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(54) **HIGH-STRENGTH NON-ORIENTED ELECTRICAL STEEL SHEET AND METHOD OF MANUFACTURING THE SAME**

HOCHFESTES NICHTORIENTIERTES ELEKTROSTAHLBLECH UND VERFAHREN ZUR HERSTELLUNG DESSELBEN

TÔLE D’ACIER ÉLECTRIQUE NON ORIENTÉE À HAUTE RÉSISTANCE ET MÉTHODE POUR SA FABRICATION

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Description

Technical Field

[0001] The present invention relates to a high-strength non-oriented electrical steel sheet suitable for an iron core material of an electric vehicle motor and an electrical apparatus motor, and a method of manufacturing the same.

Background Art

[0002] In recent years, higher performance properties are required for a non-oriented electrical steel sheet to be used as an iron core material of a rotary machine due to a worldwide increase in achievement of energy saving of an electrical apparatus. Recently in particular, as a motor to be used for an electric vehicle or the like, a demand for a small-sized high-power motor is high. Such an electric vehicle motor is designed to make high-speed rotation possible to thereby obtain high torque.

[0003] A high-speed rotation motor is also used for a machine tool and an electrical apparatus such as a vacuum cleaner. An outer size of a high-speed rotation motor for an electric vehicle is larger than that of a high-speed rotation motor for an electrical apparatus. Further, as the high-speed rotation motor for an electric vehicle, a DC brushless motor is mainly used. In the DC brushless motor, magnets are embedded in the vicinity of an outer periphery of a rotor. In the above structure, a width of a bridge portion in an outer periphery portion of the rotor (a width between magnets from the most outer periphery of the rotor to a steel sheet) is extremely narrow, which is 1 to 2 mm, depending on a position. Thus, a high-strength steel sheet has been required for the high-speed rotation motor for an electric vehicle rather than a conventional non-oriented electrical steel sheet.

[0004] In Patent Document 1, there is disclosed a non-oriented electrical steel sheet in which Mn and Ni are added to Si to achieve solid solution strengthening. However, it is not possible to obtain sufficient strength even by the above non-oriented electrical steel sheet. Further, due to the addition of Mn and Ni, its toughness is likely to be reduced, and sufficient productivity and a sufficient yield cannot be obtained. Further, prices of alloys to be added are high. In recent years in particular, the price of Ni has suddenly risen due to a worldwide demand balance.

[0005] In Patent Documents 2 and 3, there are disclosed non-oriented electrical steel sheets in which carbonitrides are dispersed in steel to achieve strengthening. However, it is not possible to obtain sufficient strength even by these non-oriented electrical steel sheets.

[0006] In Patent Document 4, there is disclosed a non-oriented electrical steel sheet in which a Cu precipitate is used to achieve strengthening. However, when manufacturing the above non-oriented electrical steel sheet, a thermal treatment condition is restricted. Thus, strength and magnetic properties to be required cannot be obtained.

[0007]

Patent Document 1: Japanese Patent Application Laid-open No. sho 62-256917
Patent Document 2: Japanese Patent Application Laid-open No. Hei 06-330255
Patent Document 3: Japanese Patent Application Laid-open No. Hei 10-018005
Patent Document 4: Japanese Patent Application Laid-open No. 2004-084053

[0008] WO2007/063581 A1 discloses a non-oriented electromagnetic steel sheet that exhibits high strength, being low in high-frequency iron loss; and a process for producing the same.

[0009] EP 1 580 289 A1 discloses that, when a non-oriented electrical steel sheet is manufactured, simultaneously having superior magnetic properties and high strengths, a composition containing 0.02% or less of C, 4.5% or less of Si, 5.0% or less (including 0) of Ni, and 0.2% to 4.0% of Cu is used, and a solute Cu is allowed to appropriately remain in finish annealing.

[0010] JP 2007 162097 A discloses a method for manufacturing a non-oriented electromagnetic steel sheet which suppresses an increase in an alloy cost, has superior surface properties, and has both of excellent mechanical properties and magnetic properties required to a rotor of a motor which rotates at a high speed.

Summary of the Invention

[0011] An object of the present invention is to provide a high-strength non-oriented electrical steel sheet capable of easily obtaining high strength and magnetic properties and a method of manufacturing the same.

[0012] According to the present invention, the above-described problems are solved by the following:

(I) A high-strength non-oriented electrical steel sheet having a chemical composition of:

by mass%,
C: not less than 0.002% nor more than 0.05%;
Si: not less than 2.0% nor more than 4.0%;
Mn: not less than 0.05% nor more than 1.0%;
N: not less than 0.002% nor more than 0.05%;
Cu: not less than 0.5% nor more than 3.0%,
Al: 3.0% or less;
and optionally at least one of Ni: not less than 0.5% nor more than 3.0%, Sn: not less than 0.01% nor more than 0.10%, and B: not less than 0.0010% nor more than 0.0050%; and
when a Nb content (%) is set to [Nb], a Zr content (%) is set to [Zr], a Ti content (%) is set to [Ti], a V content (%) is set to [V], a C content (%) is set to [C], and an N content (%) is set to [N], Formula (1) and Formula (2) are satisfied; and
a balance composed of Fe and inevitable impurities;
a recrystallization area ratio of 50% or more;
a yield stress at a tensile test of 700 MPa or more;
a fracture elongation of 10% or more; and
an eddy current loss $We_{10/400}$ (W/kg) which satisfies Formula (3) in relation to a sheet thickness t (mm) of the steel sheet.

$$2.0\times10^{-4} \leqq [Nb]/93+[Zr]/91+[Ti]/48+[V]/51 \cdots (1)$$

$$1.0\times10^{-3} \leqq [C]/12+[N]/14-([Nb]/93+[Zr]/91+[Ti]/48+[V]/51) \leqq 3.0\times10^{-3} \cdots (2)$$

$$We_{10/400} \leqq 70\times t^2 \cdots (3)$$

(II) The high-strength non-oriented electrical steel sheet described in (I) may contain by mass%, Ni: not less than 0.5% nor more than 3.0%.

(III) The high-strength non-oriented electrical steel sheet described in (I) or (II) may further contain by mass%, Sn: not less than 0.01% nor more than 0.10%.

(IV) The high-strength non-oriented electrical steel sheet described in any one of (I) to (III) may further contain by mass%, B: not less than 0.0010% nor more than 0.0050%.

(V) A method of manufacturing a high-strength non-oriented electrical steel sheet comprising:

manufacturing a slab having a chemical composition as defined in (I);
obtaining a hot-rolled sheet by hot rolling the slab;
pickling the hot-rolled sheet;
next, obtaining a cold-rolled sheet by cold rolling the hot-rolled sheet; and
finish-annealing the cold-rolled sheet, wherein
a soaking temperature T (°C) of said finish-annealing and a Cu content "a" (mass%) of the cold-rolled sheet satisfy Formula (4).

$$T \geqq 200\times a + 500 \cdots (4)$$

(VI) The method of manufacturing a high-strength non-oriented electrical steel sheet described in (V) may further comprise annealing the hot-rolled sheet between said obtaining the hot-rolled sheet and said pickling the hot-rolled sheet.

[0013] Also disclosed herein is a method of manufacturing a high-strength non-oriented electrical steel sheet which includes:
manufacturing a slab containing:

by mass%,
C: not less than 0.002% nor more than 0.05%;
Si: not less than 2.0% nor more than 4.0%;
Mn: not less than 0.05% nor more than 1.0%;
N: not less than 0.002% nor more than 0.05%; and
Cu: not less than 0.5% nor more than 3.0% and in which
an Al content is 3.0% or less,
when a Nb content (%) is set to [Nb], a Zr content (%) is set to [Zr], a Ti content (%) is set to [Ti], a V content (%) is set to [V], a C content (%) is set to [C], and an N content (%) is set to [N], Formula (1) and Formula (2) are satisfied, and a balance is composed of Fe and inevitable impurities;
obtaining a hot-rolled sheet by hot rolling the slab;
next, pickling the hot-rolled sheet;
next, obtaining a cold-rolled sheet by cold rolling the hot-rolled sheet; and
finish-annealing the cold-rolled sheet, wherein
a coiling temperature of the hot rolling is 550°C or less, and a ductile/brittle fracture transition temperature at a Charpy impact test of the hot-rolled sheet is 70°C or less.

