., wherein one or both of the chemical composition of the surface layer and the chemical composition of the inner layer further contain, in mass%, P: 0.100 % or less.

[0010] 3. The non-oriented electrical steel sheet according to 1. or 2., wherein one or both of the chemical composition of the surface layer and the chemical composition of the inner layer further contain, in mass%, one or two selected from Ge and Ga: 0.0100 % or less in total.

[0011] 4. The non-oriented electrical steel sheet according to any of 1. to 3., wherein one or both of the chemical composition of the surface layer and the chemical composition of the inner layer further contain, in mass%, one or more selected from Cu, Cr, and Ni: 1.00 % or less in total.

[0012] 5. The non-oriented electrical steel sheet according to any of 1. to 4., wherein one or both of the chemical composition of the surface layer and the chemical composition of the inner layer further contain, in mass%, one or more selected from Ca, Mg, and REM: 0.0200 % or less in total.

[0013] 6. The non-oriented electrical steel sheet according to any of 1. to 5., wherein one or both of the chemical composition of the surface layer and the chemical composition of the inner layer further contain, in mass%, Zn: 0.0500 % or less.

[0014] 7. The non-oriented electrical steel sheet according to any of 1. to 6., wherein one or both of the chemical composition of the surface layer and the chemical composition of the inner layer further contain, in mass%, one or two selected from Mo and W: 0.0500 % or less in total.

[0015] 8. The non-oriented electrical steel sheet according to any of 1. to 7., wherein a maximum intensity value of {100} plane integration degree is 6.0 or more in a $\Phi_2 = 45^\circ$ section of an orientation distribution function at a plane of a depth of 1/4 of the sheet thickness from a surface of the multilayer electrical steel sheet.

[0016] 9. The non-oriented electrical steel sheet according to any of 1. to 8., wherein the sheet thickness is 0.03 mm to 0.20 mm.

(Advantageous Effect)

[0017] It is thus possible to provide a Si-gradient magnetic material having low iron loss and high magnetic flux density.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] In the accompanying drawings:

FIG. 1 is a graph illustrating the correlation between ΔSi (mass%) defined as the difference ($[\text{Si}]_1 - [\text{Si}]_0$) in Si content between a surface layer and an inner layer and total iron loss $W_{10/10k}$ (W/kg) at 1.0 T and 10 kHz;

FIG. 2 is a graph illustrating the correlation between ΔSi and the magnetic flux density ratio (B_{50}/B_s); and

FIG. 3 is a graph illustrating the correlation between the multilayer ratio and the total iron loss ($W_{10/10k}$).

DETAILED DESCRIPTION

[0019] We conducted various experiments that led to the presently disclosed techniques. Examples of these experiments will be described below. For a non-oriented electrical steel sheet that is a multilayer electrical steel sheet in which the Si content differs between the inner layer and each of the surface layers sandwiching the inner layer from both sides, how the difference ΔSi in Si content between the surface layer and the inner layer (hereafter also simply referred to as “ ΔSi ”) influences the magnetic properties was studied. In detail, multilayer electrical steel sheets with different ΔSi were produced according to the following procedure, and their magnetic properties were evaluated. In the following description, “%” denotes “mass%” unless otherwise specified.

[0020] First, a steel material for the surface layer was bonded or joined to both sides of a steel material for the inner layer so that the ratio of the thickness of each surface layer to the sheet thickness (entire thickness) of the electrical steel sheet would be 0.3 (i.e. the ratio of the total thickness of both surface layers to the entire sheet thickness would be 0.6), and then hot rolling was performed. As the steel material for the surface layer and the steel material for the inner layer, ingots prepared by steelmaking so as to have desired chemical compositions were used. The Si content $[\text{Si}]_0$ in the inner layer was 3.7 %. A plurality of steel materials for the surface layer different in Si content were prepared so as to vary the Si content $[\text{Si}]_1$ in the surface layer in the range of 4.0 % to 7.5 %. The chemical compositions of both the surface layer and the inner layer contained C: 0.0025 %, Co: 0.0030 %, and Sn: 0.030 %, with the balance consisting of Fe and inevitable impurities. The surface layers on both sides of the inner layer had the same chemical composition.

[0021] After the hot rolling, hot-rolled sheet annealing was performed at 980

°C for 30 seconds, and then cold rolling was performed to a sheet thickness of 0.10 mm. After this, final annealing was performed at 1050 °C for 30 seconds to obtain an electrical steel sheet.

[0022] Test pieces of 30 mm in width and 180 mm in length were collected from each of the obtained electrical steel sheets, and an Epstein test was conducted to evaluate the magnetic properties. In the Epstein test, measurements were made using L-direction test pieces collected so that the length direction of the test pieces would be the rolling direction (L direction) and C-direction test pieces collected so that the length direction of the test pieces would be a direction (C direction) orthogonal to the rolling direction where the L-direction test pieces and the C-direction test pieces were equal in number, and the average value of the magnetic properties in the L-direction and the C-direction was used for evaluation.

[0023] FIG. 1 illustrates the correlation between ΔSi (mass%) defined as the difference ($[\text{Si}]_1 - [\text{Si}]_0$) in Si content between the surface layer and the inner layer and total iron loss $W_{10/10k}$ (W/kg) at 1.0 T and 10 kHz. FIG. 2 illustrates the correlation between ΔSi and the magnetic flux density ratio (B_{50}/B_s). As used herein, the term “magnetic flux density ratio” means the ratio (B_{50}/B_s) of magnetic flux density B_{50} at a magnetic field strength of 5000 A/m to saturation magnetization B_s .

[0024] As can be seen from the results illustrated in FIG. 1, the iron loss is low when ΔSi is 0.5 mass% or more and 3.3 mass% or less. Specifically, in the case where the sheet thickness $t = 0.10$ mm, the iron loss $W_{10/10k}$ can be reduced to 715 W/kg or less, which results from substituting the sheet thickness $t = 0.10$ mm to the following formula (1):

$$W_{10/10k} \leq 25 + 6900 \times t \quad \dots (1).$$

[0025] Moreover, as can be seen from the results illustrated in FIG. 2, the magnetic flux density ratio decreases sharply when ΔSi is more than 3.3 mass%. The reason for this is considered to be as follows: When the Si content is higher in the surface layer than in the inner layer, the surface layer has higher magnetic permeability than the inner layer. Consequently, magnetic flux concentrates in the surface layer, and eddy current loss decreases. However, if ΔSi is excessively large, the difference in lattice constant and the difference in magnetostriction between the surface layer and the inner layer increase accordingly. As a result, the stress applied when the steel sheet is magnetized increases, so that hysteresis loss increases and the magnetic flux density in the

medium magnetic field region decreases.

