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# (54) NON-ORIENTED ELECTROMAGNETIC STEEL SHEET AND METHOD FOR MANUFACTURING SAME

(57) The present invention provides a non-oriented electrical steel sheet at low cost that has excellent magnetic properties and mechanical properties as well as excellent quality of steel sheet. The non-oriented electrical steel sheet has a chemical composition containing, by mass%, Si: 5.0 % or less, Mn: 2.0 % or less, Al: 2.0 % or less, and P: 0.05 % or less, in a range satisfying formula (1), and furthermore, C: 0.008 % or more and 0.040 % or less; N: 0.003 % or less, and Ti: 0.04 % or less, in a range satisfying formula (2), with the balance composed of Fe and incidental impurities:

$$300 \leq 85[\mathrm{Si\%}] + 16[\mathrm{Mn\%}] + 40[\mathrm{Al\%}] + 490[\mathrm{P\%}] \leq 430 \cdots\cdots (1)$$

$$0.008 \leq \mathrm{Ti}^* < 1.2[\mathrm{C\%}] \cdots\cdots (2)$$

, where Ti* = Ti - 3.4[N%].

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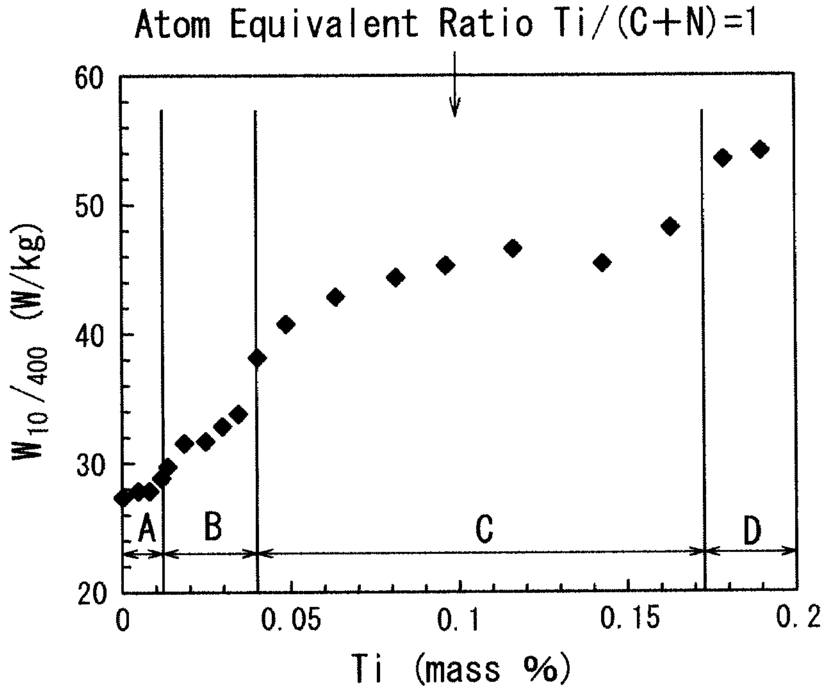
FIG. 2


Atom Equivalent Ratio Ti/(C+N)=1
60
50
40
30
20
W10/400 (W/kg)
A
B
C
D
0
0.05
0.1
0.15
0.2
Ti (mass %)

## Description

### TECHNICAL FIELD

**[0001]** The present invention relates to a non-oriented electrical steel sheet, and in particular, to a non-oriented electrical steel sheet having high strength and excellent fatigue properties, and furthermore, excellent magnetic properties that is suitably used for components that are subject to high stress, typically, drive motors for turbine generators, electric vehicles and hybrid vehicles, or rotors for high-speed rotating machinery, such as servo motors for robots, machine tools or the like, and a method for manufacturing the same. Additionally, the present invention provides the above-described non-oriented electrical steel sheet at low cost as compared to the conventional art.

### BACKGROUND ART

**[0002]** As recent advances in motor drive systems have enabled frequency control of drive power sources, more and more motors are offering variable-speed operation and enabling high-speed rotation at frequencies higher than the commercial frequency. In such motors enabling high-speed rotation, the centrifugal force acting on a rotating body is proportional to the radius of rotation and increases in proportion to the square of the rotational speed. Accordingly, in particular, rotor materials for middle- and large-sized high speed motors require high strength.

**[0003]** In addition, in IPM (interior permanent magnet)-type DC inverter control motors, which have been increasingly employed for motors in hybrid vehicles, such as drive motors or compressor motors, stress is concentrated on portions between grooves for embedding magnets in a rotor and the outer circumference of the rotor, or at narrow bridge portions of several millimeters width between the grooves for embedding magnets. Since motors can be reduced in size with increasing rotational speed, there is a growing demand for increasing the rotational speed of motors, such as in drive motors for hybrid vehicles with space and weight constraints. As such, high strength materials are advantageously used as core materials for use in rotors of high speed motors.

