



(12) **EUROPEAN PATENT APPLICATION**
published in accordance with Art. 153(4) EPC

(43) Date of publication:
04.03.2009 Bulletin 2009/10

(51) Int Cl.:
C21D 9/46 (2006.01) **C21D 8/12** (2006.01)
C22C 38/00 (2006.01) **C22C 38/60** (2006.01)

(21) Application number: **06767202.2**

(86) International application number:
PCT/JP2006/312552

(22) Date of filing: **16.06.2006**

(87) International publication number:
WO 2007/144964 (21.12.2007 Gazette 2007/51)

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IS IT LI LT LU LV MC NL PL PT RO SE SI SK TR

Designated Extension States:
AL BA HR MK RS

(72) Inventor: **MURAKAMI, Hidekuni**
Kitakyushu-shi
Fukuoka 804-8501 (JP)

(74) Representative: **Vossius & Partner**
Siebertstrasse 4
81675 München (DE)

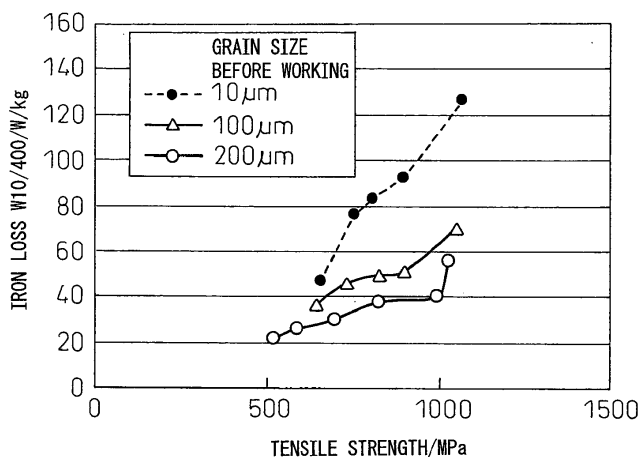
(71) Applicant: **Nippon Steel Corporation**
Tokyo 100-8071 (JP)

(54) **HIGH-STRENGTH ELECTROMAGNETIC STEEL SHEET AND PROCESS FOR PRODUCING THE SAME**

(57) The present invention has as its object the production of high strength electrical steel sheet, having a high strength of a tensile strength TS of for example 500 MPa or more, having wear resistance, and having superior magnetic properties of magnetic flux density and iron loss, that is, provides a method of production of high strength electrical steel sheet containing, by mass%, C: 0.060% or less, Si: 0.2 to 6.5%, Mn: 0.05 to 3.0%, P: 0.30% or less, S or Se: 0.040% or less, Al: 2.50% or less, N: 0.020% or less, and further one or more of Cu: 0.001

to 30.0% and Nb: 0.03 to 8.0% and having worked structures remaining inside the steel sheet, said method of production of high strength electrical steel sheet coarsening an average crystal grain size D (μm) of a sheet right before a step of forming the worked structures to finally remain inside the steel sheet to $D \geq 20 \mu\text{m}$, imparting strain in the final working step as a preferred process, then not performing any heat treatment causing the worked structures to disappear and high strength electrical steel sheet obtained by that method.

Fig.1



Description

TECHNICAL FIELD

5 **[0001]** The present invention relates to high strength electrical steel sheet, more particularly high strength nonoriented electrical steel sheet, and relates to a magnetic material for a high speed rotary machine with a low iron loss, a high magnetic flux density, and a high strength, a magnetic material for an electromagnetic switch superior in wear resistance, and a method of production of the same.

10 BACKGROUND ART

[0002] In the past, for the material for rotors, laminated electrical steel sheet has been used, but recently in applications where high speed rotation and larger rotor size are demanded, the possibility has arisen of the centrifugal force applied to the rotors exceeding the strength of the electrical steel sheets. Further, there are also many motors of structures assembling magnets into the rotors. Even if the rotational speed is not that high, the load applied to the rotor material itself during rotation of the rotor becomes large. In terms of the fatigue strength as well, the strength of the material is becoming a problem in increasing cases.

[0003] Further, electromagnetic switches become worn at the contact surfaces along with use, so a magnetic material superior in not only the electromagnetic properties, but also the wear resistance is desired.

20 **[0004]** To deal with these needs, recently high strength nonoriented electrical steel sheet has been studied and several proposals have been made. For example, Japanese Patent Publication (A) No. 1-162748 and Japanese Patent Publication (A) No. 61-84360 propose using as a material a slab raised in Si content and further containing one or more of Mn, Ni, Mo, Cr, and other solid solution strengthening ingredients, but sheet breakage is liable to frequently occur at the time of rolling. This causes a drop in productivity and a drop in yield, so there is room for improvement. Further, since
25 Ni, Mo, and Cr are included in large amounts, the material becomes extremely expensive. Japanese Patent Publication (A) No. 2005-113185 and Japanese Patent Publication (A) No. 2006-070348 disclose nonoriented electrical steel sheet in which worked structures are left to obtain strength, while Japanese Patent Publication (A) No. 2006-009048 and Japanese Patent Publication (A) No. 2006-070296 disclose nonoriented electrical steel sheet in which additionally Nb etc. are incorporated in solid solution to suppress recrystallization. However, these do not pay particular attention to the
30 crystal grain size before formation of the worked structures, so there is the problem that a stable iron loss cannot be obtained.

[0005] Further, technology relating to electrical steel sheet including a large amount of Cu is disclosed in Japanese Patent Publication (A) No. 2004-84053 and Japanese Patent Publication (A) No. 2004-99926, but due to the Cu phase precipitated in the steel, the reduction of the eddy current loss cannot be said to be sufficient. There is room for improvement for applications where the high frequency properties become a problem.
35

DISCLOSURE OF THE INVENTION

40 **[0006]** As explained above, various proposals have been made regarding high strength electrical steel sheet, but the fact is that industrially stable production using ordinary electrical steel sheet production facilities while securing the necessary magnetic properties has not yet been reached. The inventors previously filed an application for high strength electrical steel sheet leaving worked structures in the steel sheet in Japanese Patent Application No. 2003-347084.

[0007] This technology was made based on the fact that even if leaving worked structures in the crystal structure, the magnetic properties do not deteriorate that much, that if considering the effect on raising the strength, the result is in no way inferior to a material strengthened by the conventional solid solution elements or precipitates and, not only that, if
45 considering the productivity and the in-plane anisotropy of the magnetic properties, in particular the magnetic flux density, this is extremely useful technology. However, the clear metallurgy has not been established for how to improve the balance of magnetic properties and mechanical properties for electrical steel sheet having worked structures. On this point, no proof has been obtained that this technology is optimal.

50 **[0008]** The inventors engaged in detailed experiments to illuminate this point, in particular regarding the effects of the structure before rolling, and discovered that in electrical steel sheet having worked structures, there is an optimum region for achieving both good magnetic properties and mechanical properties and therefore succeeded in setting an industrially optimum range considering further productivity, in particular the processability of steel strips.

[0009] The present invention has as its object the stable on-line production of high strength nonoriented electrical steel sheet having a high strength of a tensile strength (TS) of for example 500 MPa or more and wear resistance and provided with superior magnetic properties of magnetic flux density (B50), iron loss, etc. particularly when used under
55 a high frequency magnetic field, such as a motor rotating at a high speed, without, for example, being changed in cold rollability, annealing work efficiency, etc. from ordinary electrical steel sheet. The present invention was made to solve

the above problem and has as its gist the following:

(1) A method of production of high strength electrical steel sheet containing, by mass%, C: 0.060% or less, Si: 0.2 to 6.5%, Mn: 0.05 to 3.0%, P: 0.30% or less, S or Se: 0.040% or less, Al: 2.50% or less, and N: 0.040% or less, having a balance of Fe and unavoidable impurities, and having worked structures remaining inside the steel sheet, said method of production of high strength electrical steel sheet characterized by making an average crystal grain size $\underline{d}$ of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet 20 μm or more.

(2) A method of production of high strength electrical steel sheet containing, by mass%, C: 0.060% or less, Si: 0.2 to 6.5%, Mn: 0.05 to 3.0%, P: 0.30% or less, S or Se: 0.040% or less, Al: 2.50% or less, and N: 0.040% or less, having a balance of Fe and unavoidable impurities, and having worked structures remaining inside the steel sheet, said method of production of high strength electrical steel sheet characterized by making an average crystal grain size $\underline{d}$ (μm) of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet step $d \geq (220 - 50 \times \text{Si}\% - 50 \times \text{Al}\%)$.

(3) A method of production of high strength electrical steel sheet as set forth in (1) or (2) characterized by making an average crystal grain size $\underline{d}$ (μm) of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet

$$d \leq (400 - 50 \times \text{Si}\%)$$

and

$$d \leq (820 - 200 \times \text{Si}\%)$$

(4) A method of production of high strength electrical steel sheet as set forth in any one of (1) to (3) characterized by making a recrystallization rate of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet 50% or more.

(5) A method of production of high strength electrical steel sheet as set forth in any one of (1) to (4) characterized in that the steel ingredients further contain, by mass%, one or both of Cu: 0.001 to 30.0% and Nb: 0.03 to 8.0%.

(6) A method of production of high strength electrical steel sheet as set forth in any one of (1) to (5) characterized in that the steel ingredients further contain, by mass%, one or more types of Ti: 1.0% or less, V: 1.0% or less, Zr: 1.0% or less, B: 0.010% or less, Ni: 15.0% or less, and Cr: 15.0% or less.

(7) A method of production of high strength electrical steel sheet as set forth in any one of (1) to (6) characterized in that the steel ingredients further contain, by mass%, one or more types of Bi, Mo, W, Sn, Sb, Mg, Ca, Ce, La, and Co in a total of 0.5% or less.

(8) A method of production of high strength electrical steel sheet as set forth in any one of (1) to (7) characterized in that the worked structures present inside the steel sheet are 1% or more by area rate in observation of the cross-section.

(9) A method of production of high strength electrical steel sheet as set forth in any one of (1) to (8), characterized in that an average dislocation density in the worked structures inside the steel sheet is $1 \times 10^{13}/\text{m}^2$ or more.

(10) A high strength electrical steel sheet as set forth in (1) to (9), characterized by being a single ferrite phase in a temperature region from room temperature to 1150°C and satisfying, by mass%,

$$980 - 400 \times \text{C} + 50 \times \text{Si} - 30 \times \text{Mn} + 400 \times \text{P} + 100 \times \text{Al} - 20 \times \text{Cu} - 15 \times \text{Ni} - 10 \times \text{Cr} > 900$$

(11) A high strength electrical steel sheet as set forth in (10), characterized in that heat treatment at 450°C for 30 minutes is used to make a tensile strength 100 MPa or more.

(12) A method of production of high strength electrical steel sheet characterized by producing steel sheet as set forth in (10) during the process of which making a final heat treatment after cold rolling a heat treatment holding the sheet in a temperature region of 800°C or more for 5 sec or more and not allowing formation of an austenite phase in the steel material even at a peak temperature in this heat treatment.

(13) A method of production of high strength electrical steel sheet characterized by producing steel sheet as set

forth in (10) during the process of which making a cooling step after holding the sheet in a temperature region of 800°C or more for 5 sec or more cooling by a cooling rate of 40°C/sec or more to 300°C or less.