[0026] For the above reason, in the present disclosure, ΔSi defined as the difference ($[\text{Si}]_1 - [\text{Si}]_0$) between the Si content in the surface layer and the Si content in the inner layer is 0.5 mass% to 3.3 mass%. ΔSi is preferably 1.0 mass% to 3.0 mass%.

[0027] Next, how the ratio (t_1/t) of the total thickness t_1 of the surface layers to the sheet thickness t of the multilayer electrical steel sheet (hereafter also referred to as “multilayer ratio”) influences the magnetic properties was studied. In detail, electrical steel sheets with different multilayer ratios were produced according to the following procedure, and their magnetic properties were evaluated. As used herein, the “total thickness of the surface layers” means the sum of the thicknesses of the surface layers provided on both sides of the inner layer.

[0028] First, a steel material for the surface layer and a steel material for the inner layer were bonded or joined together so that the multilayer ratio would be 0.02 to 0.80, and hot rolling was performed. As the steel material for the surface layer and the steel material for the inner layer, ingots prepared by steelmaking so as to have desired chemical compositions were used. The Si content $[\text{Si}]_1$ in the surface layer was 6.0 %, and the Si content $[\text{Si}]_0$ in the inner layer was 4.5 %. The chemical compositions of both the surface layer and the inner layer contained C: 0.0030 %, Co: 0.0020 %, and Sn: 0.050 %, with the balance consisting of Fe and inevitable impurities. The surface layers on both sides of the inner layer had the same chemical composition.

[0029] After the hot rolling, hot-rolled sheet annealing was performed at 950 °C for 30 seconds, and then cold rolling was performed to a sheet thickness of 0.08 mm. After this, final annealing was performed at 1100 °C for 30 seconds to obtain an electrical steel sheet.

[0030] FIG. 3 illustrates the correlation between the multilayer ratio and the total iron loss ($W_{10/10k}$). As can be seen from the results illustrated in FIG. 3, the iron loss decreases significantly when the multilayer ratio is 0.08 to 0.73. Specifically, in the case where the sheet thickness $t = 0.08$ mm, the iron loss $W_{10/10k}$ can be reduced to 577 W/kg or less, which results from substituting the sheet thickness $t = 0.08$ mm to the following formula (1):

$$W_{10/10k} \leq 25 + 6900 \times t \quad \dots (1).$$

The reason for such decrease in iron loss is considered to be as follows: If the multilayer ratio is less than 0.08, the proportion of the surface layer high

in resistance is low, so that eddy current which concentrates in the surface layer cannot be reduced effectively. If the multilayer ratio is more than 0.73, the difference in magnetic permeability between the surface layer and the inner layer is small, so that magnetic flux penetrates into the inner layer and eddy current loss also occurs from the inner layer. Hence, limiting the multilayer ratio to 0.08 to 0.73 can reduce iron loss. For the above reason, in the present disclosure, the multilayer ratio (t_1/t) is 0.08 to 0.73. t_1/t is preferably 0.10 to 0.70, and more preferably 0.30 to 0.60.

[0031] The thickness t_{1-1} of the surface layer on one side of the inner layer and the thickness t_{1-2} of the surface layer on the other side of the inner layer are preferably the same, but do not necessarily need to be the same. In detail, t_{1-1} and t_{1-2} may differ by about 20 % or less (i.e. when the thicker one of t_{1-1} and t_{1-2} is 100 %, the thinner one of t_{1-1} and t_{1-2} is 80 % to 100 %).

[0032] [Sheet thickness]

The sheet thickness t of the multilayer electrical steel sheet is not limited and may be any value. However, if the multilayer electrical steel sheet is excessively thin, cold rolling and annealing in the production of the multilayer electrical steel sheet are difficult, which may lead to an increase in cost. Therefore, from the viewpoint of reducing production costs, t is preferably 0.03 mm or more. If t is 0.20 mm or less, eddy current loss can be further reduced, and as a result the total iron loss can be further reduced. Therefore, t is preferably 0.20 mm or less.

[0033] [Magnetic flux density ratio]

B_{50}/B_s : 0.825 or more

The ratio (B_{50}/B_s) of magnetic flux density B_{50} at a magnetic field strength of 5000 A/m to saturation magnetization B_s is 0.825 or more. As a result of B_{50}/B_s being high (0.825 or more), the rise of the magnetization curve in the design magnetic flux density region used in small motors can be improved. This reduces the motor current required to obtain certain torque, with it being possible to reduce copper loss and improve motor efficiency.

[0034] [Iron loss]

In the present disclosure, the iron loss (total iron loss) $W_{10/10k}$ (W/kg) at a frequency of 10 kHz and a maximum magnetic flux density of 1.0 T and the sheet thickness t (mm) need to satisfy the following formula (1):

$$W_{10/10k} \leq 25 + 6900 \times t \quad \dots (1).$$

If the formula (1) is not satisfied, not only motor efficiency decreases,

but also the heat generated in the stator core exceeds 100 °C and a cooling system is required. Since the iron loss depends on the sheet thickness, the upper limit of the iron loss in the formula (1) is defined based on the influence of the sheet thickness.

5 **[0035]** In order to satisfy the formula (1), hysteresis loss is reduced by texture control, and eddy current loss is reduced by controlling each of the Si concentration gradient and the multilayer ratio within a specific range.

[0036] [Texture]

Maximum intensity value of {100} plane integration degree: 6.0 or more

10 By adding an appropriate amount of Co and adding an appropriate amount of at least one of Sn and Sb, which are segregation elements, it is possible to increase {100} plane in the non-oriented electrical steel sheet and ease magnetization within the plane. Moreover, adding an appropriate amount of P, which is a segregation element, too, enhances the effect of increasing
15 {100} plane. As a result, magnetic flux density is improved and hysteresis loss is reduced. Therefore, the {100} plane integration degree is preferably 6.0 or more. The {100} plane integration degree is defined herein as the intensity in a $\Phi_2 = 45^\circ$ section of the orientation distribution function (ODF) at a plane of a depth of 1/4 of the sheet thickness from the surface of the non-oriented
20 electrical steel sheet.

[0037] The reasons for limiting the components in the present disclosure will be explained below.

[Chemical composition]

25 The chemical compositions of the surface layer and the inner layer will be described below. In the following description, “%” representing the content of each element denotes “mass%” unless otherwise specified.

[0038] [Chemical composition of surface layer]

30 First, the chemical composition of the surface layer will be described. In the present disclosure, both a first surface layer provided on one side of the multilayer electrical steel sheet and a second surface layer provided on the other side of the multilayer electrical steel sheet have the below-described chemical composition. The chemical composition of the first surface layer and the chemical composition of the second surface layer are typically the same, but may be different. Herein, the content of each element in the surface layer
35 refers to the average content of the element in each surface layer.