[0014] Disclosed herein is further a method of manufacturing a high-strength non-oriented electrical steel sheet which includes:
manufacturing a slab containing:

by mass%,
C: not less than 0.002% nor more than 0.05%;
Si: not less than 2.0% nor more than 4.0%;
Mn: not less than 0.05% nor more than 1.0%;
N: not less than 0.002% nor more than 0.05%; and
Cu: not less than 0.5% nor more than 3.0% and in which
an Al content is 3.0% or less,
when a Nb content (%) is set to [Nb], a Zr content (%) is set to [Zr], a Ti content (%) is set to [Ti], a V content (%) is set to [V], a C content (%) is set to [C], and an N content (%) is set to [N], Formula (1) and Formula (2) are satisfied, and a balance is composed of Fe and inevitable impurities;
obtaining a hot-rolled sheet by hot rolling the slab;
next, annealing the hot-rolled sheet;
next, pickling the hot-rolled sheet;
next, obtaining a cold-rolled sheet by cold rolling the hot-rolled sheet; and
finish-annealing the cold-rolled sheet, and in which
a cooling rate from 900°C to 500°C of the annealing is 50°C/sec or more, and a ductile/brittle fracture transition temperature at a Charpy impact test of the hot-rolled sheet is 70°C or less.

Detailed Description of the Preferred Embodiments

[0015] The present inventors have investigated the reason why strength and magnetic properties are greatly affected by thermal treatment conditions in a conventional steel strengthening method in which a Cu precipitate is used. As a result, it has been found that a high annealing temperature making Cu once solid-dissolving is needed at finish-annealing after cold rolling in order to strengthen a steel sheet by precipitation of Cu.
[0016] However, it has also been learned that simply increasing the finish-annealing temperature coarsens crystal grains, and strengthening margin by the Cu precipitation is reduced.
[0017] Further, it has also been learned that when crystal grain coarsening and strengthening by the Cu precipitation are overlapped, fracture elongation at a tensile test is remarkably reduced. The above remarkable reduction in fracture elongation, in the case when a motor core is punched out from the steel sheet in particular, causes a crack in a punched-out end surface to thereby develop to a remarkable reduction in a yield and productivity of the motor core. Thus, it is desirable to avoid the remarkable reduction in fracture elongation.
[0018] Thus, the present inventors have further advanced earnest researches on a method of solving these various problems while enjoying strengthening by the Cu precipitation. As a result, it has been learned that some determined amounts of C, N, Nb, Zr, Ti, and V are contained, thereby enabling both strengthening by the Cu precipitation and making crystal grains fine to be achieved and enabling the previously described various problems to be solved.
[0019] Further, it has been learned that a magnetic property required for a rotor being the main use of a high-strength electrical steel sheet is an eddy current loss (We) at a high frequency of 400 Hz or more, and as for a reduction in the

eddy current loss (We) as well, making crystal grains fine by containing C, N, Nb, Zr, Ti, and V is effective.

[0020] Here, experimental results that have led to the present invention will be explained.

(Experiment 1)

[0021] In a vacuum melting furnace in a laboratory, steels containing, by mass%, Si: 3.1%, Mn: 0.2%, Al: 0.5%, and Cu: 2.0% with C, N, Nb, Zr, Ti, and V by mass% shown in Table 1 were manufactured and heated at 1100°C for 60 minutes, and then the steels were hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.0 mm were obtained. Thereafter, these hot-rolled sheets were pickled, and by cold rolling once, cold-rolled sheets having sheet thicknesses of 0.35 mm were obtained. Finish-annealing at 800°C to 1000°C for 30 seconds was applied to these cold-rolled sheets. In Table 2, measured results of various properties after finish-annealing are shown.

[Table 1]

Table 1						(mass%)
Material symbol	C (%)	N (%)	Nb (%)	Zr (%)	Ti (%)	V (%)
A	0.001	0.003	0.001	0.002	0.003	0.004
B	0.008	0.003	0.012	0.002	0.003	0.004
C	0.028	0.003	0.030	0.002	0.003	0.004
D	0.045	0.003	0.040	0.040	0.040	0.040
E	0.055	0.003	0.035	0.002	0.003	0.004

[Table 2]

Table 2 (Evaluation: ○ Good, × Bad)

Material symbol	Finish annealing temperature (°C)	Recrystallization area ratio (%)	Yield stress (MPa)	Fracture elongation (%)	Eddy current loss We10/400 (W/Kg)	Evaluation	Note
A	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	100	632	11	9.1	×	Low yield strength and high We
	1000	100	633	2	10.5	×	Low yield stress and elongation, and high We
B	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	20	-	-	-	×	Out of evaluation due to low recrystallization area ratio
	1000	100	635	8	10.8	×	Low yield stress and elongation, and high We
C	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	100	732	22	7.5	○	Good properties in all
	1000	100	768	18	8.2	○	Good properties in all
D	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	100	789	26	7.7	○	Good properties in all
	1000	100	823	23	7.8	○	Good properties in all
E	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	0	-	-	-	×	Out of evaluation due to non-recrystallization
	1000	100	879	8	7.7	×	Low elongation

[0022] As shown in Table 2, in Materials C and D, in which Nb, Zr, Ti, and V satisfied Formula (1), yield strength and fracture elongation were high, and an eddy current loss was low, resulting that good properties were obtained. In Material A hardly containing C, N, Nb, Zr, Ti, and V, both the yield strength and the fracture elongation were low, and the eddy current loss was high. This is because crystal grains were coarsened at finish-annealing at 900°C and 1000°C.

[0023] As for Material B, a recrystallization area ratio at finish-annealing at 900°C was low. This is inferred that Nb, which was a little contained, precipitated immediately before recrystallization during finish-annealing to delay recrystallization. Further, it is inferred that by finish-annealing at 1000°C, Nb solid-dissolved to coarsen crystal grains, and thus a result similar to that of Material A was exhibited.

[0024] It is inferred that as for Material C in which good properties were obtained, a Nb precipitate was appropriately dispersed to precipitate, and as for Material D, a Ti precipitate was appropriately dispersed to precipitate to suppress crystal grain growth at 900°C and 1000°C. On the other hand, Cu once solid-dissolved at finish-annealing temperatures of 900°C and 1000°C, and further at the time of cooling during finish-annealing, Cu precipitated finely, so that strengthening by the Cu precipitation could be optimized. As a result, it is inferred that the high yield strength and fracture elongation and the low eddy current loss could be obtained.

[0025] As for Material E, the yield strength was high, but the fracture elongation was low. This can be considered that excess C adversely affected Material E. Incidentally, under any one of the conditions as well, recrystallization did not occur at finish-annealing at 800°C. This can be considered that Cu, which had solid-dissolved before annealing, precipitated during annealing to delay recrystallization.

(Experiment 2)

[0026] In a vacuum melting furnace in a laboratory, steels containing, by mass%, Si: 2.8%, Mn: 0.1%, Al: 1.0%, and Cu: 1.8% with C, N, Nb, Zr, Ti, and V by mass% shown in Table 3 were manufactured and heated at 1150°C for 60 minutes, and then the steels were hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.2 mm were obtained. Thereafter, these hot-rolled sheets were pickled, and by cold rolling once, cold-rolled sheets having sheet thicknesses of 0.35 mm were obtained. Finish-annealing at 800°C to 1000°C for 30 seconds was applied to these cold-rolled sheets. In Table 4, measured results of various properties after finish-annealing are shown.