(14) A method of production of high strength electrical steel sheet as set forth in (10), characterized by making a residence time in 700 to 400°C in said cooling step 5 sec or less.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]

FIG. 1 is a view showing the strength-iron loss balance dependent on the grain size before working.

BEST MODE FOR CARRYING OUT THE INVENTION

[0011] The inventors engaged in various experiments and studies to achieve this object. That is, the present invention provides a steel sheet containing C: 0.060% or less, Si: 0.5 to 6.5%, Mn: 0.05 to 3.0%, P: 0.30% or less, S or Se: 0.040% or less, Al: 2.50% or less, and N: 0.040% or less and further containing, in accordance with need, one or both of Cu: 0.001 to 30.0% and Nb: 0.05 to 8.0%, wherein (1) the steel sheet structure is given worked structures and dislocation strengthening is used to increase the strength, (2) the crystal structure is coarsened right before forming the worked structures to finally remain in the steel sheet, and (3) the above crystal structure is limited from the viewpoint of the amount of Si to improve the processability so as to provide electrical steel sheet in which worked structures are left and formed wherein the balance of strength and magnetic properties is improved at a high productivity without causing trouble in work efficiency etc.

[Composition of Ingredients]

[0012] First, the composition of ingredients of the high strength electrical steel sheet according to the present invention will be explained.

[0013] C causes deterioration of the magnetic properties, so the content is made 0.060% or less. On the other hand, it effectively acts to improve the texture and has the effect of suppressing the development of the {111} orientation not preferable to the magnetic properties and promoting the development of the preferable {110}, {100}, {114}, and other orientations. Further, from the viewpoints of increasing the strength, in particular raising the yield stress, improving the warm strength and creep strength, and improving the warm fatigue characteristics, in the case of Nb-containing steel, due to having the effect of retarding the recrystallization by NbC, the content is preferably 0.0031 to 0.0301%, more preferably 0.0051 to 0.0221%, more preferably 0.0071 to 0.0181%, more preferably 0.0081 to 0.0151%.

[0014] When the above such effect by C is particularly stressed or when the demands on the magnetic aging are particularly extremely tough, up to the slab stage, from the viewpoint of the deoxidizing efficiency, it is possible to include higher C and reduce the C by decarburizing annealing after formation of the coil. When reducing the content to 0.010% or so or less, from the viewpoint of the production cost, it is advantageous to reduce the amount of C by degassing facilities at the molten steel stage. In particular, if made 0.0020% or less, there is a remarkable effect of reduction of the iron loss. In the invention steel not requiring carbides or other nonmetallic precipitates for increasing the strength, even 0.0015% or less enables an increase in strength while further even 0.0010% or less enables a sufficient increase in strength.

[0015] Si increases the inherent resistance of the steel to reduce the eddy current and reduce the iron loss and raises the tensile strength, but if the amount added is less than 0.2%, that effect is small. The content is preferably 1.0% or more, more preferably 1.5% or more, more preferably 2.0% or more, more preferably 2.5% or more. In general, when used under a high frequency magnetic field, the loss due to the eddy current becomes larger, but even in the invention steel containing worked structures, to suppress this eddy current loss, it is effective to raise the Si content. However, if over 6.5%, the steel is made remarkably brittle. To further reduce the magnetic flux density of the product, the content is made 6.5% or less, preferably 4.0% or less. The optimum range of the amount of Si, as explained above, is determined considering also the crystal structure right before the formation of the worked structures to finally remain inside the steel sheet - an important factor of the present invention. While depending on this crystal structure, to reduce the concerns over embrittlement, 3.7% or less is preferable. If 3.2% or less, while there is also the balance with the amount of other elements, it no longer becomes necessary to consider embrittlement much at all. Further, the content may be made less than 2.0%, less than 1.5%, and less than 1.0%.

[0016] Note that in the case of utilization of the later explained solid solution Cu, Si is effective for suppressing the formation of the austenite phase at a high temperature, stabilizing the ferrite phase even at a high temperature, and making the effect of reduction of the eddy current loss by the solid solution Cu remarkable, but with an amount of addition of less than 1.5%, this effect is small. In particular, in low Si steel, the effect of reduction of the eddy current loss by the

solid solution C tends to become weaker, so preferably 2.1% or more, more preferably 2.6% or more Si is contained.

[0017] Mn may be positively added to raise the strength of the steel, but is not particularly required for the purpose in the steel of the present invention utilizing the worked structures as the main means for increasing the strength. This is added for the purpose of raising the inherent resistance or enlarging the sulfides and promoting crystal grain growth and thereby reducing the eddy current loss and reducing the iron loss, but excessive addition not only causes a drop in the magnetic flux density, but also promotes the formation of the austenite phase at a high temperature, so the content is made 0.05 to 3.0%, preferably 0.5% to 2.5%, preferably 0.5% to 2.0%, more preferably 0.8% to 1.2%.

[0018] P is an element with a remarkable effect in raising the tensile strength and contributes to stabilization of the ferrite phase at a high temperature, but in the same way as the above Mn, in the present invention steel, addition is not really required. If over 0.3%, the embrittlement becomes great and industrial scale hot rolling, cold rolling, and other processing become difficult, so the upper limit is made 0.30%. The amount is preferably 0.20% or less, more preferably 0.15% or less.

[0019] S easily bonds with the Cu added in accordance with need in the invention steels, has an effect on the behavior in formation of a metal phase mainly comprised of Cu important for the purpose of addition of Cu, and sometimes causes reduction of the strengthening efficiency, so caution is required when including it in a large amount. Further, depending on the heat treatment conditions, it is possible to positively form fine Cu sulfides and promote higher strength. The produced sulfides sometime cause deterioration of the magnetic properties, in particular the iron loss. In particular, when the control value of the iron loss is strict, the content of S is preferably low and is limited to 0.040% or less. The content is preferably 0.020% or less, more preferably 0.010% or less. Se also has substantially the same effect as S.

[0020] Al is usually added as a deoxidizing agent, but it is possible to keep down the addition of Al and use Si for deoxidation. In Si deoxidized steel with an amount of Al of 0.005% or so or less, AlN is not produced, so this also has the effect of reducing the iron loss. Conversely, it is also possible to positively add it to promote the coarsening of the AlN and use the increase in inherent resistance to reduce the iron loss, but if over 2.50%, the embrittlement becomes a problem, so the content is made 2.50% to less than 2.0% or less than 1.8%.

[0021] Note that when utilizing solid solution Cu as the strengthening element, from the viewpoints of deoxidation and formation of nitrides as well, solid solution Al is positively added to stabilize the ferrite phase at a high temperature and suppress the eddy current loss due to the increase in the electrical resistance. Further, this also has the effect of promoting the remarkable effect of reduction of the eddy current loss by the solid solution Cu. In the same way as Si, this is preferably positively added. The content is preferably 0.3% or more, more preferably 0.6% or more, more preferably 1.1% or more, more preferably 1.6% or more, more preferably 2.1% or more. However, if over 2.50%, the castability and embrittlement become problems, so the content is made 2.50% or less.

[0022] N, like C, causes the magnetic properties to deteriorate, so the content is made 0.040% or less. In Si deoxidized steel with an Al content of 0.005% or so or less, like C, it is an element having the effects of increasing the strength, in particularly raising the yield stress, improving the warm strength and creep strength, and improving the warm fatigue characteristics and, in the case of Nb-containing steel, retarding recrystallization by NbN, and also effective from the viewpoint of improving the texture. From this viewpoint, the content is preferably 0.0031 to 0.0301%, more preferably 0.0051 to 0.0221%, more preferably 0.0061 to 0.0200%, more preferably 0.0071 to 0.0181%, more preferably 0.0081 to 0.0151%. When Al is 0.010% or so or more, inclusion of a large amount of N enables the formation of fine AlN and an enhancement of the recrystallization retardation effect, but the efficiency of retarding recrystallization is poor and the detrimental effect on the magnetic properties is also relatively large, so there is really no need for addition. In Al deoxidized steel, N should be 0.0040% or less. When no rise in strength due to nitrides or recrystallization retardation effect is expected, N is preferably as low as possible. If made 0.0027% or less, the effect of suppression of magnetic aging or deterioration of characteristics by AlN in Al-containing steel is remarkable. The content is more preferably 0.0022%, more preferably 0.0015% or less.

[0023] Cu is included in the present invention in accordance with need. Cu, if present as solid solution Cu, has the effect of raising the recrystallization degree of steel sheet and retarding recrystallization of the steel sheet. In the work strengthening of the present invention, such an effect appears from 0.001% or so. Depending on the amount of impurities, it is possible to obtain this effect by Cu even without positively adding Cu, but preferably Cu is made 0.002% or more, 0.003% or more, 0.005% or more, 0.007% or more, 0.01% or more, 0.02% or more, 0.03% or more, 0.04% or more, 0.05% or more, further 0.1% or more, 0.5% or more, 1.0% or more, or 2.0% or more. If so, the effect appears more. If the content of Cu is low, the recrystallization retardation effect becomes small, the heat treatment conditions for obtaining the recrystallization retardation effect are limited to a narrow range, and the freedom of management of the production conditions and adjustment of production becomes smaller in some cases. On the other hand, if the content of Cu is excessively high, the effect on the magnetic properties becomes large and in particular the rise in the iron loss becomes remarkable in some cases, so the upper limit from this viewpoint is 8.0%, particularly preferably 5.5% or less. From the viewpoint of the cost of addition, the content may be made less than 0.1%, further less than 0.01.

[0024] In conventional steel, in such a low Cu region, almost no effect of Cu is seen, but in the present invention steel, even with such a small amount of Cu, a good effect appears on the improvement of the yield strength-iron loss balance.

This mechanism is not clear, but is believed to be as follows. The high density dislocations present in steel such as the invention steels can be said to be necessary for securing strength and at the very least raise the iron loss. The rise in the yield strength is related to the interaction between the dislocations remaining in the steel and the dislocations newly introduced when deforming the steel sheet and the ease of activity of the dislocations remaining in the steel. The stronger the interactions or the harder the activity of existing dislocations, the more the yield strength rises. On the other hand, the iron loss is related to the interaction between dislocations remaining in the steel and the domain walls moving at the time of application of a magnetic field. The smaller this interaction, the more the rise in iron loss is suppressed. As a result, the interaction with the dislocations becomes greater (or the remaining dislocations themselves become less active). If a large number of dislocations with small interaction with the domain walls are left, the yield strength-iron loss balance is improved. The magnitude of the interaction is basically considered to be related to the stress fields around the dislocations (strain of crystal lattice). It is believed that a small amount of Cu segregates around the remaining dislocations and forms optimum stress fields for the improvement of the yield strength-iron loss balance, preferable dislocations are selectively proliferated in the process of forming the remaining dislocations, or preferable dislocations are made to selectively remain in the annealing process. At what stage the effect of the small amount of Cu is exhibited is not clear, but the change in the stress field due to the difference in atomic radius between the Cu and Fe may be explained as one factor.