[0039] The chemical composition of the surface layer contains Si: 4.0 % to 7.5

%, C: 0.0010 % to 0.0100 %, Co: 0.0010 % to 0.0100 %, and one or two selected from Sn: 0.010 % to 0.100 % and Sb: 0.010 % to 0.100 %, with the balance consisting of Fe and inevitable impurities.

[0040] Si: 4.0 % to 7.5 %

5 Si is an element that has the effect of increasing the electric resistance of the steel sheet and reducing eddy current loss. If the Si content ($[Si]_1$) in the surface layer is less than 4.0 %, eddy current loss cannot be reduced effectively. The Si content in the surface layer is therefore 4.0 % or more, and preferably 4.5 % or more. If the Si content in the surface layer is more than 7.5 %, saturation magnetization decreases and consequently magnetic flux density decreases. The Si content in the surface layer is therefore 7.5 % or less, preferably less than 7.0 %, and more preferably 6.5 % or less. As mentioned above, the expression “the Si content in the surface layer is 4.0 % to 7.5 %” means that the average Si content in the first surface layer is 4.0 % to 7.5 % and the average Si content in the second surface layer is 4.0 % to 7.5 %. The average Si content in the first surface layer and the average Si content in the second surface layer may be the same or different. The same definition applies to the other elements described below.

[0041] C: 0.0010 % to 0.0100 %

20 C is an element that segregates to crystal grain boundaries to enhance grain boundary strength and improve material workability. If the C content is 0.0010 % or more, material elongation is improved. The lower limit of the C content is therefore 0.0010 %. The C content is preferably 0.0015 % or more. If the C content is more than 0.0100 %, iron loss increases due to magnetic aging. The upper limit of the C content is therefore 0.0100 %. The C content is preferably 0.0060 % or less.

[0042] Co: 0.0010 % to 0.0100 %

 Adding Co can significantly improve the texture after final annealing, thus improving magnetic flux density and reducing hysteresis loss. In order to achieve this effect, in the case of adding Co, the Co content is 0.0010 % or more. The Co content is preferably 0.0015 % or more. If the Co content is more than 0.0100 %, not only the effect is saturated but also costs increase. The Co content is therefore 0.0100 % or less. The Co content is preferably 0.0050 % or less.

35 **[0043]** One or two selected from Sn and Sb: 0.010 % to 0.100 %
Sn: 0.010 % to 0.100 %

Adding Sn can significantly improve the texture after final annealing, thus improving magnetic flux density and reducing hysteresis loss. In order to achieve this effect, in the case of adding Sn, the Sn content is 0.010 % or more. The Sn content is preferably 0.020 % or more. If the Sn content is more than 0.100 %, not only the effect is saturated but also productivity decreases and costs increase. The Sn content is therefore 0.100 % or less. The Sn content is preferably 0.080 % or less.

[0044] Sb: 0.010 % to 0.100 %

Adding Sb can significantly improve the texture after final annealing, thus improving magnetic flux density and reducing hysteresis loss, as with Sn. In order to achieve this effect, in the case of adding Sb, the Sb content is 0.010 % or more. The Sb content is preferably 0.020 % or more. If the Sb content is more than 0.100 %, not only the effect is saturated but also productivity decreases and costs increase. The Sb content is therefore 0.100 % or less. The Sb content is preferably 0.080 % or less.

[0045] Preferably, the chemical composition of the surface layer optionally further contains P: 0.100 % or less.

P: 0.100 % or less

Adding P can significantly improve the texture, thus improving magnetic flux density and reducing hysteresis loss, as with Sn, Sb, and Co. In order to achieve this effect, in the case of adding P, the P content is preferably 0.010 % or more. The P content is more preferably 0.030 % or more. If the P content is more than 0.100 %, not only the effect is saturated but also productivity decreases and costs increase. The P content is therefore preferably 0.100 % or less. The P content is more preferably 0.070 % or less.

[0046] The chemical composition of the surface layer may optionally contain one or more of the following elements.

One or two selected from Ge and Ga: 0.0100 % or less in total

Ge and Ga have the effect of improving the texture. In order to achieve this effect, in the case of adding one or both of Ge and Ga, the total content of one or two selected from Ge and Ga is preferably 0.0005 % or more. The total content is more preferably 0.0020 % or more. If the total content of one or two selected from Ge and Ga is more than 0.0100 %, the effect is saturated and alloy costs merely increase. Therefore, in the case of adding one or both of Ge and Ga, the total content is 0.0100 % or less. The total content is more preferably 0.0050 % or less.

[0047] One or more selected from Cu, Cr, and Ni: 1.00 % or less in total

Cu, Cr, and Ni increase specific resistance and are advantageous in reducing iron loss. In order to achieve this effect, in the case of adding at least one of Cu, Cr, and Ni, the total content of one or more selected from Cu, Cr, and Ni is preferably 0.03 % or more. If the total content of one or more selected from Cu, Cr, and Ni is excessively high, magnetic flux density decreases. Therefore, in the case of adding at least one of Cu, Cr, and Ni, the total content is 1.00 % or less.

[0048] One or more selected from Ca, Mg, and REM: 0.0200 % or less in total

Ca, Mg, and REM have the effect of forming stable sulfides and improving grain growth. In order to achieve this effect, the total content of one or more selected from Ca, Mg, and REM is preferably 0.0010 % or more. If the total content of one or more selected from Ca, Mg, and REM is more than 0.0200 %, the effect is saturated. Therefore, in the case of adding at least one of Ca, Mg, and REM, the total content is 0.0200 % or less.

[0049] Zn: 0.0500 % or less

Zn has the effect of suppressing nitridation during final annealing. In order to achieve this effect, in the case of adding Zn, the Zn content is preferably 0.0010 % or more. The Zn content is more preferably 0.0020 % or more. If the Zn content is more than 0.0500 %, sulfides are formed and iron loss increases. Therefore, in the case of adding Zn, the Zn content is 0.0500 % or less. The Zn content is more preferably 0.0100 % or less.

[0050] One or two selected from Mo and W: 0.0500 % or less in total

Both Mo and W are elements effective in suppressing surface defects (scab) in non-oriented electrical steel sheets. The non-oriented electrical steel sheet according to the present disclosure is high-alloy steel and its surface is susceptible to oxidation, so that scab caused by surface cracking is highly likely to occur. Adding a small amount of one or both of Mo and W, which are elements that enhance high-temperature strength, can suppress such cracking. This effect cannot be achieved sufficiently if the total content of one or two selected from Mo and W is less than 0.0010 %. Therefore, in the case of adding one or both of Mo and W, the total content is preferably 0.0010 % or more. If the total content of one or two selected from Mo and W is more than 0.0500 %, the effect is saturated and alloy costs merely increase. Therefore, in the case of adding one or both of Mo and W, the total content is 0.0500 % or less.