[Table 3]

Table 3						(mass%)
Material symbol	C (%)	N (%)	Nb (%)	Zr (%)	Ti (%)	V (%)
F	0.003	0.001	0.001	0.002	0.003	0.004
G	0.003	0.009	0.011	0.002	0.003	0.004
H	0.003	0.033	0.031	0.002	0.003	0.004
I	0.003	0.049	0.041	0.039	0.039	0.039
J	0.003	0.064	0.036	0.002	0.003	0.004

[Table 4]

Table 4 (Evaluation: ○ Good, X Bad)

Material symbol	Finish annealing temperature (°C)	Recrystallization area ratio (%)	Yield stress (MPa)	Fracture elongation (%)	Eddy current loss We10/400 (W/Kg)	Evaluation	Note
F	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	100	630	12	9.3	×	Low yield strength and high We
	1000	100	632	3	10.4	×	Low yield stress and elongation, and high We
G	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	20	-	-	-	×	Out of evaluation due to low recrystallization area ratio
	1000	100	632	7	10.7	×	Low yield stress and elongation, and high We
H	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	100	735	20	7.6	○	Good properties in all
	1000	100	769	19	8.1	○	Good properties in all
I	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	100	787	24	7.8	○	Good properties in all
	1000	100	826	21	7.9	○	Good properties in all
J	800	0	-	-	-	×	Out of evaluation due to non-recrystallization
	900	0	-	-	-	×	Out of evaluation due to non-recrystallization
	1000	100	884	7	7.8	×	Low elongation

[0027] As shown in Table 4, in Materials H and I, in which Nb, Zr, Ti, and V satisfied Formula (1), the yield strength and the fracture elongation were high, and the eddy current loss was low, resulting that good properties were obtained. As for Material F hardly containing C, N, Nb, Zr, Ti, and V, both the yield strength and the fracture elongation were low, and the eddy current loss was high. This is because crystal grains were coarsened at finish-annealing at 900°C and 1000°C.

[0028] As for Material G, the recrystallization area ratio at finish-annealing at 900°C was low. This is inferred that Nb, which was a little contained, precipitated immediately before recrystallization during finish-annealing to delay recrystallization. Further, it is inferred that at finish-annealing at 1000°C, Nb solid-dissolved to coarsen crystal grains, and thus a result similar to that of Material F was exhibited.

[0029] It is inferred that as for Material H in which good properties were obtained, a Nb precipitate was appropriately dispersed to precipitate, and as for Material I, a Ti precipitate was appropriately dispersed to precipitate to suppress crystal grain growth at 900°C and 1000°C. On the other hand, Cu once solid-dissolved at finish-annealing temperatures of 900°C and 1000°C, and further at the time of cooling during finish-annealing, Cu precipitated finely, so that strengthening by the Cu precipitation could be optimized. As a result, it is inferred that the high yield strength and fracture elongation and the low eddy current loss could be obtained.

[0030] As for Material J, the yield strength was high, but the fracture elongation was low. This can be considered that excess N adversely affected Material J. Incidentally, under any one of the conditions as well, recrystallization did not occur at finish-annealing at 800°C. This can be considered that Cu, which had solid-dissolved before annealing precipitated during annealing to delay recrystallization.

[0031] Finish-annealing at 800°C has been so far performed as a process of making crystal grains fine. That is, finish-annealing at 800°C has been performed under a purpose in which by finish-annealing as above, Cu once solid-dissolves to achieve high-strengthening, and a steel sheet is recrystallized, and then crystal grains are not allowed to be coarsened. However, from Experiments 1 and 2, it has been found that even if the annealing temperature is adjusted while adding Cu, only with the above, it is difficult to obtain sufficient strength. That is, in a conventional technique, it is difficult to achieve both mechanical properties and magnetic properties. On the other hand, the present invention as will be described below makes it possible to achieve both mechanical properties and magnetic properties.

[0032] Next, a reason for limiting a numerical value in a high-strength non-oriented electrical steel sheet according to the present invention will be described. Hereinafter, % means mass%.

[0033] C is an element necessary for making crystal grains fine. Fine carbide increases nucleation sites at the time of recrystallization and further has an effect of suppressing crystal grain growth. In order to enjoy the effect, a C content is 0.002% or more. When N is less than 0.005% in particular, the preferable C content is 0.01% or more, and more preferably 0.02% or more. On the other hand, when C is added over 0.05%, the fracture elongation is remarkably reduced. Thus, an upper limit of the C content is set to 0.05%.

[0034] Si is effective for reducing the eddy current loss, and is an element effective for solid solution strengthening as well. However, when Si is added excessively, cold rolling performance is remarkably reduced. Thus, an upper limit of a Si content is set to 4.0%. On the other hand, from the viewpoint of solid solution strengthening and the eddy current loss, a lower limit is set to 2.0%.

[0035] Mn, similarly to Si, reduces the eddy current loss, and is an element effective for increasing strength. However, even when a Mn content exceeds 1.0%, an effect does not improve to be saturated, and thus an upper limit of the Mn content is set to 1.0%. On the other hand, from the viewpoint of sulfide generation, a lower limit is set to 0.05%.

[0036] Al, similarly to Si, is an element effective for increasing resistivity. However, when an Al content exceeds 3.0%, castability is reduced, and thus considering productivity, an upper limit of the Al content is set to 3.0%. A lower limit is not set in particular. However, from the viewpoint of stabilizing deoxidation (nozzle clogging prevention during casting), it is preferable that the Al content in the case of Al deoxidation is 0.02% or more, and the Al content in the case of Si deoxidation is 0.01% or more.

[0037] N is an element necessary for making crystal grains fine. Fine nitride increases nucleation sites at the time of recrystallization, and further has an effect of suppressing crystal grain growth. In order to enjoy the effect, an N content is set to 0.002% or more. When N of 0.005% or more is contained greatly over a normal level, the effect of suppressing crystal grain growth becomes further remarkable. The higher the N content is, the larger the above effect is, so that the N content is preferably further increased to 0.01% or more, and more preferably to 0.02% or more. In the case when the C content is less than 0.005% in particular, the effect to be obtained by the N addition as above appears more strongly. On the other hand, when N is added over 0.05%, the fracture elongation is remarkably reduced. Thus, an upper limit of the N content is set to 0.05%.

[0038] Cu is an important element of bringing precipitation strengthening. When a Cu content is less than 0.5%, Cu completely solid-dissolves in the steel and an effect of the precipitation strengthening cannot be obtained, so that a lower limit of the Cu content is set to 0.5%. An upper limit is set to 3.0% in consideration of the fact that strength is to be saturated.

[0039] Ni is an effective element that hardly embrittles the steel sheet to enable the steel sheet to be high-strengthened. Ni may be added depending on strength to be required because it is expensive. In the case when Ni is added, 0.5% or more is preferably contained in order to sufficiently obtain an effect of Ni. Further, an upper limit is set to 3.0% in consideration of its cost. Further, from the viewpoint of suppressing a scab to occur by the Cu addition, Ni of 1/2 or more of a Cu addition amount is preferably added.

[0040] Sn improves texture and further has an effect of suppressing nitriding and oxidation at the time of annealing. Particularly, an effect of improving a magnetic flux density to be reduced by the Cu addition is large. When an Sn content is less than 0.01%, the desired effects cannot be obtained, and on the other hand, when Sn is added over 0.10%, there is sometimes a case that an increase in a scab is caused. Thus, an Sn addition amount is preferably not less than 0.01% nor more than 0.10%.

[0041] B segregates in grain boundaries and has an effect of increasing toughnesses of a hot-rolled sheet and a hot-rolled-annealed sheet. When a B content is less than 0.0010%, the desired effect cannot be obtained, and on the other hand, when B is added over 0.0050%, there is sometimes a case that a slab crack at the time of casting occurs. Thus, a B addition amount is preferably not less than 0.0010% nor more than 0.0050%.

[0042] Four elements of Nb, Zr, Ti, and V generate carbide or nitride and have an effect of suppressing coarsening of a crystal grain diameter. Then, in the case when Formula (1) constituted by using values obtained after mass% of each of the elements is divided by an atomic weight is satisfied, the remarkable effect is exhibited. [Nb] represents a Nb content (mass%), [Zr] represents a Zr content (mass%), [Ti] represents a Ti content (mass%), and [V] represents a V content (mass%).

$$2.0\times10^{-4} \leqq [Nb]/93+[Zr]/91+[Ti]/48+[V]/51 \quad \cdots (1)$$

In Formula (1), in the case when a value on the right side is less than 2.0×10^{-4}, a precipitation amount becomes insufficient, and the sufficient effect of suppressing crystal grains cannot be obtained. Thus, a lower limit of the value on the right side is set to 2.0×10^{-4} . On the other hand, excess contents of these elements solid-dissolve in the steel and do not affect properties of the steel, so that an upper limit of the value on the right side is not defined in particular. However, in consideration of properties and costs, the value on the right side is preferably 1.0×10^{-2} or less.