[0025] On the other hand, the inventors already filed an application for technology forming a metal phase mainly comprised of Cu in electrical steel sheet (hereinafter in the Description described as a "Cu metal phase") to try to achieve higher strength. When it comes to the Cu metal phase, combination with this application does not detract from the effects of the present invention in any way. While not particularly limited to this, the size of the Cu metal phase or Nb precipitates present in the invention steel is preferably 0.20 μm or less. If exceeding this, the efficiency of recrystallization retardation falls, a large amount of metal phase becomes necessary, and also the detrimental effect on the magnetic properties easily becomes larger. Further, while not particularly limited to this, the numerical density of the Cu metal phase or Nb precipitates is limited to the range able to be handled in view of the relationship with the Cu, Nb, or C content and the size of the precipitated phase. 20/ μm^3 or more or so is desirable. This effect is achieved in the above range of concentration of Cu.

[0026] Further, when utilizing the later explained solid solution Cu as the strengthening element, the range of Cu for achieving good high frequency properties may be made 2.0 to 30.0%. If the content of Cu is low, the eddy current loss reduction effect becomes small. On the other hand, if the content of Cu is too high, suppressing production of the metal phases mainly comprised of Cu becomes difficult and the eddy current loss reduction effect becomes smaller. Not only this, when forming relatively coarse Cu metal phases, the hysteresis loss is liable to be greatly increased and cracks and defects in the steel sheet at the time of rolling are liable to become worse.

[0027] Therefore, the content of Cu in this case is preferably 2.1% or more, more preferably 2.6% or more, more preferably 3.1% or more, more preferably 3.6% or more, more preferably 4.1% or more, more preferably 4.6% or more. The upper limit, considering also the cost of addition of Cu itself and the cost of addition of Ni added for the purpose of suppressing surface defects at the time of hot rolling due to Cu (Cu defects), is preferably 20.0%, more preferably 15.0%, more preferably 12.0%, more preferably 10.0%. Note that if the Cu added in the high Si steel in such a case is in the state of a solid solution, it will not cause embrittlement of the steel or deterioration of the cold rollability like Si or Al. Rather, it will have a preferable action in suppressing embrittlement due to Si etc. Further, it does not cause a great deterioration in the magnetic flux density like the later mentioned Cr and is of little harm even if included in a relatively large amount.

[0028] Nb is added in accordance with need in the present invention. While depending on the amounts of C, N, and S contained, it forms carbides, nitrides, sulfides, and other fine precipitates in large amounts in steel sheet and causes a remarkable deterioration in the iron loss, promotes the growth of the {111} texture after cold rolling and annealing, and reduces the magnetic flux density, so in the present invention steel does not really have to be added. For this reason, making the upper limit of Nb 8% or less, preferably 0.02% or less, more preferably 0.0050% or less, still more preferably 0.0030% or less, it becomes possible to obtain good iron loss.

[0029] However, carbides and nitrides of Nb (hereinafter in this Description referred to as "Nb precipitates") have the action of retarding the recrystallization of steel sheet, so it is possible to actively use this in the present invention. Further, the fine Nb precipitates also have the effect of increasing the strength in a range not exerting a detrimental effect on the magnetic properties. Further, the Nb can also be utilized as solid solution Nb for strengthening. The range is limited to 0.05 to 8.0%. The content is preferably 0.08 to 2.0%.

[0030] In addition, almost all elements utilized for increasing the strength in high strength electrical steel sheet in the prior art are not only viewed as problems in terms of the costs of addition, but also have some detrimental effect on the magnetic properties, so do not really have to be added. When positively added, from the balance of the recrystallization retardation effect, strength increasing effect, rise in costs, and deterioration of magnetic properties, one or more of Ti, Zr, V, B, Ni, and Cr are added, but the amounts of addition are made Ti: 1.0% or less, Zr: 1.0% or less, V: 1.0% or less, B: 0.010% or less, Ni: 15.0% or less, and Cr: 15.0% or less.

[0031] Ti, Zr, and V are elements which form fine precipitates of carbides, nitrides, sulfides, etc. in steel sheet and have the effect of increasing the strength as well, but compared with Nb, the effects are small yet the tendency to cause deterioration of the iron loss is stronger. Further, when forming a partial recrystallized structure in the annealing step after cold rolling, there is a strong effect of promoting alignment in the {111} orientation disadvantageous to improvement of the magnetic flux density, so in the present invention steel, this rather can become harmful elements. For this reason, when not intending strengthening by precipitates, it is preferable to make the contents 1.0% or less. By making the contents preferably 0.50% or less, more preferably 0.30% or less, still more preferably 0.010% or less, further 0.0050% or less, good iron loss can be obtained.

[0032] Note that Nb, Zr, Ti, V, and other carbide, nitride, and sulfide forming elements should be prevented from precipitating in the present invention so long as not utilizing the precipitating effects of this as explained above. Nb+Zr+Ti+V is less than 0.1%, preferably less than 0.08%, more preferably 0.002 to 0.05%.

[0033] B segregates at the crystal grain boundaries and has the effect of suppressing embrittlement due to grain boundary segregation of P, but in the present invention steel, embrittlement does not become a particular problem like with the conventional mainly solid solution strengthened high strength electrical steel sheet, so addition for this objective is not important. Rather, 0.0002% or more should be added for the purpose of retarding recrystallization due to the effects of the solid solution B on the recrystallization degree. If over 0.010%, remarkable embrittlement occurs, so the upper limit is made 0.010%.

[0034] Ni is also recognized as having the effect of raising the recrystallization degree from about 0.001%. Even with a content of 0.01% or less, it has a certain effect in fixing dislocations, but preferably is contained in 0.05%, 0.1%, 0.5%, 1.0%, 2.0%, or further 3.0% whereby its effects are manifested more clearly. Ni further is known to be effective for the prevention of surface defects at the time of hot rolling due to the Cu as an element included in accordance with need in the invention steel (Cu defects). This may also be positively added for this objective as well. Further, it is relatively small in detrimental effects on the magnetic properties and has the effect of improvement of the magnetic flux density and is further recognized as being effective for increasing the strength, so is an element often used in high strength electrical steel sheet. When using Ni for the purpose of preventing Cu defects, it is as a rough standard added in an amount of 1/8 to 1/2 or so of the amount of Cu.

[0035] When utilizing solid solution Cu to increase the strength as explained later, by including Ni compositely, a remarkable effect of reduction of the eddy current loss never seen in the past is exhibited. The reason for this is not clear, but it could be the effect of the positions occupied by the solid solution Cu and solid solution Ni on the Fe crystal lattice and somehow the formation of a regular lattice relating to Ni and Cu.

[0036] Further, Ni is also effective for improving the corrosion resistance, but considering the cost of addition and the detrimental effect on the magnetic properties, the upper limit is preferably made 15%, further 10%, still further 5.0%.

[0037] Cr is an element added for improving the corrosion resistance and improving the magnetic properties in the high frequency range, but again considering the cost of addition and the detrimental effect on the magnetic properties, the upper limit is preferably made 15.0%.

[0038] In particular, when utilizing solid solution Cu as explained later, these roles are sufficiently filled by the Cu (or other elements like Ni), so there is really no need for addition for this purpose. When utilizing solid solution Cu, the Cr is rather added for controlling the stability of the ferrite phase at a high temperature, but the drop in the magnetic flux density due to the addition is remarkable and the element rather can become harmful. Further, the effect of reduction of the eddy current loss due to the solid solution Cu is remarkably expressed in low Cr steel, so unless there is some sort of need, Cr is preferably not added. The reason is not clear, but the effect of the solid solution Cu is believed to become remarkable due to the phenomenon of interaction with not only the above Si, Al, and Ni, but also other elements including Cr. From this viewpoint, considering also the cost of addition, the upper limit of Cr is made 15%, preferably 8.0%, more preferably 4.9%, more preferably 2.9%, more preferably 1.9%, more preferably 0.9%, and more preferably 0.4%.

[0039] Further, regarding other trace amount elements, in addition to the amounts unavoidably included from the ore, scraps, etc., even if added in various known ways, the effect of the present invention is not impaired in any way. Further, even if the amounts are small, these are elements forming fine carbides, sulfides, nitrides, oxides, etc. and exhibiting not insignificant recrystallization retardation effects or strength increasing effects, but these fine precipitates also have large detrimental effects on the magnetic properties. Further, in the present invention steel, the residual worked and restored structures enable a sufficient recrystallization retardation effect to be obtained, so these elements need not really be added.

[0040] The unavoidable content of these trace amount elements is usually 0.005% or less for each element, but addition of 0.01% or so or more is also possible for various purposes not described in this description. In this case as well, from the balance with the magnetic properties, the one or more types of Bi, Mo, W, Sn, Sb, Mg, Ca, Ce, and Co are made a total of 0.5% or less.

[0041] The steel including the above ingredients is melted by a converter in the same way as ordinary electrical steel sheet, is continuously cast into a slab, then is hot rolled. The hot rolled sheet is annealed, cold rolled, final annealed,

etc. to be produced. Going through steps for formation of an insulating coating or decarburization etc. in addition to these steps does not detract from the effects of the present invention in any way. Further, there is also no problem even if produced not by the usual steps, but by the steps of production of strip by rapid cooling and solidification, the continuous casting of thin slabs without any hot rolling step, etc.

[Worked Structures]

[0042] In the present invention, it is necessary to form special structures called "worked structures" in the present invention in the steel sheet. The "worked structures" in the present invention are differentiated from the "recrystallized structures" accounting for almost the entire steel sheet in ordinary electrical steel sheet. In general, this indicates structures where the strain accumulated in the steel sheet due to cold rolling etc. has not fully disappeared. More specifically, in the process of annealing cold rolled steel sheet, structures deformed by cold rolling and containing a high density of dislocations are encroached upon by structures with a low density of dislocations formed by holding the steel at a high temperature in the annealing step ("recrystallized structures") resulting in progression of recrystallization. The regions not encroached upon by these "recrystallized structures" are defined as the "worked structures". The worked structures generally become lower in density of dislocations due to the so-called restoration etc. during annealing, but do not become as low as the recrystallized structures. In the distribution of strain, there is an uneven state between the "worked structures" and "recrystallized structures". Further, the "worked structures" may be obtained by further working the recrystallized structures. In this case, if viewed overall, the state becomes one where uniform strain remains in the structure. In the present invention, the worked structures are utilized to achieve the targeted higher strength.

[Grain Size Before Working]

[0043] Next, the average crystal grain size $\bar{d}$ of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet characterizing the present invention will be explained. Below, this grain size will be called the "grain size before working". The present invention basically coarsens the "grain size before working" to greatly improve the properties after working, in particular the strength-iron loss balance. The "grain size before working" becomes the grain size at the point of time of the hot rolled sheet when cold rolling the hot rolled sheet, then suppressing recrystallization in the subsequent annealing so as to leave worked structures in the final product. At this time, if annealing the hot rolled sheet as generally performed in electrical steel sheet, the grain size after annealing the hot rolled sheet becomes the "grain size before working". Further, when again cold rolling steel sheet cold rolled, then recrystallized so as to leave worked structures in the final product, this becomes the grain size at the point of time of the annealed sheet. Further, when for example cold rolling the sheet, then again cold rolling it while leaving worked structures in the annealing step, the effect of the working by the repeated cold rolling may be great, but the worked structures formed by the cold rolling will not completely disappear and will remain until after the repeated cold rolling when repeatedly being cold rolled, so the grain size before cold rolling, that is, if the usual steps, the hot rolled sheet grain size, will become the "grain size before working".