[0051] In one embodiment of the present disclosure, the surface layer has a

chemical composition that contains the above-described elements with the balance consisting of Fe and inevitable impurities.

An example of an element that can be contained in the electrical steel sheet as such inevitable impurities is Al. If the Al content is limited to 0.10 % or less, magnetic flux density can be further improved. The Al content is
5 therefore preferably 0.10 % or less.

[0052] [Chemical composition of inner layer]

Next, the chemical composition of the inner layer will be described. Herein, the content of each element in the inner layer refers to the average
10 content of the element in the inner layer.

The chemical composition of the inner layer contains Si: 3.0 % to 6.0 %, C: 0.0010 % to 0.0100 %, Co: 0.0010 % to 0.0100 %, and one or two selected from Sn: 0.010 % to 0.100 % and Sb: 0.010 % to 0.100 %, with the balance consisting of Fe and inevitable impurities.

15 **[0053]** Si: 3.0 % to 6.0 %

If the Si content ($[Si]_0$) in the inner layer is less than 3.0 %, high-frequency iron loss increases. The Si content in the inner layer is therefore 3.0 % or more. The Si content in the inner layer is preferably 3.3 % or more. If the Si content in the inner layer is more than 6.0 %, the motor core cracks during
20 blanking. The Si content in the inner layer is therefore 6.0 % or less. The Si content in the inner layer is preferably 5.5 % or less.

[0054] C: 0.0010 % to 0.0100 %

C is an element that segregates to crystal grain boundaries to enhance grain boundary strength and improve material workability. If the C content is
25 0.0010 % or more, material elongation is improved. The lower limit of the C content is therefore 0.0010 %. The C content is preferably 0.0015 % or more. If the C content is more than 0.0100 %, iron loss increases due to magnetic aging. The upper limit of the C content is therefore 0.0100 %. The C content is preferably 0.0060 % or less.

30 **[0055]** Co: 0.0010 % to 0.0100 %

Adding Co can significantly improve the texture after final annealing, thus improving magnetic flux density and reducing hysteresis loss, as with Sn and Sb. In order to achieve this effect, in the case of adding Co, the Co content is 0.0010 % or more. The Co content is preferably 0.0015 % or more. If the Co
35 content is more than 0.0100 %, not only the effect is saturated but also costs increase. The Co content is therefore 0.0100 % or less. The Co content is

preferably 0.0050 % or less.

[0056] One or two selected from Sn and Sb: 0.010 % to 0.100 %

Sn: 0.010 % to 0.100 %

Adding Sn can significantly improve the texture after final annealing,
5 thus improving magnetic flux density and reducing hysteresis loss. In order to
achieve this effect, in the case of adding Sn, the Sn content is 0.010 % or more.
The Sn content is preferably 0.020 % or more. If the Sn content is more than
0.100 %, not only the effect is saturated but also productivity decreases and
costs increase. The Sn content is therefore 0.100 % or less. The Sn content is
10 preferably 0.080 % or less.

[0057] Sb: 0.010 % to 0.100 %

Adding Sb can significantly improve the texture after final annealing,
thus improving magnetic flux density and reducing hysteresis loss, as with Sn.
In order to achieve this effect, in the case of adding Sb, the Sb content is 0.010
15 % or more. The Sb content is preferably 0.020 % or more. If the Sb content is
more than 0.100 %, not only the effect is saturated but also productivity
decreases and costs increase. The Sb content is therefore 0.100 % or less. The
Sb content is preferably 0.080 % or less.

[0058] The chemical composition of the inner layer may optionally further
20 contain P: 0.100 % or less.

P: 0.100 % or less

Adding P can significantly improve the texture, thus improving
magnetic flux density and reducing hysteresis loss, as with Sn, Sb, and Co. In
order to achieve this effect, in the case of adding P, the P content is preferably
25 0.010 % or more. The P content is more preferably 0.030 % or more. If the P
content is more than 0.100 %, not only the effect is saturated but also
productivity decreases and costs increase. The P content is therefore preferably
0.100 % or less. The P content is more preferably 0.070 % or less.

[0059] The chemical composition of the inner layer may optionally contain
30 one or more of the following elements.

One or two selected from Ge and Ga: 0.0100 % or less in total

Ge and Ga have the effect of improving the texture. In order to achieve
this effect, in the case of adding one or both of Ge and Ga, the total content of
one or two selected from Ge and Ga is preferably 0.0005 % or more. The total
35 content is more preferably 0.0020 % or more. If the total content of one or two
selected from Ge and Ga is more than 0.0100 %, the effect is saturated and

alloy costs merely increase. Therefore, in the case of adding one or both of Ge and Ga, the total content is 0.0100 % or less. The total content is more preferably 0.0050 % or less.

[0060] One or more selected from Cu, Cr, and Ni: 1.00 % or less in total

5 Cu, Cr, and Ni increase specific resistance and are advantageous in reducing iron loss. In order to achieve this effect, in the case of adding at least one of Cu, Cr, and Ni, the total content of one or more selected from Cu, Cr, and Ni is preferably 0.03 % or more. If the total content of one or more selected from Cu, Cr, and Ni is excessively high, magnetic flux density decreases.
10 Therefore, in the case of adding at least one of Cu, Cr, and Ni, the total content is 1.00 % or less.

[0061] One or more selected from Ca, Mg, and REM: 0.0200 % or less in total

 Ca, Mg, and REM have the effect of forming stable sulfides and improving grain growth. In order to achieve this effect, the total content of one
15 or more selected from Ca, Mg, and REM is preferably 0.0010 % or more. If the total content of one or more selected from Ca, Mg, and REM is more than 0.0200 %, the effect is saturated. Therefore, in the case of adding at least one of Ca, Mg, and REM, the total content is 0.0200 % or less.

[0062] Zn: 0.0500 % or less

20 Zn has the effect of suppressing nitridation during final annealing. In order to achieve this effect, in the case of adding Zn, the Zn content is preferably 0.0010 % or more. The Zn content is more preferably 0.0020 % or more. If the Zn content is more than 0.0500 %, sulfides are formed and iron loss increases. Therefore, in the case of adding Zn, the Zn content is 0.0500 %
25 or less. The Zn content is more preferably 0.0100 % or less.