[0043] Formula (2), where a relationship of the six elements of C, N, Nb, Zr, Ti, and V is defined, is an important parameter for making crystal grains fine in alliance with Formula (1). [C] represents the C content (mass%) and [N] represents the N content (mass%).

$$1.0\times10^{-3} \leqq [C]/12+[N]/14-([Nb]/93+[Zr]/91+[Ti]/48+[V]/51) \leqq 3.0\times10^{-3} \quad \cdots (2)$$

[0044] Formula (1) is merely such that a maximum amount capable of forming carbide or nitride is defined, and it is not possible to sufficiently suppress crystal grain growth during final annealing only by the above condition.

[0045] The second term in Formula (2) is such that the right side in Formula (1) is subtracted from the sum of a value obtained after mass% of C is divided by an atomic weight and a value obtained after mass% of N is divided by an atomic weight, and is a parameter representing the excess C amount and/or N amount that do/does not form carbonitride.

[0046] Excess C and/or N as above are/is extremely important for making crystal grains fine. This is because in the case when C and/or N are/is contained excessively, carbonitride is appropriately dispersed to precipitate before finish-annealing to thereby enable crystal grain growth at the time of annealing to be suppressed securely.

[0047] In the present invention, carbide, nitride, and carbonitride have extremely important roles, and among them, nitride and carbonitride are effective, and particularly, nitride has a remarkable effect. That is, when carbide and nitride are compared, nitride is more effective for the effect of the present invention, and nitride rather exhibits the effect contributing to the effect of the present invention by a reduced amount. Further, when carbide and nitride in the same amount are compared, nitride rather can obtain a large favorable effect, and can suppress an unfavorable side effect. The "favorable effect" to be described here means making crystal grains fine, high-strengthening, and stability at a high temperature, and the "unfavorable side effect" means an increase in a core loss and a crack originating from a precipitate (embittlement in particular).

[0048] A mechanism in which properties of a non-oriented electrical steel sheet change depending on types of the precipitates as above is unclear, but it is possible to consider that this is because the properties of a non-oriented electrical steel sheet are affected by precipitate sizes, forms (anisotropy), consistency with a parent phase, precipitation places, and so on. Further, it is possible to consider that the precipitate sizes and so on are affected by difference in solubility of the constituent elements, difference in crystal structures of the precipitates, difference in sizes of constituent atoms, and so on.

[0049] As described above, balances with not only the Nb, Zr, Ti, and V contents but also the C content and a thermal history in a manufacturing process are considered to set the N content appropriately, so that in the present invention, nitride is preferentially formed as compared with a conventional electrical steel sheet. As a result, crystal grain growth at a high temperature is suppressed, thereby enabling an increase in a core loss and embrittlement to be suppressed.

[0050] Further, as for carbonitride, a composition thereof varies depending on forming processes, so that properties and effects of carbonitride do not become the same, but it is said that carbonitride exhibits a more favorable effect than the precipitate composed of at least only carbide. Thus, a ratio of the N content to the C content is preferably high, and [N]/[C] is preferably three or more, and more preferably five or more. Incidentally, a composition of carbonitride is considered to change by effects such that, for example, carbide is set as initial formation, nitride is set as initial formation, structure similar to that of carbide is held in a growth process, structure similar to that of nitride is held in a growth process and the like.

[0051] In the case when the value (parameter value) of the second term in Formula (2) is less than 1.0×10^{-3}, thermal stability of carbonitride weakens. For example, when carbonitride precipitates immediately before recrystallization during finish-annealing to delay recrystallization, and further an annealing temperature is increased, the precipitate solid-dissolves again and crystal grains are coarsened, resulting that it becomes difficult to form fine grains stably. On the other hand, when C and/or N become/becomes excessive to a level where the parameter value exceeds 3.0×10^{-3}, hardening occurs during cooling, and elongation and toughness of the steel sheet deteriorate.

[0052] From the reasons as above, a lower limit of the parameter value in Formula (2) is set to 1.0×10^{-3}, and an upper limit is set to 3.0×10^{-3}.

[0053] In the case when a recrystallization area ratio of the high-strength non-oriented electrical steel sheet itself is less than 50%, product properties, particularly, the fracture elongation is remarkably reduced. Thus, the above recrystallization area ratio is set to 50% or more.

[0054] The yield stress at a tensile test is set to 700 MPa or more in consideration of strength to be required for a rotor to rotate at a high speed. Note that the yield stress to be defined here is a lower yield point.

[0055] The fracture elongation is set to 10% or more from the viewpoint of suppressing a crack in a punched-out end surface of a motor core.

[0056] The eddy current loss is a loss to occur after current flows through a steel sheet at excitation, and in the case when the above loss is large, the motor core easily generates heat to cause demagnetization of magnets. An eddy current loss $We_{100/400}$ has large dependence on a sheet thickness of the steel sheet, and thus a sheet thickness t (mm) is set as a parameter to set the eddy current loss $We_{100/400}$ to $70\times t^2$ or less as shown in Formula (3) as a tolerance range of the rotor heat generation.

$$We_{10/400} \leqq 70 \times t^2 \quad \cdots (3)$$

[0057] As a method of calculating the above eddy current loss, a dual frequency method is used. When, for example, at a maximum magnetic flux density Bmax of 1.0 T, a core loss at a frequency f_1 is set to W_1 and a core loss at a frequency f_2 is set to W_2, the eddy current loss $We_{10/400}$ of $W_{10/400}$ can be calculated by "$(W_2/f_2-W_1/f_1)/(f_2-f_1)\times400\times400$".

[0058] As long as a plurality of core loss values at different frequencies exist at the maximum magnetic flux density Bmax of 1.0 T, the calculation is possible to be performed, and thus a measurement frequency is not defined in particular. However, if possible, the calculation is preferably performed at a frequency close to 400 Hz, or in a frequency range of, for example, 100 to 800 Hz or so. Note that the maximum magnetic flux density Bmax is a maximum magnetic flux density to be excited when measuring a core loss.

[0059] Next, a reason for limiting a numerical value in a method of manufacturing the high-strength non-oriented electrical steel sheet according to the present invention will be described.

[0060] At finish-annealing, Cu once solid-dissolves and precipitates during cooling, and thereby high strength can be obtained. Thus, a soaking temperature T (°C) of finish-annealing has to be a solid solution temperature of Cu or more. The solid solution temperature depends on the Cu content. When the Cu content is set to "a" (mass%), when a temperature (°C) is $200\times a + 500$ or more, Cu completely solid-dissolves, so that the soaking temperature T (°C) of finish-annealing is set to $200\times a + 500$ or more as shown in Formula (4).

$$T \geqq 200 \times a + 500 \quad \cdots (4)$$

[0061] When a coiling temperature at the time of hot rolling exceeds 550°C, carbonitride and a Cu precipitate, depending on a hot-rolled sheet, remarkably reduce its toughness. Thus, the coiling temperature at the time of hot rolling is set to 550°C or less. With regard to the toughness of a hot-rolled sheet, a ductile/brittle fracture transition temperature at a

Charpy impact test is set to 70°C or less from the viewpoint of fracture suppression at the time of cold rolling.

[0062] With regard to annealing of the hot-rolled sheet, when a cooling rate from 900°C to 500°C is lower than 50°C/sec, toughness of a hot-rolled-annealed sheet is remarkably reduced by carbonitride and the Cu precipitate. Thus, the cooling rate in the above temperature range is set to 50°C/sec or more. With regard to the toughness of the steel sheet after annealing, the ductile/brittle fracture transition temperature at the Charpy impact test is set to 70°C or less from the viewpoint of fracture suppression at the time of cold rolling.