[0044] In the present invention, this "grain size before working" $\bar{d}$ (μm) is defined as a specific range in relation to the amount of Si and the amount of Al. That is, by satisfying the following formula (1) or (2) and further (3) and (4), the superior strength-iron loss balance characteristic of the present invention is achieved:

$$\bar{d} \geq 20 \mu\text{m} \dots (1)$$

$$\bar{d} \geq (220 - 50 \times \text{Si}\% - 50 \times \text{Al}\%) \dots (2)$$

$$\bar{d} \leq (400 - 50 \times \text{Si}\%) \dots (3),$$

and

$$\bar{d} \leq (820 - 200 \times \text{Si}\%) \dots (4)$$

[0045] Formula (1) simply shows the case where the "grain size before working" is coarser than a specific size. The crystal grain size of usual steel sheet is controlled to a range of several μm to several hundreds of $100\ \mu\text{m}$, but to obtain the effect of the present invention, it must be made $20\ \mu\text{m}$ or more. The size is preferably $50\ \mu\text{m}$ or more, more preferably $100\ \mu\text{m}$ or more, more preferably $150\ \mu\text{m}$ or more, more preferably $200\ \mu\text{m}$ or more, more preferably $250\ \mu\text{m}$ or more.

[0046] Formula (2) defines the "grain size before working" obtained by the effect of the invention in relation to the amount of Si and the amount of Al. In general, the higher the amount of Si and the amount of Al in steel sheet, the better the strength-iron loss balance, so the higher the Si and the higher the Al in the material, the easier it is to obtain an excellent strength-iron loss balance even if the "grain size before working" is small. $d \geq (200 - 50 \times \text{Si}\% - 50 \times \text{Al}\%)$, $d \geq (180 - 50 \times \text{Si}\% - 50 \times \text{Al}\%)$, further $d \geq (150 - 50 \times \text{Si}\% - 50 \times \text{Al}\%)$ are possible. On the other hand, $d \geq (220 - 50 \times \text{Si}\%)$ is also possible.

[0047] Formula (3) and Formula (4) give rough standards for the upper limit of the "grain size before working". In general, the higher the Si in the material, the brittler the material, but if the "grain size before working" becomes excessively coarse, it becomes further brittle and cold rolling and other working become difficult, so sometimes an upper limit becomes necessary. This upper limit depends not only the steel ingredients other than the amount of Si and the heat history up until working, but also the method of working the steel sheet and the properties aimed at.

[0048] The specific conditions for controlling the "grain size before working" to the above range depend also on the steel ingredients and the heat history until working, so cannot be limited to specific ranges, but a person skilled in the art having the usual knowledge would not find it hard to determine suitable conditions by running heat treatment tests several times on steel sheet with the ingredients and heat history corresponding to the targeted steel sheet. To point is to confirm the steel sheet recrystallization and grain growth behavior and just control the heat history so that the aimed at structure is obtained.

[0049] As the steel ingredients, raising the purity facilitates formation of coarse grains. In particular, reduction of the C, N, and P is effective. Further, making by ingredients a ferrite single phase steel and suppressing transformation during hot rolling makes coarsening of the grains of the hot rolled sheet easier to achieve.

[0050] Further, if oriented at coarser grains in the hot rolled sheet, raising the hot rolling heating temperature, raising the hot rolling finishing temperature, reducing the reduction rate after hot rolling finishing, slow cooling after final rolling, high temperature coiling, high temperature long term hot rolled sheet annealing, etc. may be considered. Further, if oriented at coarser grains in the annealed sheet, high temperature long term annealing is simple, but it is also possible to make the precipitates coarser and improve the grain growth at the time of annealing by low temperature slab heating or high temperature coiling in the hot rolling or high temperature hot rolled sheet annealing conditions. Specifically, for example, it is preferable to make the annealing step right before forming the worked structures any one of the following.

(1) When performing the cold rolling two times or more interspaced with process annealing, performing the process annealing right before the final cold rolling at a temperature of over 850°C (preferably 860°C or more) or for a time over 30 sec (preferably 35 sec or more).

(2) When performing the cold rolling just a single time, when annealing the hot rolled sheet, annealing the hot rolled sheet at a temperature of over 1100°C (preferably 1110°C or more) or for a time over 30 sec (preferably 35 sec or more).

(3) When not either the above (1) or (2), performing the coiling at the hot rolling at a temperature of over 700°C (preferably 710°C or more).

[Recrystallization Rate in Structure Before Working]

[0051] Note that depending on the conditions, sometimes worked structures remain in the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet. In this case, to obtain the effect of the present invention, it is preferable not to allow worked structures to remain right before the step of forming the worked structures as much as possible. Making the recrystallization rate r right before the step of forming the worked structures

$$r \geq 50\% \dots (5)$$

is preferable. More preferably, r is 90% or more. Needless to say, right before the step of forming the worked structures, a complete recrystallized structure satisfying the above formulas (1) to (4) is preferable. Further, when not yet recrystallized regions partially remain in the structure right before the step of forming the worked structures, it is possible to obtain the effect of the invention by satisfying the above formula (5), but when the grain size of the recrystallized parts is coarse, even if the not yet recrystallized parts exceed 50%, the effects of present invention will sometimes appear. At this time, by assuming the not yet recrystallized parts are fine crystal grains of a grain size of $5\ \mu\text{m}$ and finding the

average grain size, it is possible to judge the effect of the invention by the formulas (1) and (2). This case is also included in the present invention.

[Method of Measurement of Grain Size Before Working]

[0052] Note that the crystal grain size and recrystallization rate are found by observation of the structure of the sheet cross-section by etching as usually performed in observation of the structure of ferrous metals. The grain size is the diameter found from the area per crystal grain observed when assuming the cross-sectional area of the grain is a circle, while the recrystallization rate is found from the area rate of not yet recrystallized parts in the observed area. Needless to say the measurement has to be performed for a sufficiently average region without segregation.

[Effect of Grain Size Before Working]

[0053] The mechanism for the effect of the "grain size before working" is not certain, but the effects of the change of the dislocation structure, the change of the texture, further the change in the dislocation structure after working due to the difference in texture before working, etc. may be considered. While the details are unclear, it is conjectured that in the end, the dislocation structures in the worked structures change to structures acting as powerful obstructions to dislocations trying to move due to external stress and not easily acting as obstructions to domain walls trying to move due to the external magnetic field.

[Tensile Strength]

[0054] The steel sheet covered by the present invention has a tensile strength of 500 MPa or more. If a steel sheet with a tensile strength of an extent lower than this, even with a steel sheet mainly strengthened by the usual Si, Mn, and other solid solution elements and structurally completely occupied by recrystallized structures, production becomes possible without causing the productivity to deteriorate that much. This is because such a material gives sheet remarkably superior in magnetic properties. The present invention is limited to high strength materials mainly strengthened by the usual solid solution strengthening and unable to be produced without deterioration of the productivity. To enjoy the merits of the present invention more, the invention should be applied to preferably 600 MPa or more steel sheet, more preferably 700 MPa or more, more preferably 800 MPa or more steel sheet. Even production of 900 MPa or more steel sheet not being produced at all at the present is possible. Further, even 1000 MPa or more steel sheet not even imagined for production in the future can be produced with a high productivity.

[0055] Note that when used as the rotor of a motor, a slight deformation means the end of the life of the part, so not the tensile strength, but the yield stress should be used for evaluation. The invention steels have worked structures remaining in them, so compared with solid solution strengthened steel or precipitation strengthened steel, if the same strength, the yield stress is higher and, in comparison with these conventional materials, more desirable properties are exhibited. That is, the yield ratio becomes a relatively high value of 0.7 to 1.0 or so. The correlation between the yield stress and the tensile strength becomes extremely strong in the material. For this reason, even if using the yield stress for evaluation, the superiority of the invention steels does not change at all. The effect of the invention is exhibited without problem even for applications like rotors where the yield stress becomes a problem.

[Area Rate of Worked Structures]

[0056] The worked structures are present in an area rate in observation of the cross-sectional structure of steel sheet of 1% or more. The cross-sectional area is observed in the present invention by a cross-section where one side of the cross-section becomes the steel sheet rolling direction and the other side becomes the steel sheet thickness direction. The method performed with ordinary steel sheet of using Nital or another chemical to etch and expose the structure is used, but the invention is not particularly limited in method of observation. Any technique enabling differentiation of the recrystallized structure and the worked structures may be used.

[0057] If the area rate of the worked structures is 1% or less, the effect of increasing the strength becomes smaller. When the worked structures are substantially 0%, the result becomes the ordinary steel sheet itself. By controlling the rate to the range of 0 to 1%, the effect of increasing the strength is smaller yet it is necessary to extremely strictly control the temperature of the annealing so this is not practical. To obtain the level of strength actually required, the area rate of the worked structures is controlled to preferably 5% or more, more preferably 10% or more, more preferably 20% or more, more preferably 30% or more, more preferably 50% or more, more preferably 70% or more. There is no problem at all even if made 100% worked structures where substantially no recrystallized structures are observed at all. In this case, the result becomes a so-called "full hard" state which does not anneal at all or the state where annealing is performed, but the structure is restored to the state before the start of recrystallization.

[0058] Note that even if the worked structures are less than 95%, 90%, 85%, 80%, or further 75%, the effect of the present invention is obtained.

[Formation of Worked Structures]

[0059] In the steel sheet of the present invention, the structure is adjusted in accordance with the strength and magnetic properties needed, but this adjustment can be performed by the steel ingredients, hot rolling history, cold rolling rate, annealing temperature, annealing time or heating speed, cooling rate, etc. A person skilled in the art can perform this without any problem at all by repeated trials. Alternatively, steel sheet annealed so that the recrystallized structures account for the entire weight may be given strain by repeated cold rolling etc. to form worked structures. In this case, usually the strain is given macroscopically evenly, so the entire amount of the structure becomes worked structures or corresponding to 100% worked structures. In this case, the steel ingredients, heat history, properties, etc. before working are considered and the amount of work is used to control the strength and magnetic properties. This is also possible for a person skilled in the art without problem by several trials.

[0060] As a rough standard, with so-called ordinary low grade electrical steel sheet with an amount of Si of 1% or so or less, the temperature is not over 700°C, while even with so-called ordinary high grade electrical steel sheet with an amount of Si of 3% or so, the temperature is not over 800°C or so, but for example by adding suitable amounts of Cu, Nb, etc., it is possible to obtain invention steels of completely restored structures not recrystallizing at all even at a temperature of 900°C or so or more. On the other hand, annealing at a temperature very different from ordinary electrical steel sheet requires a major change in the furnace temperature and not only invites a drop in the work efficiency, but also causes problems in safety as well as mentioned above due to the production of unburned gas. The lower limit of the annealing temperature for avoiding these problems due to extremely low temperature annealing is 400°C or so or more.

[0061] The rough standard for the annealing time depends on the temperature as well, but at least 5 seconds or so is required for giving an annealing effect. The annealing time cannot be unambiguously explicitly shown since it depends on the ingredients, production history up to the heat treatment, etc., but the rough standard is, if 850°C, within 5 minutes, if 750°C, within one hour, and, if 600°C, without 10 hours. As explained above, the temperature and time conditions enabling the effect of the invention to be enjoyed can be found without problem by a person skilled in the art by several trials. The point is confirmation of the recrystallization behavior of the steel sheet covered.