[0063] One or two selected from Mo and W: 0.0500 % or less in total

 Both Mo and W are elements effective in suppressing surface defects (scab) in non-oriented electrical steel sheets. The non-oriented electrical steel sheet according to the present disclosure is high-alloy steel and its surface is
30 susceptible to oxidation, so that scab caused by surface cracking is highly likely to occur. Adding a small amount of one or both of Mo and W, which are elements that enhance high-temperature strength, can suppress such cracking. This effect cannot be achieved sufficiently if the total content of one or two selected from Mo and W is less than 0.0010 %. Therefore, in the case of adding
35 one or both of Mo and W, the total content is preferably 0.0010 % or more. If the total content of one or two selected from Mo and W is more than 0.0500 %, the

the effect is saturated and alloy costs merely increase. Therefore, in the case of adding one or both of Mo and W, the total content is 0.0500 % or less.

[0064] [Production method]

A method of producing the electrical steel sheet according to the present disclosure is not limited, and any production method may be used. An example of the production method is cladding of steel materials that differ in Si content. The chemical compositions of the steel materials can be adjusted, for example, by blowing materials with different compositions in a converter and degassing the molten steels.

[0065] The cladding method is not limited. For example, a steel slab (steel material) for the surface layer having the above-described chemical composition and a steel slab (steel material) for the inner layer having the above-described chemical composition are prepared. The steel slab for the surface layer is then bonded or joined to both sides of the steel slab for the inner layer, with such a thickness that enables the final multilayer ratio to be the desired value. The bonded or joined steel slabs are then subjected to rolling. The rolling may be, for example, one or more selected from the group consisting of hot rolling, warm rolling, and cold rolling. Typically, a combination of hot rolling and subsequent warm rolling or a combination of hot rolling and subsequent cold rolling is preferably used. After the hot rolling, it is preferable to perform hot-rolled sheet annealing. The warm rolling may be performed two or more times with intermediate annealing therebetween. The cold rolling may be performed two or more times with intermediate annealing therebetween. The finish temperature and the coiling temperature in the hot rolling are not limited, and may be determined according to a conventional method. After the rolling, final annealing is performed.

[0066] As another production method, siliconizing treatment may be used. In the case of using siliconizing treatment, a steel sheet having a constant Si content in the thickness direction is subjected to siliconizing treatment, as a result of which the Si content in the surface layers on both sides of the steel sheet can be increased. The method of siliconizing treatment is not limited, and any method may be used. For example, a method may be used that involves depositing Si on the surface of a steel sheet by a chemical vapor deposition (CVD) method and then performing heat treatment to diffuse Si to the inside of the steel sheet. The Si content in each of the surface layer and the inner layer can be controlled by adjusting the amount of Si deposited by the CVD method

and the heat treatment conditions.

EXAMPLES

5 [0067] In order to determine the effects according to the present disclosure, multilayer electrical steel sheets were produced according to the following procedure and their magnetic properties were evaluated.

For each of No. 3 to No. 27 and No. 30 to No. 72 shown in Tables 1 to 3, first, two types of steel slabs were prepared: one for the surface layer having the chemical composition shown in Table 1 and one for the inner layer having
10 the chemical composition shown in Table 2. Next, the steel slab for the surface layer was stacked on both sides of the steel slab for the inner layer, and the stacked steel slabs were welded on their periphery. Hence, the chemical compositions of the surface layers on both sides of the inner layer were the same. The chemical compositions of the steel slabs were adjusted by
15 performing blowing in a converter and then performing degassing. The chemical compositions were maintained in the finally obtained multilayer electrical steel sheet.

[0068] After this, the stacked steel slabs were heated at 1120 °C for 1 hour, and then hot rolled to a thickness of 2.0 mm to obtain a hot-rolled steel sheet.
20 The hot-rolling finish temperature in the hot rolling was 800 °C. The hot-rolled steel sheet was coiled at a coiling temperature of 610 °C, and then subjected to hot-rolled sheet annealing at 950 °C for 30 seconds. Subsequently, the hot-rolled steel sheet was pickled and cold rolled, and further annealed at the final annealing temperature shown in Table 3 to obtain an electrical steel sheet. The
25 entire sheet thickness t of the finally obtained electrical steel sheet and the ratio (multilayer ratio) of the total thickness t_1 of the surface layers to t are shown in Table 3.

[0069] For comparison, the same test was conducted using ordinary electrical steel sheets that were not clad (i.e. non-clad electrical steel sheets) (No. 1 and
30 No. 2). The electrical steel sheets of these Comparative Examples did not have a layered structure in which the composition differs in the thickness direction. In other words, these electrical steel sheets had no surface layer.

[0070] Multilayer electrical steel sheets of No. 28 and No. 29 were each produced by a siliconizing method. Specifically, a cold-rolled steel sheet with
35 a Si content of 3.0 % and a sheet thickness of 0.1 mm was subjected to siliconizing and diffusion treatment at 1200 °C. The average value of the Si

content in the entire sheet thickness of the steel sheet was calculated, and a part having a Si concentration higher than the average value was taken to be the surface layer and a part having a Si concentration lower than the average value was taken to be the inner layer. The Si content in the surface layer is the
5 average value of the Si content in the surface layer.

[Table 1] (cont'd)

No.	Surface layer																
	[Si] ₁ (%)	C (%)	Co (%)	Sn (%)	Sb (%)	P (%)	Ga (%)	Ge (%)	Cu (%)	Cr (%)	Ni (%)	Zn (%)	Mo (%)	W (%)	Ca (%)	Mg (%)	REM (%)
36	6.3	0.0039	0.0028	0.010	0.010	0.010	-	-	-	-	-	-	-	-	-	-	-
37	6.5	0.0032	0.0024	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
38	6.5	0.0035	0.0019	0.030	-	-	0.0008	-	-	-	-	-	-	-	-	-	-
39	6.5	0.0035	0.0019	0.030	-	-	0.0045	-	-	-	-	-	-	-	-	-	-
40	6.5	0.0035	0.0019	0.030	-	-	-	0.0007	-	-	-	-	-	-	-	-	-
41	6.5	0.0035	0.0019	0.030	-	-	-	0.0048	-	-	-	-	-	-	-	-	-
42	6.5	0.0035	0.0019	0.030	-	-	0.0012	0.0008	-	-	-	-	-	-	-	-	-
43	6.3	0.0039	0.0028	0.010	-	0.010	-	-	0.05	-	-	-	-	-	-	-	-
44	6.3	0.0039	0.0028	0.010	-	0.010	-	-	0.30	-	-	-	-	-	-	-	-
45	6.3	0.0039	0.0028	0.010	-	0.010	-	-	0.50	-	-	-	-	-	-	-	-
46	6.3	0.0039	0.0028	0.010	-	0.010	-	-	-	0.10	-	-	-	-	-	-	-
47	6.3	0.0039	0.0028	0.010	-	0.010	-	-	-	0.30	-	-	-	-	-	-	-
48	6.3	0.0039	0.0028	0.010	-	0.010	-	-	-	0.90	-	-	-	-	-	-	-
49	6.3	0.0039	0.0028	0.010	-	0.010	-	-	-	-	0.04	-	-	-	-	-	-
50	6.3	0.0039	0.0028	0.010	-	0.010	-	-	-	-	0.50	-	-	-	-	-	-
51	6.3	0.0039	0.0028	0.010	-	0.010	-	-	-	-	0.80	-	-	-	-	-	-
52	6.3	0.0039	0.0028	0.010	-	0.010	-	-	0.30	0.10	0.10	-	-	-	-	-	-
53	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0015	-	-	-	-	-
54	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0045	-	-	-	-	-
55	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0210	-	-	-	-	-
56	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	0.0029	-	-	-	-
57	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	0.0300	-	-	-	-
58	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0068	0.0050	-	-	-	-
59	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	0.0011	-	-	-
60	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	0.0140	-	-	-
61	6.4	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	0.0360	-	-	-
62	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0024	-	-
63	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0940	-	-
64	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0180	-	-
65	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	0.0008	-
66	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	0.0025	-
67	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	0.0086	-
68	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	-	0.0007
69	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	-	0.0034
70	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	-	0.0091
71	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0019	-	0.0008
72	5.5	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0026	0.0014	-