[0063] Incidentally, an annealing temperature of the hot-rolled sheet is not defined in particular, but the purpose of annealing of the hot-rolled sheet is recrystallization and grain growth promotion of the hot-rolled sheet, and thus the annealing temperature is preferably 900°C or more, and on the other hand, from the viewpoint of brittleness, it is preferably 1100°C or less.

[0064] The transition temperature defined here is a temperature such that as defined in Japan Industrial Standard (JIS), in a transition curve showing a relationship between a test temperature and a ductile fracture rate, the ductile fracture rate is 50%. A temperature corresponding an average value of absorbed energy at the ductile fracture rate of 0% and absorbed energy at the ductile fracture rate of 100% may also be employed.

[0065] A length and height of a test piece to be used for the Charpy impact test are set to sizes defined in JIS. On the other hand, a width of the test piece is set to a thickness of the hot-rolled sheet. Thus, the size, in a rolling direction, is 55 mm in length and 10 mm in height, and the width is 1.5 mm to 3.0 mm or so depending on the thickness of the hot-rolled sheet. Further, when performing the test, it is rather preferable that the plural test pieces are stacked to approximate a thickness of 10 mm that is a regular test condition.

(Embodiment 1)

[0066] In a vacuum melting furnace, steels containing, by mass%, Si: 2.9%, Mn: 0.2%, Al: 0.7%, and Cu: 1.5%, in which C, N, Nb, Zr, Ti, and V differ in mass%, were manufactured and heated at 1150°C for 60 minutes, and then the steels were hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.3 mm were obtained. Thereafter, these hot-rolled sheets were pickled, and by cold rolling once, cold-rolled sheets having sheet thicknesses of 0.5 mm were obtained. Finish-annealing at 900°C for 60 seconds was applied to these cold-rolled sheets. In Table 5, measured results of components and various properties are shown.

[Table 5]

[0067]

Table 5

Material symbol	C	N	Nb	Zr	Ti	V	Formula (1) (×10^{-4})	Formula (2) (×10^{-3})	Recrystallization area ratio (%)	Yield stress (MPa)	Fracture elongation (%)	Formula (3)*1 We10/400	Note
a1	0.012	0.003	0.005	0.002	0.003	0.002	1.77	1.04	100	540	15	20.2	Comparative example
a2	0.022	0.003	0.012	0.002	0.003	0.004	2.92	1.76	100	750	19	16.3	Invention example
a3	0.031	0.003	0.030	0.002	0.003	0.004	4.85	2.31	100	770	19	16.5	Invention example
a4	0.025	0.003	0.045	0.002	0.003	0.004	6.47	1.65	100	780	19	16.5	Invention example
a5	0.024	0.003	0.003	0.007	0.003	0.002	2.11	2.00	100	790	15	17.0	Invention example
a6	0.036	0.003	0.003	0.015	0.003	0.002	2.99	2.92	90	795	19	16.4	Invention example
a7	0.033	0.003	0.003	0.037	0.003	0.002	5.41	2.42	80	801	18	16.3	Invention example
a8	0.026	0.003	0.003	0.002	0.006	0.002	2.18	2.16	60	783	12	16.3	Invention example
a9	0.037	0.003	0.003	0.002	0.011	0.002	3.23	2.98	90	790	19	16.6	Invention example
a10	0.041	0.003	0.003	0.002	0.032	0.002	7.60	2.87	60	810	11	16.8	Invention example
a11	0.014	0.003	0.003	0.002	0.003	0.005	2.15	1.17	100	740	19	16.4	Invention example
a12	0.034	0.003	0.003	0.002	0.003	0.013	3.72	2.68	90	760	18	16.3	Invention example
a13	0.024	0.003	0.003	0.002	0.003	0.028	6.66	1.55	70	780	15	16.5	Invention example
a14	0.003	0.002	0.033	0.002	0.003	0.002	4.79	-0.09	30	800	5	16.2	Comparative example
a15	0.003	0.003	0.003	0.034	0.003	0.002	5.08	-0.04	40	760	8	16.1	Comparative example
a16	0.003	0.003	0.003	0.002	0.032	0.002	7.60	-0.30	10	850	2	16.5	Comparative example
a17	0.003	0.003	0.003	0.002	0.003	0.029	6.85	-0.22	20	820	6	16.4	Comparative example
a18	0.045	0.002	0.033	0.002	0.003	0.002	4.79	3.41	90	680	5	16.5	Comparative example
a20	0.054	0.003	0.003	0.002	0.032	0.002	7.60	3.95	100	820	4	16.4	Comparative example

*1: From Formula (3), $We_{10/400} \leqq 17.5$ W/kg at a sheet thickness of 0.5 mm

[0068] In Symbol a1 not satisfying Formula (1), the yield stress and the eddy current loss $We_{10/400}$ were out of the range defined in the present invention. Further, in Symbols a14 to a17 not satisfying Formula (2), the recrystallization area ratio and the fracture elongation were out of the range defined in the present invention. In Symbol a20, whose C content exceeds the upper limit of the range defined in the present invention and which does not satisfy Formula (2), the fracture elongation was out of the range defined in the present invention. In other samples (Symbols a2, a3, and a18), whose requirements each fell within the range defined in the present invention, good properties were obtained.

(Embodiment 2)

[0069] In a vacuum melting furnace, steels containing, by mass%, Si: 3.7%, Mn: 0.1%, Al: 0.2%, and Cu: 1.4%, in which C, N, Nb, Zr, Ti, and V differ in mass%, were manufactured and heated at 1150°C for 60 minutes, and then the steels were hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.3 mm were obtained. Thereafter, these hot-rolled sheets were pickled, and by cold rolling once, cold-rolled sheets having sheet thicknesses of 0.5 mm were obtained. Finish-annealing at 900°C for 60 seconds was applied to these cold-rolled sheets. In Table 6, measured results of components and various properties are shown.

[Table 6]

[0070]

Table 6

Material symbol	C	N	Nb	Zr	Ti	V	Formula (1) ($\times 10^{-4}$)	Formula (2) ($\times 10^{-3}$)	Recrystallization area ratio (%)	Yield stress (MPa)	Fracture elongation (%)	Formula (3) We10/400 *1	Note
b1	0.003	0.014	0.005	0.002	0.003	0.002	1.77	1.07	100	542	14	20.1	Comparative example
b2	0.003	0.022	0.012	0.002	0.003	0.004	2.92	1.53	100	755	20	16.2	Invention example
b3	0.003	0.018	0.030	0.002	0.003	0.004	4.85	1.05	100	776	22	16.7	Invention example
b4	0.003	0.020	0.045	0.002	0.003	0.004	6.47	1.03	100	782	22	16.3	Invention example
b5	0.003	0.017	0.003	0.007	0.003	0.002	2.11	1.25	100	793	20	16.8	Invention example
b6	0.003	0.018	0.003	0.015	0.003	0.002	2.99	1.24	90	792	22	16.2	Invention example
b7	0.003	0.019	0.003	0.037	0.003	0.002	5.41	1.07	80	803	21	16.1	Invention example
b8	0.008	0.009	0.003	0.002	0.006	0.002	2.18	1.09	60	784	13	16.4	Invention example
b9	0.003	0.016	0.003	0.002	0.011	0.002	3.23	1.07	90	793	22	16.7	Invention example
b10	0.005	0.019	0.003	0.002	0.032	0.002	7.60	1.01	60	804	12	16.2	Invention example
b11	0.005	0.012	0.003	0.002	0.003	0.005	2.15	1.06	100	750	18	16.1	Invention example
b12	0.003	0.016	0.003	0.002	0.003	0.013	3.72	1.02	90	766	23	16.0	Invention example
b13	0.008	0.016	0.003	0.002	0.003	0.028	6.66	1.14	70	782	14	16.8	Invention example
b14	0.003	0.009	0.033	0.002	0.003	0.002	4.79	0.41	30	803	4	16.3	Comparative example
b15	0.003	0.011	0.003	0.034	0.003	0.002	5.08	0.53	40	763	6	16.2	Comparative example
b16	0.003	0.009	0.003	0.002	0.032	0.002	7.60	0.13	10	849	1	16.6	Comparative example
b17	0.003	0.008	0.003	0.002	0.003	0.029	6.85	0.14	20	823	6	16.8	Comparative example
b18	0.003	0.007	0.033	0.002	0.003	0.002	4.79	0.27	90	688	4	16.4	Comparative example
b20	0.032	0.043	0.003	0.002	0.032	0.002	7.60	4.98	100	821	3	16.7	Comparative example

*1: From Formula (3), We10/400 ≦ 17.5 W/kg at a sheet thickness of 0.5 mm

[0071] In Symbol b1 not satisfying Formula (1), the yield stress and the eddy current loss $We_{10/400}$ were out of the range defined in the present invention. Further, in Symbols b14 to b17 not satisfying Formula (2), the recrystallization ratio and the fracture elongation were out of the range defined in the present invention. Similarly, in Symbol b20 not satisfying Formula (2), the fracture elongation was out of the range defined in the present invention. In other samples (Symbols b2, b3, and b18),
whose requirements each fell within the range defined in the present invention, good properties were obtained.