[0062] When newly forming worked structures by repeated cold rolling etc., if the amount of work is low, it is sometimes difficult to clearly determine the existence of worked structures by the above method of observation of structure, but as a rough standard for sufficiently obtaining the effect of the invention, it is possible to use the (size of crystal grains in sheet thickness direction)/(size of crystal grains in rolling direction) in observation of the cross-sectional structure. This value is made 0.9 or less. If 0.8 or less, the effect of increasing the strength is clearly obtained. The value is preferably 0.7 or less, more preferably 0.6 or less, more preferably 0.5 or less, more preferably 0.3 or less. However, if this value is excessively low, the deterioration of the magnetic properties becomes remarkable, so caution is required.

[0063] The above working is usually performed by cold rolling, but there is no need to insist on this so long as there is a change in amount of strain or material quality with the prescription of the present invention. Warm rolling, hot rolling of an extent where the worked structures do not disappear, tensile deformation by imparting tension, bending deformation by a leveler etc., shot blasting, forging, or another method may be used. Rather, due to the method of imparting strain, the dislocation structure is made to change to one preferable for the present invention explained later, so further improvement in properties becomes possible.

[0064] In the case of performing this working by cold rolling, the rough standard of the reduction rate can be easily estimated from the ratio of the size of the crystal grains, but is 10 to 70% or so. When further again cold rolling material softened to a certain extent in such an annealing step so as to harden it, the material can easily be made thinner and the productivity of the very thin electrical steel sheet which had been difficult to make in the past is also improved. Such very thin electrical steel sheet according to the present invention enables suppression of the eddy current loss in the case of use under a high frequency magnetic field, so also has the merit of being effective for reduction of the iron loss.

[0065] Note that even now there is electrical steel sheet being shipped out after rolling recrystallization annealed steel sheet by 1 to 20% or so skin pass rolling like with the other method of the present invention, that is, so-called semiprocess electrical steel sheet. This skin pass rolled sheet is shipped out as a product, worked by motor manufacturers into motor parts, then annealed under conditions whereby recrystallization will sufficiently occur to cause strain-induced grain growth and thereby obtain a coarse recrystallized structure. This is a means for improving the magnetic properties and is also sometimes called the skin pass method. In this method, no worked structures are ever left at the time of use as a member.

[Heat Treatment After Formation of Worked Structures]

[0066] The present invention inherently differs from this steel sheet and method. It basically does not perform any

heat treatment after working the sheet into the part of the electrical equipment. Even when performing some sort of heat treatment by bonding the steel sheet or surface control etc., the worked structures prescribed in the present invention will not disappear and will remain in the range prescribed by the present invention. This is because if the worked structures disappear or deviate from the prescribed range of the present invention, the strength of the steel sheet required in the state of use as an actual motor will become insufficient. The rough standard of the temperature of this heat treatment is the same as the temperature conditions in the above step of annealing the steel sheet. The optimal conditions for enjoying the effect of the invention can be found with the cooperation of persons skilled in the art of production of steel sheet or, even without such cooperation, without any problem by several trials by a usual manufacturer of electrical equipment.

[Dislocation Density]

[0067] The effect of the "worked structures" explained above can also be evaluated by the dislocation density in the "worked structures". The average dislocation density in the worked structures is $1 \times 10^{13}/\text{m}^2$ or more, more preferably $3 \times 10^{13}/\text{m}^2$ or more, more preferably $1 \times 10^{14}/\text{m}^2$ or more, more preferably $3 \times 10^{14}/\text{m}^2$ or more. This dislocation density is measured by a transmission type electron microscope. In ordinary electrical steel sheet where the entire amount of the steel sheet is recrystallized structures, the average dislocation density is $1 \times 10^{12}/\text{m}^2$ or so or less, so is 10 times or more the difference sufficient for discrimination of the worked structures.

[0068] Note that strictly speaking, to use even ordinary electrical steel sheet as various members, manufacturers etc. shear, swage, and otherwise work it. Due to this, it is known that some strain remains introduced into the steel sheet and that this has an effect on the properties of the members. This sort of strain is introduced only to the worked locations of the steel sheet and differs from the strain consciously made present at the entire surface of the steel sheet in the present invention, so does not contribute much at all to achieving high strength of the member as a whole.

[Reason Why Magnetic Properties Can Be Maintained]

[0069] The reason why the good magnetic properties can be maintained even if leaving worked structures in the material as in the present invention is not clear, but is believed to be something like the following. In the past, worked structures were considered to cause the magnetic properties to greatly deteriorate and were not regarded as means for achieving high strength of the material. High strength was achieved by refinement of the crystal grains, solid solution strengthening, precipitation strengthening, etc. However, demands for higher strength of materials have been steadily escalating. The conventional means for achieving high strength are now being forced to deal with even regions of conditions remarkably degrading the magnetic properties. When viewing the means for achieving high strength utilizing worked structures once again under such conditions, it appears in some sense that it can no longer be said to be such a disadvantageous method.

[0070] Further, what had been conventionally studied was the effect of worked structures in cold rolling of materials where the amount of strain was relatively small in range. Under such conditions, it is believed that the dislocation structures in the material are not relatively even and relatively stable dislocation arrangements like so-called cell structures or restored structures are not formed. Such an extent of working was not attractive at all as means for achieving high strength. Further, with such dislocation structures, the dislocations only became obstructions to domain wall movement. The magnetic properties remarkably deteriorated so this was apparently never practically applied.

[0071] On the other hand, when cold working with a relatively high amount of strain like in the present invention or in worked structures restored by annealing, the dislocations form relatively stable cell structures. The cells are normally of a diameter of $1 \mu\text{m}$ to $0.1 \mu\text{m}$ or so. Except for the fact that the cell boundaries are formed by dislocations and the difference in crystal orientations with adjacent cells is small, they have structures similar to general crystal grains. They can be viewed as one type of superfine crystal grains and are believed not to easily obstruct domain wall movement. Further, such superfine crystal grains are high in strength and have corresponding ductility when working is required. When considering the balance of strength and magnetic properties, this is believed to be of a level sufficiently enabling practical use. Further, even in the invention steels where worked structures are present, in applications such as use under a high frequency magnetic field where the contribution of the eddy current loss is particularly large in the iron loss, the addition of Si, Mn, Al, Cr, Ni, etc. is important. This has a great effect on the work hardening behavior, the recrystallization behavior, etc., so the development of dislocation strengthened steel based on electrical steel sheet has completely different meaning from that in so-called working use ordinary steel used for automobiles, containers, etc.

[Utilization of Solid Solution Cu]

[0072] Note that in the present invention, separate from Si and other conventionally known solid solution strengthening elements, it is also possible to introduce solid solution Cu and obtain electrical steel sheet superior in high frequency

magnetic properties without inviting the deterioration of the magnetic properties or productivity accompanying the addition of conventional alloy elements (below, referred to as "solid solution Cu strengthening"). In this case, by the measures of

- 1) adding a larger amount of Cu than ever seen in the past,
 - 2) suppressing the formation of the austenite phase in the high temperature region,
 - 3) performing the high temperature heat treatment in the ferrite region to make a large amount of Cu enter solid solution, and
 - 4) controlling the cooling so that oversaturated Cu does not precipitate during the cooling,
- the added Cu will be present as solid solution Cu even in the final product, an effect of suppression of eddy current loss never before conceived of in the past is expressed, a good high frequency iron loss can be obtained, and the effect on deterioration of the magnetic flux density can be kept relatively small.

[0073] The solid solution Cu strengthening is an effect independent from the above work strengthening and can be performed independently even without being accompanied by work strengthening. In this case, for example, the electrical steel sheet is made one containing, by mass%, C: 0.06% or less, Si: 1.5 to 6.5%, Mn: 0.05 to 3.0%, P: 0.30% or less, S or Se: 0.040% or less, Al: 2.50% or less, Cu: 2.0 to 30.0%, and N: 0.0400% or less, having a balance of Fe and unavoidable impurities, and not containing any metal phase made of Cu inside it. In some cases, it may further contain one or more of Nb: 8% or less, Ti: 1.0% or less, B: 0.010% or less, Ni: 15.0% or less, and Cr: 15.0% or less.

[0074] On the other hand, by using this for work strengthening, a synergistic strengthening effect is obtained together with the effect of raising the recrystallization degree by the solid solution Cu.

[0075] The effect of reduction of the eddy current loss and the effect of embrittlement at the time the amount of solid solution Cu increases is not due just to the amount of solid solution element. As explained above, an interactive effect is seen. Therefore, this is also considered in setting the preferable range of ingredients. Further, at the time of utilization for solid solution Cu strengthening, finally it is preferable to apply heat treatment for causing recrystallization and grain growth, so it is necessary to determine the ingredients while considering also the change in the amount of solid solution Cu due to formation of precipitates containing Cu at the time of this heat treatment. In particular, the transformation of the steel matrix phase at the time of heat treatment not only results in a great change in the solubility of Cu, but also ends up causing the structures preferable for magnetic flux density to disappear, so when utilizing solid solution Cu strengthening, basically transformation at the time of heat treatment should be avoided. Specifically, a single ferrite phase at the temperature region from room temperature to 1150°C or satisfaction, by mass%, of

$$980-400 \times C + 50 \times Si - 30 \times Mn + 400 \times P + 100 \times Al - 20 \times Cu - 15 \times Ni - 10 \times Cr > 900 \dots \text{formula 1}$$

is preferable. If off from this range, unpreferable transformation occurs during the heat treatment and the possibility increases of the effect of solid solution Cu strengthening being obstructed.

[0076] The features of solid solution Cu strengthening can be clearly shown even with comparison of the properties with general materials. In comparison with steel sheet where the steel ingredients other than the Cu are the same, the Cu is 0.1%, and the crystal grain size is the same, a solid solution Cu strengthened steel sheet having an iron loss $W_{10/400}$ of 0.8 or less, 0.7 or less, 0.6 or less, 0.5 less, 0.4 less, more preferably 0.30 or less, is obtained.

[0077] Further, in solid solution Cu strengthened steel sheet, the tensile strength is 2.0 times or less than of the comparative steel. In general, if the amount of solid solution element increases, the solid solution strengthening causes the strength to rise. If the amount of solid solution is large as with solid solution Cu strengthening, depending on the element, the rise in strength also becomes remarkable, but the solid solution Cu in high Si steel characteristic of solid solution Cu strengthened steel does not harden the material that much. The ratio is more preferably suppressed to 1.7 or less, more preferably 1.5 or less. If the amount of solid solution Cu is increased, while the result can be said to be solid solution Cu strengthened steel, the strength becomes higher. It is not that the smaller the rise in strength the better, but if compared with the Si, Cr, etc. used as the solid solution element, the rise in strength is small and embrittlement is also suppressed.