**[0004]** On the other hand, since rotating equipment such as motors or generators makes use of electromagnetic phenomenon, the core materials of iron cores of rotating equipment are also required to have excellent magnetic properties. In particular, it is necessary for rotors of high speed motors to assume low iron loss at high frequency; iron loss at high frequency would otherwise lead to a rise in core temperature due to the eddy current induced by a high-frequency magnetic flux, causing thermal demagnetization of embedded permanent magnets, reducing motor efficiency, and so on. Therefore, there is a demand for such an electrical steel sheet as a material for rotors that possesses high strength and excellent magnetic properties.

**[0005]** Steel-strengthening mechanisms include solid solution strengthening, precipitation strengthening, crystal grain refinement, work hardening, and so on. To date, a number of high-strength non-oriented electrical steel sheets have been considered and proposed to meet the needs, such as those of rotors of high speed motors.

As an example utilizing solid solution strengthening, for instance, JP 60-238421 A (PTL 1) proposes a method for increasing the strength of steel by adding elements such as Ti, W, Mo, Mn, Ni, Co or Al to the steel for the purposes of primarily increasing Si content from 3.5 % to 7.0 %, and furthermore, achieving solid solution strengthening. Moreover, in addition to the above-described strengthening methods, JP 62-112723 A (PTL 2) proposes a method for improving magnetic properties by controlling the crystal grain size in the range of 0.01 mm to 5.0 mm through manipulation of the final annealing conditions.

**[0006]** However, when these methods are applied to factory production, the factory production may be more prone to a trouble such as sheet fracture in a rolling line after hot rolling, which would cause a reduction in yield and production line stop by necessity. Sheet fracture may be reduced if cold rolling is performed in warm conditions at sheet temperatures of hundreds of degrees centigrade, in which case, however, process control issues will be of considerable concern, such as adaptation of the facility to warm rolling, tighter production constraints, and so on.

**[0007]** In addition, as a technique utilizing precipitation of carbonitrides, JP 06-330255 A (PTL 3) proposes a technique that makes use of strengthening by precipitation and grain refining effects provided by carbonitrides in steel, the steel containing Si in the range of 2.0 % or more and less than 4.0 %, C in the range of 0.05 % or less, and one or two of Nb, Zr, Ti and V in the range of $0.1 < (Nb + Zr) / 8(C + N) < 1.0$, and $0.4 < (Ti + V) / 4(C + N) < 4.0$. Similarly, JP 02-008346 A (PTL 4) proposes a technique, in addition to the features described in PTL 3, to add Ni and Mn in a total amount of 0.3 % or more and 10 % or less to steel for solid solution strengthening, and further add Nb, Zr, Ti and V in the same ratios as those described in PTL 3 to the steel, thereby balancing high strength with magnetic properties.

**[0008]** However, if these methods are applied to obtain high strength, problems arise that not only unavoidably cause a deterioration of magnetic properties, but also make the resulting products susceptible to surface defects such as scabs caused by precipitates, internal defects, and so on, resulting in lower product quality, and furthermore, prone to a reduction in yield due to removal of defects and a fracture trouble during production of steel sheets, resulting in an increased cost. In addition, the technique described in PTL 4 will lead to an even greater increase in cost because it involves adding an expensive solid-solution-strengthening element, such as Ni.

**[0009]** Further, as a technique utilizing work hardening, JP 2005-113185 A (PTL 5) proposes a technique for enhancing the strength of steel containing Si in the range of 0.2 % to 3.5 % by allowing worked microstructures to remain in the steel material. Specifically, PTL 5 discloses means that does not perform heat treatment after cold rolling, or, if it does, retains the steel material at 750 °C for 30 seconds at most, preferably at 700 °C or lower, more preferably at 650 °C or lower, 600 °C or lower, 550 °C or lower, and 500 °C or lower. PTL 5 reports the actual results indicating that the worked microstructure ratio is 5 % with annealing at 750 °C for 30 seconds, 20 % with annealing at 700 °C for 30 seconds, and 50 % with annealing at 600 °C for 30 seconds. In this case, there is a problem that such low annealing temperatures lead to insufficient shape correction of rolling strips. Improperly-shaped steel sheets have a problem that would lead to a lower stacking factor after worked into a motor core in a stacked fashion, a non-uniform stress distribution when rotating at high speed as a rotor, and so on. There is another problem that the ratio of worked grains to recrystallized grains varies greatly with the steel compositions and annealing temperatures, which makes it difficult to obtain stable properties. Further, a non-oriented electrical steel sheet is generally subjected to final annealing using a continuous annealing furnace, which is usually maintained in an atmosphere containing at least several percent of hydrogen gas in order to reduce oxidation of surfaces of the steel sheet. To carry out low-temperature annealing at temperatures below 700 °C in such a continuous annealing facility, there will be tremendous operational constraints, such as requirements of time-consuming switching of furnace temperature settings, replacement of the atmosphere in the furnace for avoiding hydrogen explosion, and so on.