(Embodiment 3)

[0072] In a vacuum melting furnace, steels containing, by mass%, C: 0.022%, Mn: 0.5%, Al: 2.0%, N: 0.003%, Ni: 1.0%, Nb: 0.031%, Zr: 0.004%, Ti: 0.003%, and V: 0.004%, in which the Si amount and the Cu amount were changed, were manufactured and heated at 1120°C for 120 minutes, and then the steels were hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.0 mm were obtained. Thereafter, these hot-rolled sheets were pickled, and by cold rolling once, cold-rolled sheets having sheet thicknesses of 0.25 mm were obtained. Finish-annealing at 1000°C for 45 seconds was applied to these cold-rolled sheets. In Table 7, measured results of the Si amount, the Cu amount, and various properties are shown.

[Table 7]

[0073]

Table 7

Material symbol	Si (%)	Cu (%)	Ni/Cu	Yield stress (MPa)	Fracture elongation (%)	Eddy current loss We10/400*2 (W/kg)	Scab	Note
c1	1.8	0.4	2.5	540	15	5.4	Non-existence	Comparative example
c2	1.8	0.6	1.7	570	19	5.5	Non-existence	Comparative example
c3	1.8	1.1	0.9	620	21	5 .7	Non-existence	Comparative example
c4	1.8	1.7	0.6	670	21	5.9	Non-existence	Comparative example
c5	1.8	2.4	0.4	690	15	6.2	Existence	Comparative example
c6	2.1	0.3	3.3	610	21	4.3	Non-existence	Comparative example
c7	2.1	0.7	1.4	700	18	4.3	Non-existence	Invention example
c8	2.1	1.3	0.8	720	12	4.2	Non-existence	Invention example
c9	2.1	1.7	0.6	740	21	4.2	Non-existence	Invention example
c10	2.1	2.5	0.4	760	11	4.1	Existence	Invention example

(continued)

Material symbol	Si (%)	Cu (%)	Ni/Cu	Yield stress (MPa)	Fracture elongation (%)	Eddy current loss We10/400*2 (W/kg)	Scab	Note
c11	3.5	0.4	2.5	650	17	3.4	Non-existence	Comparative example
c12		0.6	1.7	710	14	3.3	Non-existence	Invention example
c13		1.1	0.9	730	13	3.2	Non-existence	Invention example
c14		2.1	0.5	790	13	3.3	Non-existence	Invention example
c15		2.5	0.4	810	12	3.2	Existence	Invention example
c16	3.9	0.4	2.5	690	15	2.9	Non-existence	Comparative example
c17		0.6	1.7	720	11	2.8	Non-existence	Invention example
c18		1.1	0.9	770	11	2.9	Non-existence	Invention example
c19		1.9	0.5	880	11	3.0	Non-existence	Invention example
c20		2.6	0.4	900	10	2.8	Existence	Invention example
c21	4.1	0.4	2.5	820	1	2.6	Non-existence	Comparative example
c22		0.6	1.7	850	1	2.5	Non-existence	Comparative example
c23		1.1	0.9	880	1	2.4	Non-existence	Comparative example
c24		1.9	0.5	910	1	2.5	Non-existence	Comparative example
c25		2.6	0.4	950	1	2.6	Existence	Comparative example
*2: From Formula (3), We10/400 ≦ 4.4 W/kg at a sheet thickness of 0.25 mm								

[0074] In samples (Symbols c1 to c5), in which the Si content is 1.8%, which is lower than the range defined in the present invention, the yield stress and the eddy current loss $We_{10/400}$ were out of the range defined in the present invention. Further, in samples (Symbols c21 to c25), in which the Si content is 4.1%, which exceeds the range defined in the present invention, the fracture elongation is remarkably reduced.

[0075] Further, in samples (Symbols c6, c11, and c16), in which the Si content was within the range defined in the present invention, but the Cu content was less than 0.5%, the yield stress was reduced to be out of the range defined in the present invention. Further, in samples (Symbols c1 to c4, c6, to c9, c11 to c14, c16 to c19, and c21 to c24), in which Ni/Cu was 0.5 or more, scabs did not exist.

[Reference 4]

[0076] In a vacuum melting furnace, steels containing, by mass%, C: 0.003%, Si: 3.3%, Mn: 0.2%, Al: 0.7%, N: 0.022%, Ni: 1.5%, Nb: 0.032%, Zr: 0.004%, Ti: 0.003%, and V: 0.003%, in which the B amount and the Sn amount were changed, were manufactured and heated at 1110°C for 80 minutes, and then the steels were hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.7 mm were obtained. The coiling temperature in hot rolling as above is set to 530°C. Thereafter, these hot-rolled sheets were annealed (intermediate annealed) at 1050°C for 60 seconds and further are pickled, and by cold rolling once, cold-rolled sheets having sheet thicknesses of 0.35 mm were obtained. Finish-annealing at 950°C for 60 seconds was applied to these cold-rolled sheets. In Table 8, the B amount, the Sn amount, the transition temperature after intermediate annealing, and the magnetic flux density after finish-annealing are shown.

[Table 8] (For reference)

[0077]

Table 8

Material symbol	B (%)	Sn (%)	Yield stress (MPa)	Transition temperature (°C)	Magnetic flux density B50 (T)	Scab	Note
d1	0.0008	0.008	751	60	1.60	Non-existence	Low magnetic flux density
d2		0.012	763	60	1.63	Non-existence	○
d3		0.056	761	70	1.65	Non-existence	○
d4		0.096	759	60	1.66	Non-existence	○
d5		0.012	762	70	1.66	Existence	Scab exists
d6	0.0012	0.009	766	30	1.59	Non-existence	Low magnetic flux density
d7		0.013	767	40	1.63	Non-existence	◎
d8		0.058	768	30	1.64	Non-existence	◎
d9		0.094	760	40	1. 65	Non-existence	◎
d10		0.014	758	30	1.66	Existence	Scab exists
d11	0.0031	0.007	759	40	1.60	Non-existence	Low magnetic flux density
d12		0.011	760	40	1.65	Non-existence	◎
d13		0.053	763	30	1.66	Non-existence	◎
d14		0.091	765	20	1.66	Non-existence	◎
c15		0.011	767	20	1.66	Existence	Scab exists

(continued)

Material symbol	B (%)	Sn (%)	Yield stress (MPa)	Transition temperature (°C)	Magnetic flux density B50 (T)	Scab	Note
d16	0.0048	0.008	760	30	1.59	Non-existence	Low magnetic flux density
d17		0.015	762	30	1. 64	Non-existence	◎
d18		0.049	768	20	1.64	Non-existence	◎
d19		0.089	764	20	1.65	Non-existence	◎
d20		0.012	758	30	1.66	Existence	Scab exists
d21	0.0056	0.007	753	40	1.60	Non-existence	Low magnetic flux density
d22		0.012	755	30	1.65	Non-existence	Slab crack exists
d23		0.047	757	30	1.65	Non-existence	Slab crack exists
d24		0.085	760	2.0	1.65	Non-existence	Slab crack exists
d25		0.012	763	30	1.65	Existence	Scab exists
○ the magnetic flux density is good. ◎ the magnetic flux density is good and the transition temperature is also good.							