[0078] Further, in solid solution Cu strengthened steel, when excessive Cu is included, remarkable precipitation of metal Cu phases is seen in some cases. Further, in terms of properties, along with the precipitation of the metal Cu phases, a large rise in strength is observed. Further, in this case, simultaneously, a rise in iron loss, in particular the eddy current loss, follows. Specifically, by heat treatment at 450°C for 30 minutes, the density of the number of metal phases comprised mainly of Cu having a size of 0.02 μm or less in the steel increases to 20/ μm^3 or more or the tensile strength rises to 100 MPa or more. As explained above, such heat treatment greatly increases the eddy current loss and degrades the high frequency magnetic properties aimed at by the solid solution Cu strengthening, so this is not

performed for controlling the quality of the steel sheet, but it can be performed for judgment of the invention steels in the same way as for example the analysis of ingredients.

[0079] To include the large amount of solid solution Cu characterized by solid solution Cu strengthening, it is effective to go through the following heat history. In the final heat treatment in the process of production of the product sheet, usually the recrystallization annealing after cold rolling, the sheet is held in the temperature region of 800°C or more for 5 sec or more and the conditions are set so that no austenite phase is produced in the steel material even at the peak temperature in this heat treatment. The temperature is preferably 900°C or more, more preferably 1000°C or more, more preferably 1050°C or more. Further, the time is preferably 10 sec or more, more preferably 30 sec or more, more preferably 60 sec or more, but if a temperature and time where sufficiently solubility of Cu occurs in the balance with the Cu content, the characterizing effect of the present invention can be sufficiently obtained. However, it is of course necessary to control this taking into account the viewpoint of controlling the crystal grain size having a large effect on the magnetic properties as well.

[0080] If the crystal grain size is too fine or too coarse, the magnetic properties will sometimes be degraded. It is well known that there is an optimal grain size in the usage conditions. Further, the peak temperature has to be set to a temperature region where no austenite phase is produced. If a small amount is produced, the detrimental effect in the properties will be small, but the annealing is preferably performed with a complete ferrite phase. The temperature depends mainly on the steel ingredients, so no specific temperature can be described, but the above formula 1 is a general standard. Further, a person having knowledge of general metallurgy would be able to set a suitable temperature range without any difficulty by the generally performed experiments in heat treatment and observation of structure or recent remarkable advances in thermodynamic computations.

[0081] Further, the cooling rate in the heat treatment step also becomes an important control factor. The reason is that the Cu sufficiently dissolved by holding the steel at a high temperature becomes supersaturated during cooling, so depending on the cooling rate will end up precipitating as a metal Cu phase and sometimes reduce the effect of the present invention. In the present invention, the preferable conditions are made a cooling step after holding the steel in the temperature region of 800°C or more for 5 sec or more of cooling by a cooling rate of 40°C/sec or more to 300°C or less. From the object of the present invention, there is nothing better than a high cooling rate, but if cooling too rapidly, the properties sometimes deteriorate due to the heat history etc., so caution is required. The rate is preferably 60°C/sec or more, more preferably 80°C/sec or more, more preferably 100°C/sec or more.

[0082] In particular, in the present invention, attention should be paid to the cooling in the temperature region where precipitation of the metal Cu phase occurs. The residence time at 700 to 400°C becomes important. At 700°C or more, the degree of supersaturation of Cu is small and precipitation is difficult to occur, while at 400°C or less, diffusion of Cu is suppressed, so precipitation becomes hard. If the time is made 5 sec or less, preferably 3 sec or less, more preferably 2 sec or less, precipitation of the metal Cu phase can be suppressed and a sufficient amount of solid solution Cu for obtaining the effect of the invention can be secured.

[0083] Further, after this heat treatment, the steel is preferably held at a temperature region of over 400°C for 30 sec or more. This is because by such heat treatment, the precipitation of the metal Cu phase is promoted and the eddy current loss is increased.

[0084] By the above such ingredients and steps, the effect of reduction of the eddy current loss by the characteristic large amount of solid solution Cu is efficiently expressed and production of high Cu electrical steel sheet becomes possible without impairing the castability or rollability much at all. On the other hand, in production by the usual ingredients and heat treatment conditions not considering maintenance of the amount of solid solution Cu, the parts where the amount of Cu added become small are present as metal Cu phases or Cu sulfides with small eddy current loss reduction effects, embrittlement becomes remarkable, and normal production becomes difficult.

[0085] Note that in the case of also using the work strengthening of the present invention, the above heat treatment may be annealing in a range 350 to 700°C for 10 sec to 360 minutes so that the Cu metal phases finely precipitate while recrystallization remains suppressed. Needless to say, the Cu metal phases end up coarsening by annealing at a high temperature for a long time and the strengthening ability falls. At a high temperature, attention must be paid so that the annealing time does not become too long. The lower the temperature, the longer the annealing possible.

[0086] The present invention is characterized by the lack of any metal Cu phases in the steel material. This can be identified and confirmed by the diffraction pattern of an electron microscope etc. or an attached X-ray analysis device. Of course, confirmation is also possible by a method other than this such as chemical analysis. In the present invention, the "metal phase mainly comprised of Cu" covers ones with a diameter of 0.010 μm or more. The reason is that if less than 0.005 μm , it is too fine, so even using the current highest precision analysis equipment, it would be hard to identify the metal Cu phases covered by the present invention. Further, no matter what kind of treatment is performed, in the invention steels containing Cu in large amounts, there are locally precipitates containing Cu in some form or another, so it is impossible to completely remove the metal Cu phases. The present invention is limited to electrical steel sheet containing a considerable amount of Cu and hardened or formed with a large amount of the metal Cu phases by the considerable heat treatment described in the present invention. The inherent feature of the present invention of course

lies in the large amount of solid solution Cu.

[Applications]

[0087] Note that the effects of present invention do not depend on the presence or type of the surface coating formed on the surface of ordinary electrical steel sheet or further on the production steps, so the invention can be applied to nonoriented or grain-oriented electrical steel sheet. In particular, the invention steel can give features very different from steel sheet of conventional recrystallized structures in the in-plane anisotropy of properties. If viewing the magnetic flux density, in the as cold rolled full hard state, the properties of the direction 45° from the coil rolling direction (D direction) are higher than the properties in the rolling direction (L direction) or coil width direction (C direction). Electrical steel sheet having ordinary recrystallized structures in almost all cases have properties in the D direction lower than the properties in the L or C direction. Considering this, by suitably adjusting the extents of the recrystallization and restoration and controlling the structure to the intermediate recrystallization stage, it is possible to easily obtain steel sheet with almost no in-plane anisotropy. Almost no in-plane anisotropy means steel sheet having features enabling extremely preferable properties to be exhibited depending on the applications such as rotary machines.

[0088] The applications are not particularly limited. In addition to the applications for rotors of motors used in household electrical appliances, automobiles, etc., the invention may also be applied to all applications where strength and magnetic properties are sought.

EXAMPLES

(Example 1)

[0089] A slab of 200 mm thickness having the ingredients of 0.002%C-3.0%Si-0.5%Mn-0.03%P-0.001%S-0.3%Al-0.002%N was hot rolled by a slab heating temperature of 1100°C and a coiling temperature of 700°C. The hot rolled sheets were annealed to 800, 950, and 1050°C to change the grain sizes to 10, 100, and 200 μm. These hot rolled sheets were cold rolled, then either not annealed or annealed at 400 to 1000°C for 30 sec to produce product sheets of sheet thicknesses of 0.5 mm differing in recrystallization rate and strength. These were evaluated for mechanical properties using JIS No. 5 test pieces and properties of iron loss $W_{10/400}$ by 55 mm square SST tests. The average values of the mechanical properties and magnetic properties for the coil rolling direction, 45° direction, and direction perpendicular to that were found by the following formula:

$$X = (X_0 + 2 \times X_{45} + X_{90}) / 4$$

where, X_0 , X_{45} , and X_{90} are the properties in the coil rolling direction, 45° direction, and direction perpendicular to that.

[0090] The results are shown in FIG. 1. As clear from the results, materials with coarse hot rolled sheet grain sizes, that is, materials produced under the conditions of the present invention, are excellent in strength-iron loss balance.

Table 1

No	Ingredients (mass%)									
	C	Si	Mn	P	S	Al	N	Cu	Nb	Others
1	0.0010	3.0	0.8	0.0	0.0005	1.64	0.0019	-	-	-
2	0.0010	3.0	0.8	0.010	0.0005	1.64	0.0019	-	-	-
3	0.0010	3.0	0.8	0.010	0.0005	1.64	0.0019	-	-	-
4	0.0025	0.7	0.21	0.090	0.0025	0.001	0.0024	-	-	-
5	0.0025	0.7	0.21	0.090	0.0025	0.001	0.0024	-	-	-
6	0.0025	0.7	0.21	0.090	0.0025	0.001	0.0024	-	-	-
7	0.0025	0.7	0.21	0.090	0.0025	0.001	0.0024	-	-	-
8	0.0019	2.1	0.20	0.060	0.0012	0.22	0.0026	-	-	-
9	0.0019	2.1	0.20	0.060	0.0012	0.22	0.0026	-	-	-
10	0.0019	2.1	0.20	0.060	0.0012	0.22	0.0026	-	-	-

EP 2 031 079 A1

(continued)

No	Ingredients (mass%)									
	C	Si	Mn	P	S	Al	N	Cu	Nb	Others
11	0.0038	3.1	0.20	0.044	0.0018	1.0	0.0020	-	-	-
12	0.0012	2.9	0.40	0.030	0.0005	0.5	0.0013	3.9	-	Ni: 1.8
13	0.0012	2.9	0.40	0.030	0.0005	0.5	0.0013	3.9	-	Ni: 1.8
14	0.0006	3.1	0.30	0.008	0.0009	0.15	0.0025	-	-	Ni: 2.0 Cr: 5.0
15	0.0230	2.5	1.20	0.022	0.0006	0.06	0.0036	-	0.11	B: 0.008
16	0.0230	2.5	1.20	0.022	0.0006	0.06	0.0036	-	0.11	B: 0.008
17	0.0008	3.4	0.53	0.041	0.0004	0.02	0.0024	-	0.37	Ti: 0.35
18	0.0008	3.4	0.53	0.041	0.0004	0.02	0.0024	-	0.37	Ti: 0.35
19	0.0322	3.1	0.50	0.016	0.0002	1.2	0.0011	-	1.3	-
20	0.0322	3.1	0.50	0.016	0.0002	1.2	0.0011	-	1.3	-
21	0.0077	2.9	0.29	0.023	0.0015	0.8	0.0022	2.1	-	-
22	0.0021	3.7	0.05	0.002	0.0009	0.24	0.0026	-	-	Sn: 0.09 Ce: 0.002
(Balance of Fe and unavoidable impurities)										

(Example 2)

[0091] From slabs of 200 mm thickness having the ingredients of Table 1, product sheets were produced under the production conditions shown in Table 2. Some of the materials were heat treated assuming the heat treatment at motor manufacturers (user annealing). These were evaluated for mechanical properties using JIS No. 5 test pieces and properties of iron loss $W_{10/400}$ and magnetic flux density B_{25} by 55 mm square SST tests. The average values of the mechanical properties and magnetic properties for the coil rolling direction, 45° direction, and direction perpendicular to that were found by the following formula:

$$X = (X_0 + 2 \times X_{45} + X_{90}) / 4$$

where, X_0 , X_{45} , and X_{90} are the properties in the coil rolling direction, 45° direction, and direction perpendicular to that.