[0072] [Table 2]

[Table 2]

No.	Inner layer																
	[Si]₀ (%)	C (%)	Co (%)	Sn (%)	Sb (%)	P (%)	Ga (%)	Ge (%)	Cu (%)	Cr (%)	Ni (%)	Zn (%)	Mo (%)	W (%)	Ca (%)	Mg (%)	REM (%)
1	3.0 (non-clad)	0.0025	0.0026	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
2	5.0 (non-clad)	0.0021	0.0019	0.020	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
4	3.0	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
5	5.8	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
6	3.0	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
7	6.0	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
8	4.5	0.0056	0.0059	-	0.020	-	-	-	-	-	-	-	-	-	-	-	-
9	4.5	0.0056	0.0059	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	4.5	0.0056	0.0006	0.020	-	-	-	-	-	-	-	-	-	-	-	-	-
11	6.0	0.0092	0.0094	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
12	6.0	0.0092	0.0094	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
13	4.3	0.0028	0.0024	0.080	-	0.040	-	-	-	-	-	-	-	-	-	-	-
14	4.3	0.0028	0.0024	0.080	-	0.080	-	-	-	-	-	-	-	-	-	-	-
15	3.9	0.0035	0.0015	0.040	0.040	-	-	-	-	-	-	-	-	-	-	-	-
16	3.9	0.0150	0.0015	0.040	0.040	-	-	-	-	-	-	-	-	-	-	-	-
17	3.9	0.0007	0.0015	0.040	0.040	-	-	-	-	-	-	-	-	-	-	-	-
18	5.0	0.0032	0.0024	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
19	5.0	0.0032	0.0024	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
20	5.0	0.0032	0.0024	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
21	5.0	0.0032	0.0024	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
22	5.0	0.0032	0.0024	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
23	5.0	0.0032	0.0130	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
24	4.0	0.0031	0.0014	0.050	0.010	-	-	-	-	-	-	-	-	-	-	-	-
25	4.0	0.0031	0.0014	0.050	0.010	-	-	-	-	-	-	-	-	-	-	-	-
26	5.8	0.0039	0.0028	0.030	-	0.010	-	-	-	-	-	-	-	-	-	-	-
27	4.0	0.0025	0.0025	0.060	-	-	-	-	-	-	-	-	-	-	-	-	-
28	5.0	0.0035	0.0019	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
29	5.5	0.0038	0.0031	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
30	2.5	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
31	5.0	0.0032	0.0024	-	-	-	-	-	-	-	-	-	-	-	-	-	-
32	4.3	0.0028	0.0024	0.040	-	-	-	-	-	-	-	-	-	-	-	-	-
33	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	-	-
34	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	-	-	-	-	-	-	-	-
35	5.8	0.0039	0.0028	-	0.010	0.010	-	-	-	-	-	-	-	-	-	-	-

[Table 2] (cont'd)

No.	Inner layer																
	[Si]₀ (%)	C (%)	Co (%)	Sn (%)	Sb (%)	P (%)	Ga (%)	Ge (%)	Cu (%)	Cr (%)	Ni (%)	Zn (%)	Mo (%)	W (%)	Ca (%)	Mg (%)	REM (%)
36	5.8	0.0039	0.0028	0.030	0.010	0.010	-	-	-	-	-	-	-	-	-	-	-
37	5.0	0.0032	0.0024	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
38	5.0	0.0035	0.0019	0.030	-	-	0.0008	-	-	-	-	-	-	-	-	-	-
39	5.0	0.0035	0.0019	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
40	5.0	0.0035	0.0019	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
41	5.0	0.0035	0.0019	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
42	5.0	0.0035	0.0019	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-
43	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	-	-	-	-	-	-	-	-
44	5.8	0.0039	0.0028	0.010	-	0.010	-	-	0.30	-	-	-	-	-	-	-	-
45	5.8	0.0039	0.0028	0.010	-	0.010	-	-	0.50	-	-	-	-	-	-	-	-
46	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	0.10	-	-	-	-	-	-	-
47	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	0.30	-	-	-	-	-	-	-
48	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	0.90	-	-	-	-	-	-	-
49	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	-	0.04	-	-	-	-	-	-
50	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	-	0.50	-	-	-	-	-	-
51	5.8	0.0039	0.0028	0.010	-	0.010	-	-	-	-	0.80	-	-	-	-	-	-
52	5.8	0.0039	0.0028	0.010	-	0.010	-	-	0.30	0.10	0.10	-	-	-	-	-	-
53	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0015	-	-	-	-	-
54	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0045	-	-	-	-	-
55	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0210	-	-	-	-	-
56	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	0.0029	-	-	-	-
57	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	0.0300	-	-	-	-
58	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	0.0068	0.0050	-	-	-	-
59	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	0.0011	-	-	-
60	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	0.0140	-	-	-
61	3.9	0.0035	0.0015	0.040	-	-	-	-	-	-	-	-	-	0.0360	-	-	-
62	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0024	-	-
63	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0940	-	-
64	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0180	-	-
65	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	0.0008	-
66	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	0.0025	-
67	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	0.0086	-
68	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	-	0.0007
69	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	-	0.0034
70	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	-	-	0.0091
71	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0019	-	0.0008
72	4.3	0.0028	0.0024	-	0.050	-	-	-	-	-	-	-	-	-	0.0026	0.0014	-