[0078] In Symbols d6 to d25, in which the B amount was 0.0010% or more, the transition temperature of hot-rolled-annealed sheets was low. In Symbols d2 to d5, d7 to d10, d12 to d15, d17 to d20, and d22 to d25, in which the Sn amount was 0.010% or more, the high magnetic flux density was obtained. Incidentally, in Symbols d21 to d25, in which the B amount exceeded 0.0050%, slab cracks occur, and in Symbols d5, d10, d15, d20, and d25, in which the Sn amount exceeded 0.010%, scabs occurred.

(Embodiment 5)

[0079] In a vacuum melting furnace, steels containing, by mass%, C: 0.028%, Si: 2.9%, Mn: 0.8%, Al: 1.4%, N: 0.012%, Ni: 1.4%, Nb: 0.003%, Zr: 0.04%, Ti: 0.003%, and V: 0.003%, in which the Cu amount was changed, were manufactured and heated at 1120°C for 90 minutes, and then the steels were hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.0 mm were obtained. Thereafter, these hot-rolled sheets were hot-rolled sheet annealed at 950°C for 60 seconds and further were pickled, and by cold rolling once, cold-rolled sheets having sheet thicknesses of 0.35 mm were obtained. Finish-annealing was applied to these cold-rolled sheets while changing the soaking temperature. In Table 9, results of the Cu amount, the temperature of finish-annealing, and various properties are shown.

[Table 9]

[0080]

Table 9

Material symbol	Cu (%)	Soaking temperature (℃)	Formula (4) (200 × a + 500)	Recrystallization area ratio (%)	Yield stress (MPa)	Fracture elongation (%)	Eddy current loss We10/400*3 (W/kg)	Note
e1	0.6	700	620	60	701	11	7.5	Invention example
e11		700		0	850	2	7.5	Comparative example
e12		750		20	790	6	6.9	Comparative example
e13	1.5	800	800	100	770	19	7.3	Invention example
e14		900		100	730	15	7.7	Invention example
e15		1000		100	710	13	7.9	Invention example
e16		800		0	860	1	7.4	Comparative example
e17		900		40	840	3	7.7	Comparative example
e18	2.1	950	920	100	780	16	7.6	Invention example
e19		1000		100	790	15	7.9	Invention example
e20		1050		100	750	11	8.1	Invention example
e21		800		0	870	1	7.5	Comparative example
e22		900		0	860	1	7.6	Comparative example
e23	2.6	950	1020	20	840	4	7.4	Comparative example
e24		1000		40	800	8	7.7	Comparative example
e25		1050		100	890	12	7.9	Invention example

*3: From Formula (3), $We_{10/400} \leqq 8.6$ W/kg at a sheet thickness of 0.35 mm

[0081] In samples (Symbols e1 , e13 to e15, e18 to e20, and e25), in which the soaking temperature satisfied Formula (4), the yield stress, the fracture elongation, the eddy current loss $We_{10/400}$ were within the range defined in the present invention, resulting that good properties were obtained.

[0082] In samples (Symbols e11, e12, e16, e17, e21, and e22), in which the soaking temperature did not satisfy Formula (4), the recrystallization area ratio was less than 50% and/or the fracture elongation was less than 10%, resulting that the recrystallization area ratio and/or the fracture elongation were/was out of the range defined in the present invention.

(Embodiment 6)

[0083] In a vacuum melting furnace, a plurality of steel pieces containing, by mass%, C: 0.027%, Si: 3.6%, Mn: 0.1%, Al: 1.8%, N: 0.005%, Ni: 2.0%, Nb: 0.003%, Zr: 0.004%, Ti: 0.03%, and V: 0.01% were manufactured. These steel pieces were heated at 1170°C for 90 minutes, and then they are hot rolled immediately, and hot-rolled sheets having sheet thicknesses of 2.5 mm were obtained. When manufacturing the above hot-rolled sheets, the coiling temperature was changed. Further, the manufactured hot-rolled sheets were annealed at 1000°C for 60 seconds and annealed sheets were obtained. When annealing as above, the cooling rate from 900°C to 500°C was changed. From these hot-rolled sheets and annealed sheets, Charpy test pieces were manufactured, and the transition temperature was measured by the impact test. Results thereof are shown in Table 10.

[Table 10] (For reference)

[0084]

Table 10

Material symbol	Hot rolling coiling temperature (°C)	Cooling rate of hot-rolled sheet annealing (°C /sec)	Transition temperature (°C)
f1	500	No hot-rolled sheet annealing	30
f 2	520		40
f3	540		60
f4	560		80
f5	620		100
f6	540	20	100
f7		40	80
f8		60	60
f9		80	40
f10		100	20
f11	560	20	100
f12		40	80
f13		60	60
f14		80	40
f15		100	20
f16	620	20	100
f17		40	80
f18		60	60
f19		80	40
f20		100	20

[0085] In samples (Symbols f1 to f3), in which the coiling temperature was 550°C or less, the good toughness at the transition temperature of 70°C or less was obtained. Further, as for the annealed sheets, regardless of the coiling temperature, in samples (Symbols f8 to f10, f13 to f15, and f18 to f20), in which the cooling rate from 900°C to 500°C was 50°C/sec or more, the good toughness at the transition temperature of 70°C or less was obtained.

Industrial Applicability

[0086] According to the present invention, without sacrificing yields and productivity at the time of manufacturing a motor core and a steel sheet, a non-oriented electrical steel sheet excellent in strength can be provided at a low cost.

Claims

1. A high-strength non-oriented electrical steel sheet, having a chemical composition consisting of:

   by mass%,
   C: not less than 0.002% nor more than 0.05%;
   Si: not less than 2.0% nor more than 4.0%;
   Mn: not less than 0.05% nor more than 1.0%;
   N: not less than 0.002% nor more than 0.05%;
   Cu: not less than 0.5% nor more than 3.0%,
   Al: 3.0% or less;
   and optionally at least one of Ni: not less than 0.5% nor more than 3.0%, Sn: not less than 0.01% nor more than 0.10%, and B: not less than 0.0010% nor more than 0.0050%; and
   when a Nb content (%) is set to [Nb], a Zr content (%) is set to [Zr], a Ti content (%) is set to [Ti], a V content (%) is set to [V], a C content (%) is set to [C], and an N content (%) is set to [N], Formula (1) and Formula (2) are satisfied; and
   a balance composed of Fe and inevitable impurities;
   a recrystallization area ratio of 50% or more;
   a yield stress at a tensile test of 700 MPa or more;
   a fracture elongation of 10% or more; and
   an eddy current loss $We_{10/400}$ (W/kg) which satisfies Formula (3) in relation to a sheet thickness t (mm) of the steel sheet.

$$2.0\times10^{-4} \leqq [Nb]/93+[Zr]/91+[Ti]/48+[V]/51 \cdots (1)$$

$$1.0\times10^{-3} \leqq [C]/12+[N]/14-([Nb]/93+[Zr]/91+[Ti]/48+[V]/51) \leqq 3.0\times10^{-3} \cdots (2)$$

$$We_{10/400} \leqq 70\times t^2 \cdots (3)$$

2. The high-strength non-oriented electrical steel sheet according to claim 1, containing, by mass%, Ni: not less than 0.5% nor more than 3.0%.

3. The high-strength non-oriented electrical steel sheet according to claim 1 or 2, containing, by mass%, Sn: not less than 0.01% nor more than 0.10%.

4. The high-strength non-oriented electrical steel sheet according to any one of claims 1 to 3, containing, by mass%, B: not less than 0.0010% nor more than 0.0050%.