[0092] The results are shown in Table 2. As clear from the results, materials produced under the conditions of the present invention are hard and further superior in magnetic properties. Caution is required in that generally electrical steel sheet greatly differ in properties due to the amount of Si so are graded and sold according to the amount of Si contained. Further, the iron loss greatly changes depending on the sheet thickness. A high Si material, compared with a low Si material, greatly drops in iron loss due to the difference in Si content. Further, even sheets with thin sheet thicknesses fall in iron loss, so when evaluating the effect of the present invention, it is necessary to bear in mind the differences in the amounts of Si and sheet thicknesses and compare sheets with equivalent amounts of Si and sheet thicknesses.

Table 2

No	Hot rolling step		Hot rolled sheet annealing (°Cxsec)	Cold rolling and annealing steps			Structure before working				Product		Properties		Remarks					
	Heating temp. (°C)	Coiling temp. (°C)		Finished sheet thickness (nm)	Primary Cold rolling rate (%)	Annealing (°Cxsec)	Secondary cold rolling rate (%)	Sheet thickness (nm)	Judge-ment of grain size before work	Grain size work (μm)	Recry-stalliza-tion rate before work (%)	A	B	C		Worked struc-ture (%)	Worked struc-ture (m³)	TS (MPa)	B ₂₅ (T)	W _{10/400} (W/kg)
1	1150	700	2.0	1050x30	85	850x30	0	0.30	HRS	150	100	*	*	*	0	8exp11	530	1.57	20	D
2	1150	700	2.0	800x30	85	650x30	0	0.30	HRS	10	100	*	*	*	100	4exp14	890	1.62	50	D
3	1150	700	2.0	1050x30	85	650x30	0	0.30	HRS	150	100	*	*	*	100	6exp14	910	1.65	30	A
4	1050	550	2.1	-	88	600x30	0	0.25	HRS	15	100	*	*	*	100	5exp15	580	1.72	70	D
5	1050	750	2.1	-	88	600x30	0	0.25	HRS	50	100	*	*	*	100	4exp15	660	1.70	45	B
6	1050	750	2.1	-	83	950x30	30	0.25	CRS	100	100	*	*	*	100	4exp14	570	1.73	40	A
7	1050	750	2.1	-	83	700x30	30	0.25	CRS	3*	20	*	*	*	100	7exp14	550	1.74	75	D
8	1100	700	2.0	850x30	85	650x30	0	0.30	HRS	15*	90	*	*	*	100	3exp14	750	1.63	65	D
9	1100	700	2.0	1150x60	85	650x30	0	0.30	HRS	300	100	*	*	*	100	1exp15	840	1.64	50	A
10	1100	700	2.0	1150x60	85	750x30	0	0.30	HRS	300	100	*	*	*	40	7exp12	660	1.64	25	B
11	1100	700	2.0	1150x180	85	750x30	0	0.30	HRS	320	100	*	*	*	60	2exp13	700	1.61	25	B
12	1200	700	2.0	1100x60	75	850x30	0	0.50	HRS	170	100	*	*	*	100	9exp14	880	1.65	35	A
13	1200	700	2.0	1100x60	75	950x90	0	0.50	HRS	170	100	*	*	*	85	2exp14	850	1.65	35	A
14	1000	650	2.5	1050x90	85	650x30	20	0.30	HRS	200	100	*	*	*	100	2exp15	1150	1.65	55	A
15	1150	550	2.3	1100x60	85	700x120	0	0.35	HRS	120	100	*	*	*	95	5exp13	900	1.65	25	A
16	1150	550	2.3	950x30	85	700x120	0	0.35	HRS	30	100	*	*	*	90	5exp13	870	1.66	40	B
17	1100	700	2.0	1000x60	75	750x30	0	0.50	HRS	80	100	*	*	*	100	5exp14	810	1.63	35	A
18	1100	700	2.0	950x30	75	750x30	0	0.50	HRS	15	100	*	*	*	100	6exp14	820	1.63	90	D
19	1100	600	2.0	950x120	90	850x60	0	0.20	HRS	30	97	*	*	*	100	3exp14	1040	1.67	20	A
20	1100	600	2.0	950x30	90	850x60	0	0.20	HRS	10	92	*	*	*	100	2exp14	1000	1.64	40	D
21	1100	700	2.5	1150x30	90	850x30	0	0.25	HRS	200	100	*	*	*	100	2exp15	1100	1.65	25	A
22	1250	700	2.2	-	85	1000x30	10	0.30	CRS	130	100	*	*	*	100	8exp12	700	1.63	30	B

"Grain size before work" column asterisks: worked structures remaining

"A" column asterisks: formula (2) satisfied

"B" column asterisks: formula (3) satisfied

"C" column asterisks: formula (4) satisfied

A: Invention steel

(Particularly good)

B: Invention steel

D: Comparative steel

HRS: Hot rolled sheet

CRS: Cold rolled sheet

(Example 3)

[0093] Slabs of the steels of the ingredients of Table 3 of 250 mm thickness were used to produce product sheets under the conditions of Tables 3 and 4. 55 mm square SST tests were used to measure the magnetic flux density B₁₀ and iron loss _{W_{10/400}}. The average values of the magnetic properties in the coil rolling direction, 45° direction, and direction perpendicular were found by the following formula:

$$X = (X_0 + 2 \times X_{45} + X_{90}) / 4$$

[0094] Here, X₀, X₄₅, X₉₀ are the characteristics in the coil rolling direction, 45° direction, and direction perpendicular to that.

[0095] As clear from the results shown in Table 4, the samples produced under the conditions of the present invention are good in rollability in the cold rolling step and superior in magnetic properties. Note that it was confirmed that the good iron loss in the invention steels was main due to the reduction of the eddy current loss.

Table 3

	Ingredients (mass%)											Hot rolling step			Jot rolled sheet annealing (°C×sec)	Cold rolling step	
	C	Si	Mn	P	S	Al	N	Cu	Ni	Cr	Others	Slab heating (°C)	Finish. temp. (°C)	Coil. temp. (°C)		Cold rolling rate (%)	Sheet thickness (mm)
1	0.0017	3.40	0.28	0.050	0.0010	1.29	0.0018	0.01	0.01	0.01	-	1100	880	750	1050×30	85	0.35
2	0.0031	3.05	0.88	0.013	0.0006	0.32	0.0025	0.00	0.00	5.20	-	1100	780	700	1150×30	85	0.35
3	0.0031	2.05	0.88	0.013	0.0006	0.32	0.0025	4.40	2.00	5.20	-	1100	780	700	1150×30	85	0.35
4	0.0031	1.35	0.88	0.013	0.0006	0.32	0.0025	4.40	2.00	5.20	-	1100	780	700	1150×30	85	0.35
5	0.0021	2.65	0.34	0.014	0.0007	0.54	0.0022	2.78	1.00	0.00	-	1100	850	750	1000×30	85	0.35
6	0.0021	2.65	0.34	0.014	0.0007	0.54	0.0022	2.78	1.00	0.00	-	1100	850	750	1000×30	85	0.35
7	0.0021	2.65	0.34	0.014	0.0007	0.54	0.0022	2.78	1.00	0.00	-	1100	850	750	1000×30	85	0.35
8	0.0017	3.40	0.28	0.050	0.0010	1.29	0.0018	0.01	0.01	0.01	-	1100	880	750	1050×30	80	0.5
9	0.0031	3.05	0.88	0.013	0.0006	0.32	0.0025	0.00	0.00	5.20	-	1100	780	700	1150×30	80	0.5
10	0.0008	3.52	0.31	0.017	0.0004	1.10	0.0016	3.58	1.50	0.00	-	1150	900	700	950×30	75	0.5
11	0.0131	3.14	1.10	0.017	0.0021	0.50	0.0021	5.20	2.31	1.90	-	1250	940	830	1000×30	75	0.5
12	0.0066	2.35	0.31	0.079	0.0011	0.01	0.0027	4.23	0.00	0.00	-	1100	880	700	1150×30	75	0.5
13	0.0024	2.89	0.27	0.018	0.0016	0.53	0.0016	2.68	0.45	5.60	Se: 0.0041	1100	800	600	1050×30	75	0.5
14	0.0014	3.35	0.11	0.005	0.0012	2.11	0.0019	6.69	1.55	0.00	-	1050	760	650	1050×30	90	0.2
15	0.0014	3.35	0.11	0.005	0.0012	2.11	0.0019	6.69	1.55	0.00	-	1050	760	650	1050×30	90	0.2
16	0.0014	3.35	0.11	0.005	0.0012	2.11	0.0019	6.69	1.55	0.00	-	1050	760	650	1050×30	90	0.2
17	0.0014	3.35	0.11	0.005	0.0012	2.11	0.0019	6.69	1.55	0.00	-	1050	760	650	1050×30	90	0.2
18	0.0014	4.43	0.31	0.002	0.0007	0.45	0.0022	18.5	5.30	0.00	Ce: 0.005	1200	890	800	1000×60	75	0.5
19	0.0005	3.11	0.29	0.052	0.0013	1.65	0.0022	5.02	2.60	0.00	-	1100	830	750	1000×60	80	0.5
20	0.0005	3.11	0.29	0.052	0.0013	1.65	0.0022	5.02	2.60	10.5	-	1100	850	780	1000×60	80	0.5
21	0.0010	3.80	0.31	0.013	0.0006	1.51	0.0028	8.94	4.89	0.20	Nb: 0.3	1000	790	700	950×60	83	0.35
22	0.0036	3.04	0.83	0.011	0.0031	0.24	0.0028	12.6	1.60	0.20	-	1050	800	750	1050×30	83	0.35
23	0.0023	2.78	0.32	0.019	0.0015	0.48	0.0015	35.0	3.70	0.00	-	1150	830	750	1000×30	85	0.35