[0073] [Table 3]

No.	Entire sheet thickness t (mm)	ΔSi (%)	Multilayer ratio (Total surface layer thickness t_1 /entire sheet thickness t)	Final annealing temperature (°C)	Remarks
1	0.10	0.0	-	1000	Comparative Example
2	0.20	0.0	-	1000	Comparative Example
3	0.10	2.5	0.35	1050	Example
4	0.10	3.5	0.35	1050	Comparative Example
5	0.10	0.6	0.35	1050	Example
6	0.10	3.8	0.35	1050	Comparative Example
7	0.10	0.4	0.35	1050	Comparative Example
8	0.08	2.0	0.50	1100	Example
9	0.08	2.0	0.50	1100	Comparative Example
10	0.08	2.0	0.50	1100	Comparative Example
11	0.07	0.7	0.50	1000	Example
12	0.05	1.0	0.40	1000	Example
13	0.10	1.2	0.30	1050	Example
14	0.10	1.2	0.30	1050	Example
15	0.10	2.5	0.35	1050	Example
16	0.10	2.5	0.35	1050	Comparative Example
17	0.10	2.5	0.35	1050	Comparative Example
18	0.15	1.5	0.08	1000	Example
19	0.15	1.5	0.15	1000	Example
20	0.15	1.5	0.40	1000	Example
21	0.15	1.5	0.65	1000	Example
22	0.15	1.5	0.75	1000	Comparative Example
23	0.15	1.5	0.65	1000	Comparative Example
24	0.06	2.0	0.40	1050	Example
25	0.20	2.0	0.40	1050	Example
26	0.10	0.5	0.40	1050	Example
27	0.10	1.0	0.40	1100	Example
28	0.10	1.5	0.30	1200	Example
29	0.10	1.0	0.30	1200	Example
30	0.10	2.5	0.35	1050	Comparative Example
31	0.15	1.5	0.40	1000	Comparative Example
32	0.10	1.2	0.30	1050	Example
33	0.10	1.2	0.30	1050	Example
34	0.10	0.5	0.40	1050	Example
35	0.10	0.5	0.40	1050	Example

[Table 3]

[Table 3] (cont'd)

No.	Entire sheet thickness t (mm)	ΔSi (%)	Multilayer ratio (Total surface layer thickness t_l /entire sheet thickness t)	Final annealing temperature (°C)	Remarks
36	0.10	0.5	0.40	1050	Example
37	0.15	1.5	0.05	1000	Comparative Example
38	0.10	1.5	0.30	1200	Example
39	0.10	1.5	0.30	1200	Example
40	0.10	1.5	0.30	1200	Example
41	0.10	1.5	0.30	1200	Example
42	0.10	1.5	0.30	1200	Example
43	0.10	0.5	0.40	1050	Example
44	0.10	0.5	0.40	1050	Example
45	0.10	0.5	0.40	1050	Example
46	0.10	0.5	0.40	1050	Example
47	0.10	0.5	0.40	1050	Example
48	0.10	0.5	0.40	1050	Example
49	0.10	0.5	0.40	1050	Example
50	0.10	0.5	0.40	1050	Example
51	0.10	0.5	0.40	1050	Example
52	0.10	0.5	0.40	1050	Example
53	0.10	2.5	0.35	1050	Example
54	0.10	2.5	0.35	1050	Example
55	0.10	2.5	0.35	1050	Example
56	0.10	2.5	0.35	1050	Example
57	0.10	2.5	0.35	1050	Example
58	0.10	2.5	0.35	1050	Example
59	0.10	2.5	0.35	1050	Example
60	0.10	2.5	0.35	1050	Example
61	0.10	2.5	0.35	1050	Example
62	0.10	1.2	0.30	1050	Example
63	0.10	1.2	0.30	1050	Example
64	0.10	1.2	0.30	1050	Example
65	0.10	1.2	0.30	1050	Example
66	0.10	1.2	0.30	1050	Example
67	0.10	1.2	0.30	1050	Example
68	0.10	1.2	0.30	1050	Example
69	0.10	1.2	0.30	1050	Example
70	0.10	1.2	0.30	1050	Example
71	0.10	1.2	0.30	1050	Example
72	0.10	1.2	0.30	1050	Example

[0074] (Magnetic properties)

Next, the magnetic properties of each of the obtained electrical steel sheets were measured. The magnetic measurement was performed using a 25 cm Epstein frame in accordance with JIS C 2550-1. As the magnetic properties,
5 iron loss $W_{10/10k}$ (W/kg) at 1.0 T and 10 kHz, magnetic flux density B_{50} at a magnetic field strength of 5000 A/m, and saturation magnetization B_s were measured. The measurement results are shown in Table 4.

[0075] [Table 4]

No.	25+6900×t	W _{10/10k} (W/kg)	B ₅₀ (T)	Saturation magnetization B _s (T)	B ₅₀ /B _s	Maximum intensity of {100} plane	Remarks
1	715	850	1.67	2.01	0.832	9.3	Comparative Example
2	1405	1500	1.56	1.88	0.830	8.6	Comparative Example
3	715	650	1.57	1.89	0.829	9.1	Example
4	715	735	1.60	1.93	0.828	8.7	Comparative Example
5	715	635	1.52	1.82	0.837	8.6	Example
6	715	735	1.56	1.92	0.811	7.3	Comparative Example
7	715	730	1.51	1.81	0.836	8.2	Comparative Example
8	577	535	1.54	1.85	0.833	9.1	Example
9	577	595	1.48	1.85	0.801	2.5	Comparative Example
10	577	600	1.49	1.85	0.806	2.9	Comparative Example
11	508	485	1.49	1.79	0.831	6.9	Example
12	370	350	1.48	1.79	0.827	6.5	Example
13	715	670	1.60	1.90	0.841	9.8	Example
14	715	660	1.61	1.90	0.847	10.5	Example
15	715	640	1.59	1.89	0.839	10.1	Example
16	715	730	1.59	1.89	0.839	9.8	Comparative Example
17	715	-	-	-	-	-	Comparative Example (cracking of product sheet)
18	1060	1020	1.59	1.87	0.849	9.4	Example
19	1060	1000	1.59	1.87	0.852	9.5	Example
20	1060	980	1.58	1.84	0.858	9.5	Example
21	1060	975	1.56	1.82	0.858	9.5	Example
22	1060	1100	1.53	1.81	0.846	9.4	Comparative Example
23	1060	1090	1.52	1.82	0.836	9.2	Comparative Example
24	439	400	1.60	1.89	0.845	8.4	Example
25	1405	1250	1.62	1.89	0.856	9.6	Example
26	715	650	1.53	1.82	0.843	9.9	Example
27	715	680	1.63	1.92	0.850	9.7	Example
28	715	650	1.55	1.85	0.837	9.1	Example
29	715	630	1.54	1.83	0.842	9.1	Example
30	715	770	1.61	1.98	0.813	6.3	Comparative Example
31	1060	1150	1.50	1.84	0.815	2.4	Comparative Example
32	715	680	1.59	1.90	0.836	8.8	Example
33	715	680	1.59	1.90	0.836	8.8	Example
34	715	680	1.50	1.82	0.826	7.2	Example
35	715	680	1.50	1.82	0.826	7.3	Example