5. A method of manufacturing a high-strength non-oriented electrical steel sheet comprising:

   manufacturing a slab having a chemical composition as defined in claim 1;
   obtaining a hot-rolled sheet by hot rolling the slab;
   pickling the hot-rolled sheet;
   next, obtaining a cold-rolled sheet by cold rolling the hot-rolled sheet; and
   finish-annealing the cold-rolled sheet, wherein
   a soaking temperature T (°C) of said finish-annealing and a Cu content "a" (mass%) of the cold-rolled sheet satisfy Formula (4).

$$T \geqq 200\times a+ 500 \cdots (4)$$

6. The method of manufacturing a high-strength non-oriented electrical steel sheet according to claim 5, further comprising annealing the hot-rolled sheet between said obtaining the hot-rolled sheet and said pickling the hot-rolled sheet.

Patentansprüche

1. Ein hochfestes nichtorientiertes Elektrostahlblech mit einer chemischen Zusammensetzung bestehend aus: in Massen-%:

C: nicht weniger als 0,002% auch nicht mehr als 0,05%;
Si: nicht weniger als 2,0% auch nicht mehr als 4,0%;
Mn: nicht weniger als 0,05% auch nicht mehr als 1,0%;
N: nicht weniger als 0,002% auch nicht mehr als 0,05%;
Cu: nicht weniger als 0,5% auch nicht mehr als 3,0%,
Al: 3,0% oder weniger;
und gegebenenfalls mindestens einem von Ni: nicht weniger als 0,5% auch nicht mehr als 3,0%, Sn: nicht weniger als 0,01% auch nicht mehr als 0,10% und B: nicht weniger als 0,0010% auch nicht mehr als 0,0050%; und wenn ein Nb-Gehalt (%) auf [Nb] eingestellt ist, ein Zr-Gehalt (%) auf [Zr] eingestellt ist, ein Ti-Gehalt (%) auf [Ti] eingestellt ist, ein V-Gehalt (%) auf [V] eingestellt ist, ein C-Gehalt (%) auf [C] eingestellt ist und ein N-Gehalt (%) auf [N] eingestellt ist, sind Formel (1) und Formel (2) erfüllt; und
einem Rest bestehend aus Fe und unvermeidbaren Verunreinigungen;
einem Rekristallisationsflächenanteil von 50% oder mehr;
einer Streckgrenze in einem Zugversuch von 700 MPa oder mehr;
einer Bruchdehnung von 10% oder mehr; und
einem Wirbelstromverlust $We_{10/400}$ (W/kg), der Formel (3) in Relation zu einer Blechdicke t (mm) des Stahlblechs erfüllt.

$$2{,}0\times10^{-4} \leqq [Nb]/93+[Zr]/91+[Ti]/48+[V]/51 \quad \cdots (1)$$

$$1{,}0\times10^{-3} \leqq [C]/12+[N]/14-([Nb]/93+[Zr]/91+[Ti]/48+[V]/51) \leqq 3{,}0\times10^{-3} \quad \cdots (2)$$

$$We_{10/400} \leqq 70\times t^2 \quad \cdots (3)$$

2. Das hochfeste nichtorientierte Elektrostahlblech nach Anspruch 1, enthaltend, in Massen-%, Ni: nicht weniger als 0,5% auch nicht mehr als 3,0%.

3. Das hochfeste nichtorientierte Elektrostahlblech nach Anspruch 1 oder 2, enthaltend, in Massen-%, Sn: nicht weniger als 0,01% auch nicht mehr als 0,10%.

4. Das hochfeste nichtorientierte Elektrostahlblech nach einem der Ansprüche 1 bis 3, enthaltend, in Massen-%, B: nicht weniger als 0,0010% auch nicht mehr als 0,0050%.

5. Ein Verfahren zur Herstellung eines hochfesten nichtorientierten Elektrostahlblechs, umfassend:

Herstellen einer Bramme mit einer chemischen Zusammensetzung wie in Anspruch 1 definiert;
Erhalten eines warmgewalzten Blechs durch Warmwalzen der Bramme;
Beizen des warmgewalzten Blechs;
anschließend Erhalten eines kaltgewalzten Blechs durch Kaltwalzen des warmgewalzten Blechs; und
Fertigglühen des kaltgewalzten Blechs, wobei
eine Haltetemperatur T (°C) des Fertigglühens und ein Cu-Gehalt "a" (Massen-%) des kaltgewalzten Blechs Formel (4) erfüllen.

$$T \geqq 200\times a+ 500 \quad \cdots (4)$$

6. Das Verfahren zur Herstellung eines hochfesten nichtorientierten Elektrostahlblechs nach Anspruch 5, ferner umfassend Glühen des warmgewalzten Blechs zwischen dem Erhalten des warmgewalzten Blechs und dem Beizen des warmgewalzten Blechs.

Revendications

1. Tôle d'acier électrique non orientée à haute résistance, ayant une composition chimique consistant, en % en masse, en :

   C : pas moins de 0,002 % et pas plus de 0,05 % ;
   Si : pas moins de 2,0 % et pas plus de 4,0 % ;
   Mn : pas moins de 0,05 % et pas plus de 1,0 % ;
   N : pas moins de 0,002 % et pas plus de 0,05 % ;
   Cu : pas moins de 0,5 % et pas plus de 3,0 % ;
   Al : 3,0 % ou moins ;
   et éventuellement au moins l'un parmi Ni : pas moins de 0,5 % et pas plus de 3,0 % ; Sn : pas moins de 0,01 % et pas plus de 0,10 % ; et B : pas moins de 0,0010 % et pas plus de 0,0050 % ; et
   quand la teneur en Nb (%) est indiquée par [Nb], la teneur en Zr (%) est indiquée par [Zr], la teneur en Ti (%) est indiquée par [Ti], la teneur en V (%) est indiquée par [V], la teneur en C (%) est indiquée par [C], et la teneur en N (%) est indiquée par [N], la formule (1) et la formule (2) sont satisfaites ; et
   une balance composée de Fe et d'impuretés inévitables ;
   un taux de zone de recristallisation de 50 % ou plus ;
   une limite élastique lors d'un test de traction de 700 MPa ou plus ;
   un allongement à la rupture de 10 % ou plus ; et
   une perte par courant de Foucault $We_{10/400}$ (W/kg) qui satisfait à la formule (3) en relation avec une épaisseur de tôle t (mm) de la tôle d'acier.

$$2{,}0 \times 10^{-4} \leq [Nb]/93 + [Zr]/91 + [Ti]/48 + [V]/51 \quad \ldots (1)$$

$$1{,}0 \times 10^{-3} \leq [C]/12 + [N]/14 - ([Nb]/93 + [Zr]/91 + [Ti]/48 + [V]/51) \leq 3{,}0 \times 10^{-3} \quad \ldots (2)$$

$$We_{10/400} \leq 70 \times t^2 \quad \ldots (3)$$

2. Tôle d'acier électrique non orientée à haute résistance selon la revendication 1, contenant, en % en masse, Ni : pas moins de 0,5 % et pas plus de 3,0 %.

3. Tôle d'acier électrique non orientée à haute résistance selon la revendication 1 ou 2, contenant, en % en masse, Sn : pas moins de 0,01 % et pas plus de 0,10 %.

4. Tôle d'acier électrique non orientée à haute résistance selon l'une quelconque des revendications 1 à 3, contenant, en % en masse, B : pas moins de 0,0010 % et pas plus de 0,0050 %.

5. Méthode de fabrication d'une tôle d'acier électrique non orientée à haute résistance, comprenant :

   la fabrication d'une brame ayant une composition chimique telle que définie dans la revendication 1 ;
   l'obtention d'une tôle laminée à chaud par laminage à chaud de la brame;
   le décapage de la tôle laminée à chaud ;
   ensuite l'obtention d'une tôle laminée à froid par laminage à froid de la tôle laminée à chaud ; et
   le recuit de finition de la tôle laminée à froid,
   dans laquelle
   la température de trempe T (°C) dudit recuit de finition et une teneur en Cu "a" (% en masse) de la tôle laminée à froid satisfont à la formule (4) :

$$T \geq 200 \times a + 500 \quad \ldots (4).$$

6. Méthode de fabrication d'une tôle d'acier électrique non orientée à haute résistance selon la revendication 5, comprenant en outre le recuit de la tôle laminée à chaud entre ladite obtention de la tôle laminée à chaud et ledit décapage de la tôle laminée à chaud.

REFERENCES CITED IN THE DESCRIPTION

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