Table 4

	Annealing step				Cu metal phase	Comparison with 0.01% Cu		Change in material quality after heat treatment at 450°C for 30 min		Magnetic properties		Forge-ability	Cold roll-ability	Eval.
	Soaking (°C×sec)	Cooling until 300°C (°C/s)	A	B	C	W _{10/400} ratio	TS ratio	Cu phase density (Am ² /μm ³)	TS rise (MPa)	810 (T)	W _{10/400} (W/kg)			
1	1000×30	70	4	Good	1289	1.00	1.0	0	<20	1.38	13	Fair	Poor	C
2	1000×30	70	4	Good	1090	1.00	1.0	0	<20	1.41	16	V.Good	Good	C
3	1000×30	70	4	Poor	922	0.70	1.3	>100	350	1.43	13	V.Good	V.Good	B
4	1000×30	70	4	x	887	0.86	1.6	>100	200	1.46	18	V.Good	V.Good	C
5	900×30	70	4	Good	1091	0.75	1.4	60	300	1.46	10	V.Good	V.Good	A
6	900×30	30	10	Good	1091	0.80	1.7	40	200	1.45	13	V.Good	V.Good	B
7	900×30	10	30	Good	1091	0.92	2.2	20	<20	1.34	30	V.Good	V.Good	C
8	1000×30	60	5	Good	1289	1.00	1.0	0	<20	1.38	17	Fair	Poor	C
9	1000×30	60	5	Good	1090	1.00	1.0	0	<20	1.41	21	V.Good	Good	C
10	1050×30	120	3	Good	1169	0.72	1.3	>100	400	1.42	14	V.Good	V.Good	A
11	1000×30	120	3	Good	998	0.74	1.4	>100	450	1.40	14	V.Good	V.Good	A
12	950×30	150	2	Good	1034	0.77	1.2	>100	500	1.48	16	V.Good	V.Good	A
13	1000×30	40	8	Good	1058	0.80	1.7	40	300	1.37	17	V.Good	Good	B
14	1000×30	80	2	Good	1200	0.38	1.3	>100	750	1.46	5	Good	V.Good	A
15	1000×30	80	5	Good	1200	0.61	1.9	>100	550	1.43	8	Good	V.Good	B
16	1000×30	40	2	Good	1200	0.55	1.6	>100	550	1.44	6	Good	V.Good	B
17	1000×30	40	13	Good	1200	0.81	2.1	40	70	1.31	13	Good	V.Good	C
18	1100×30	200	1	x	788	0.61	1.8	>100	150	1.34	16	V.Good	V.Good	A
19	1000×30	60	5	Good	1173	0.51	1.2	>100	250	1.45	12	V.Good	V.Good	A
20	1000×30	60	5	Good	1068	0.81	1.2	>100	100	1.38	18	V.Good	Good	B
21	1050×30	100	3	Good	1062	0.44	1.4	>100	400	1.40	9	Good	Good	A
22	1000×60	100	3	x	858	0.68	1.8	>100	350	1.37	10	Fair	Fair	B
23	1000×30	100	3	x	409	0.92	2.4	20	50	1.20	22	Fair	Poor	C

A: Residence time at 700 to 400°C in cooling
 step (sec)
 B: Formation of austenite phase at peak temperature (Good: None, Poor: Yes)
 C: Left side of formula 1

Castability, cold rollability
 V.Good: Excellent (no problem at all)
 Good: Excellent (fine adjustment required, but no problem)
 Fair: Possible (processable if adjusting conditions)
 Poor: Difficult (large danger of breakage, cracking, etc.)

Evaluation
 A: Invention steel (extremely good)
 B: Invention steel (good)
 C: Comparative steel

INDUSTRIAL APPLICABILITY

[0096] According to the present invention, it is possible to stably produce hard high strength electrical steel sheet superior in magnetic properties. That is, the present invention enables the targeted strength to be obtained even with relatively low amounts of the added elements used for solid solution strengthening and precipitation strengthening, so the cold rollability is improved, the productivity of the cold rolling step is improved, and annealing in the usual operating range becomes possible, so the work efficiency in the annealing step also is improved. Further, by cold rolling again after annealing, it becomes possible to simply produce extremely thin materials which were difficult to produce in the past.

[0097] Further, if utilizing solid solution Cu, it becomes possible to suppress embrittlement and stably produce electrical steel sheet superior in high frequency magnetic properties using low eddy current loss high alloy ingredients without problems in cold rollability etc.

[0098] From the above, the strength, fatigue strength, and wear resistance can be secured, so increased efficiency, smaller size, longer lifetime, etc. of superhigh speed motors, motors with magnets built into the rotors, and materials for electromagnetic switches are achieved.

Claims

1. A method of production of high strength electrical steel sheet containing, by mass%, C: 0.060% or less, Si: 0.2 to 6.5%, Mn: 0.05 to 3.0%, P: 0.30% or less, S or Se: 0.040% or less, Al: 2.50% or less, and N: 0.040% or less, having a balance of Fe and unavoidable impurities, and having worked structures remaining inside the steel sheet, said method of production of high strength electrical steel sheet **characterized by** making an average crystal grain size d of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet $20\ \mu\text{m}$ or more.

2. A method of production of high strength electrical steel sheet containing, by mass%, C: 0.060% or less, Si: 0.2 to 6.5%, Mn: 0.05 to 3.0%, P: 0.30% or less, S or Se: 0.040% or less, Al: 2.50% or less, and N: 0.040% or less, having a balance of Fe and unavoidable impurities, and having worked structures remaining inside the steel sheet, said method of production of high strength electrical steel sheet **characterized by** making an average crystal grain size d (μm) of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet $d \geq (220 - 50 \times \text{Si}\% - 50 \times \text{Al}\%)$.

3. A method of production of high strength electrical steel sheet as set forth in claim 1 or 2 **characterized by** making an average crystal grain size d (μm) of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet

$$d \leq (400 - 50 \times \text{Si}\%)$$

and

$$d \leq (820 - 200 \times \text{Si}\%)$$

4. A method of production of high strength electrical steel sheet as set forth in any one of claims 1 to 3 **characterized by** making a recrystallization rate of the steel sheet right before the step of forming the worked structures to finally remain inside the steel sheet 50% or more.

5. A method of production of high strength electrical steel sheet as set forth in any one of claims 1 to 4 **characterized in that** the steel ingredients further contain, by mass%, one or both of Cu: 0.001 to 30.0% and Nb: 0.03 to 8.0%.

6. A method of production of high strength electrical steel sheet as set forth in any one of claims 1 to 5 **characterized in that** the steel ingredients further contain, by mass%, one or more types of Ti: 1.0% or less, V: 1.0% or less, Zr: 1.0% or less, B: 0.010% or less, Ni: 15.0% or less, and Cr: 15.0% or less.

7. A method of production of high strength electrical steel sheet as set forth in any one of claims 1 to 6 **characterized in that** the steel ingredients further contain, by mass%, one or more types of Bi, Mo, W, Sn, Sb, Mg, Ca, Ce, La,

and Co in a total of 0.5% or less.

8. A method of production of high strength electrical steel sheet as set forth in any one of claims 1 to 7 **characterized in that** the worked structures present inside the steel sheet are 1% or more by area rate in observation of the cross-section.

9. A method of production of high strength electrical steel sheet as set forth in any one of claims 1 to 8, **characterized in that** an average dislocation density in the worked structures inside the steel sheet is $1 \times 10^{13}/\text{m}^2$ or more.

10. A high strength electrical steel sheet as set forth in claim 1, **characterized by** being a single ferrite phase in a temperature region from room temperature to 1150°C and satisfying, by mass%,

$$980 - 400 \times \text{C} + 50 \times \text{Si} - 30 \times \text{Mn} + 400 \times \text{P} + 100 \times \text{Al} - 20 \times \text{Cu} - 15 \times \text{Ni} - 10 \times \text{Cr} > 900$$

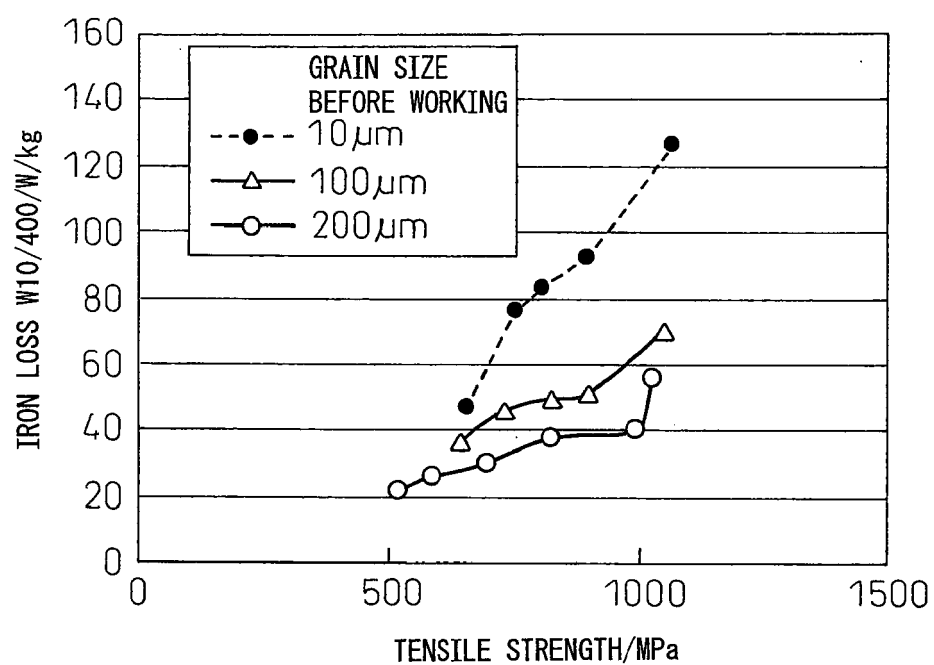
11. A high strength electrical steel sheet as set forth in claim 10, **characterized in that** heat treatment at 450°C for 30 minutes is used to make a tensile strength 100 MPa or more.

12. A method of production of high strength electrical steel sheet **characterized by** producing steel sheet as set forth in claim 10 during the process of which making a final heat treatment after cold rolling a heat treatment holding the sheet in a temperature region of 800°C or more for 5 sec or more and not allowing formation of an austenite phase in the steel material even at a peak temperature in this heat treatment.

13. A method of production of high strength electrical steel sheet **characterized by** producing steel sheet as set forth in claim 10 during the process of which making a cooling step after holding the sheet in a temperature region of 800°C or more for 5 sec or more cooling by a cooling rate of 40°C/sec or more to 300°C or less.

14. A method of production of high strength electrical steel sheet as set forth in claim 10, **characterized by** making a residence time in 700 to 400°C in said cooling step 5 sec or less.

Fig.1



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2006/312552

A. CLASSIFICATION OF SUBJECT MATTER

C21D9/46(2006.01)i, C21D8/12(2006.01)i, C22C38/00(2006.01)i, C22C38/60(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C21D9/46, C21D8/12, C22C38/00-38/60

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2006

Kokai Jitsuyo Shinan Koho 1971-2006 Toroku Jitsuyo Shinan Koho 1994-2006

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI (DIALOG)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	JP 2006-9048 A (Sumitomo Metal Industries, Ltd.), 12 January, 2006 (12.01.06), Examples (Family: none)	1, 4-9 2, 3, 10-14
X A	JP 2005-113185 A (Nippon Steel Corp.), 28 April, 2005 (28.04.05), Examples (Family: none)	1, 4-9 2, 3, 10-14
X	JP 2006-70348 A (Nippon Steel Corp.), 16 March, 2006 (16.03.06), Examples (Family: none)	5-12

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

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
19 September, 2006 (19.09.06)Date of mailing of the international search report
10 October, 2006 (10.10.06)Name and mailing address of the ISA/
Japanese Patent Office

Authorized officer

Facsimile No.

Telephone No.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2006/312552

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2005/033349 A1 (Nippon Steel Corp.), 14 April, 2005 (14.04.05), Examples & EP 1679386 A1	10-12
E,X	JP 2006-169611 A (Nippon Steel Corp.), 29 June, 2006 (29.06.06), Full text (Family: none)	1-9
E,X	JP 2006-169615 A (Nippon Steel Corp.), 29 June, 2006 (29.06.06), Full text (Family: none)	10-14

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- JP 1162748 A [0004]
- JP 61084360 A [0004]
- JP 2005113185 A [0004]
- JP 2006070348 A [0004]
- JP 2006009048 A [0004]
- JP 2006070296 A [0004]
- JP 2004084053 A [0005]
- JP 2004099926 A [0005]
- JP 2003347084 A [0006]