[Table 4]

[Table 4] (cont'd)

No.	25+6900×t	W _{10/10k} (W/kg)	B ₅₀ (T)	Saturation magnetization Bs (T)	B ₅₀ /Bs	Maximum intensity of {100} plane	Remarks
36	715	665	1.51	1.82	0.831	7.9	Example
37	1060	1090	1.59	1.87	0.849	9.4	Comparative Example
38	715	645	1.55	1.85	0.837	9.3	Example
39	715	640	1.56	1.85	0.843	9.5	Example
40	715	640	1.56	1.85	0.843	9.6	Example
41	715	645	1.55	1.85	0.837	9.2	Example
42	715	635	1.57	1.85	0.848	9.7	Example
43	715	640	1.53	1.82	0.843	9.9	Example
44	715	635	1.53	1.82	0.843	9.9	Example
45	715	630	1.53	1.82	0.843	9.9	Example
46	715	644	1.53	1.82	0.843	9.9	Example
47	715	632	1.53	1.82	0.843	9.9	Example
48	715	620	1.53	1.82	0.843	9.9	Example
49	715	641	1.53	1.82	0.843	9.9	Example
50	715	630	1.53	1.82	0.843	9.9	Example
51	715	621	1.53	1.82	0.843	9.9	Example
52	715	620	1.53	1.82	0.843	9.9	Example
53	715	645	1.57	1.89	0.829	9.1	Example
54	715	643	1.57	1.89	0.829	9.1	Example
55	715	642	1.57	1.89	0.829	9.1	Example
56	715	643	1.57	1.89	0.829	9.1	Example
57	715	640	1.57	1.89	0.829	9.1	Example
58	715	643	1.57	1.89	0.829	9.1	Example
59	715	642	1.57	1.89	0.829	9.1	Example
60	715	646	1.57	1.89	0.829	9.1	Example
61	715	642	1.57	1.89	0.829	9.1	Example
62	715	671	1.59	1.90	0.836	8.8	Example
63	715	668	1.59	1.90	0.836	8.8	Example
64	715	673	1.59	1.90	0.836	8.8	Example
65	715	665	1.59	1.90	0.836	8.8	Example
66	715	668	1.59	1.90	0.836	8.8	Example
67	715	672	1.59	1.90	0.836	8.8	Example
68	715	664	1.59	1.90	0.836	8.8	Example
69	715	673	1.59	1.90	0.836	8.8	Example
70	715	663	1.59	1.90	0.836	8.8	Example
71	715	665	1.59	1.90	0.836	8.8	Example
72	715	664	1.59	1.90	0.836	8.8	Example

[0076] As can be seen from the results shown in Table 4, the electrical steel sheet of each Example satisfying the conditions according to the present disclosure had excellent properties such as low high-frequency iron loss and high magnetic flux density.

5

INDUSTRIAL APPLICABILITY

[0077] An electrical steel sheet according to the present disclosure is very suitable for use as a core material for motor cores of hybrid electric vehicles, electric vehicles, vacuum cleaners, high-speed generators, air conditioner
10 compressors, machine tools, etc. that are driven at high frequencies, as well as transformers, reactors, etc.

CLAIMS

- [Claim 1] A non-oriented electrical steel sheet that is a multilayer electrical steel sheet having a stacked structure of an inner layer and a surface layer located on each of both sides of the inner layer,
- 5 wherein the surface layer has a chemical composition containing, in mass%, Si: 4.0 % to 7.5 %, C: 0.0010 % to 0.0100 %, Co: 0.0010 % to 0.0100 %, and one or two selected from Sn: 0.010 % to 0.100 % and Sb: 0.010 % to 0.100 %, with a balance consisting of Fe and inevitable impurities,
- 10 the inner layer has a chemical composition containing, in mass%, Si: 3.0 % to 6.0 %, C: 0.0010 % to 0.0100 %, Co: 0.0010 % to 0.0100 %, and one or two selected from Sn: 0.010 % to 0.100 % and Sb: 0.010 % to 0.100 %, with a balance consisting of Fe and inevitable impurities,
- 15 ΔSi defined as a difference $[\text{Si}]_1 - [\text{Si}]_0$ between a Si content $[\text{Si}]_1$ in the surface layer and a Si content $[\text{Si}]_0$ in the inner layer is 0.5 mass% to 3.3 mass%,
- a ratio t_1/t of a total thickness t_1 , in mm of the surface layers on both sides of the inner layer to a sheet thickness t , in mm of the electrical steel sheet is 0.08 to 0.73, and
- 20 a ratio B_{50}/B_s of magnetic flux density B_{50} at a magnetic field strength of 5000 A/m to saturation magnetization B_s is 0.825 or more, and iron loss $W_{10/10k}$, in W/kg, at a frequency of 10 kHz and a maximum magnetic flux density of 1.0 T and the sheet thickness t satisfy the following formula (1):
- $$W_{10/10k} \leq 25 + 6900 \times t \quad \dots (1).$$
- 25
- [Claim 2] The non-oriented electrical steel sheet according to claim 1, wherein one or both of the chemical composition of the surface layer and the chemical composition of the inner layer further contain, in mass%, at least one of the groups consisting of
- 30 a) P: 0.100 % or less,
- b) one or two selected from Ge and Ga: 0.0100 % or less in total,
- c) one or more selected from Cu, Cr, and Ni: 1.00 % or less in total,
- d) one or more selected from Ca, Mg, and REM: 0.0200 % or less in total,
- e) Zn: 0.0500 % or less, and
- 35 f) one or two selected from Mo and W: 0.0500 % or less in total.

[Claim 3] The non-oriented electrical steel sheet according to claim 1 or 2, wherein a maximum intensity value of {100} plane integration degree is 6.0 or more in a $\Phi_2 = 45^\circ$ section of an orientation distribution function at a plane of a depth of 1/4 of the sheet thickness from a surface of the multilayer electrical steel sheet.

5

[Claim 4] The non-oriented electrical steel sheet according to claim 1 or 2, wherein the sheet thickness is 0.03 mm to 0.20 mm.