**[0010]** In view of the aforementioned technical background, the inventors of the present invention proposed in JP 2007-186790 A (PTL 6) a high strength electrical steel sheet balancing the ability of shape correction of the steel sheet with the ability of strengthening by non-recrystallized microstructures during final annealing, which steel sheet is obtained by adding Ti sufficiently and excessively in relation to C and N to a silicon steel with reduced C and N contents and thereby raising the recrystallization temperature of the silicon steel. This method still has a difficulty in that it may increase alloy cost due to a relatively high Ti content, cause variations in mechanical properties due to the remaining recrystallized microstructures, and so on.

## CITATION LIST

### Patent Literature

**[0011]**

PTL 1: JP 60-238421 A
PTL 2: JP 62-112723 A
PTL 3: JP 6-330255 A
PTL 4: JP 2-008346 A
PTL 5: JP 2005-113185 A
PTL 6: JP 2007-186790 A

## SUMMARY OF INVENTION

### (Technical Problem)

**[0012]** As described above, some proposals have been made on high-strength non-oriented electrical steel sheets. In the proposals made to date, however, it has not been possible until now to manufacture, with the use of an ordinary facility for manufacturing electrical steel sheets, such a high-strength non-oriented electrical steel sheet in an industrially stable manner with good yield and at low cost that has good magnetic properties in addition to high tensile strength and high fatigue strength, and furthermore, satisfy the quality requirements of steel sheet, such as those relating to surface defects, internal defects, sheet shape or the like. Particularly, the high-strength electrical steel sheets that have so far been provided for rotors of high speed motors are in a situation where the resulting rotors will be subject to unavoidable heat generation due to their magnetic property, i.e., high iron loss at high frequency, which necessarily poses limitations on the design specification of the motors.

**[0013]** Therefore, an object of the present invention is to provide a high-strength non-oriented electrical steel sheet at low cost, having excellent magnetic properties and quality of steel sheet, and a method for manufacturing the same. Specifically, an object of the present invention is to provide means for manufacturing such a non-oriented electrical steel sheet in an industrially stable manner and yet at low cost that has both a tensile strength of 650 MPa or more, desirably 700 MPa or more, and good low iron loss properties at high frequency such that, for example, a steel material having a sheet thickness of 0.35 mm has a value of $W_{10/400}$ of 40 W/kg or lower, desirably 35 W/kg or lower.

(Solution to Problem)

**[0014]** The inventors of the present invention made intensive studies on high-strength electrical steel sheets that can achieve the above-described objects at a high level and methods for manufacturing the same. As a result, the inventors have revealed that the amount and ratio of Ti and C to be added to steel are deeply concerned with the balance between the strength properties and the magnetic properties of an electrical steel sheet, and that a high-strength electrical steel sheet having excellent properties may be manufactured in an stable manner and at low cost by optimizing the amount of precipitation of Ti carbides.
That is, the present invention relies upon the following findings:

(A) The growth of crystal grains of an electrical steel sheet during final annealing may be inhibited by the presence of a relatively small amount of Ti carbides, whereby strengthening by refinement of crystal grains may be achieved.
(B) The presence of excessive Ti carbides does not contribute to effective inhibition of the growth of crystal grains, but rather has adverse effects such as causing more surface defects and internal defects, degrading quality of steel sheet, contributing to origins of fracture, and so on. To this extent, surface defects such as scabs and internal defects are significantly reduced by controlling the amount of Ti to be added to the steel within an appropriate range. On the other hand, Ti nitrides are formed at higher temperatures than Ti carbides. Thus, they are less effective for inhibiting the growth of crystal grains and not useful for crystal grain refinement control intended by the present invention. Therefore, in an approach for inhibiting the growth of crystal grains by controlling the amount of Ti carbides, it is desirable to reduce the N content in a stable manner. This is entirely different from the conventional approaches utilizing strengthening by precipitation, where the effects of C and N are dealt with in the same manner.
(C) In a steel sheet with refined crystal grains, solute C has an effect of not only enhancing tensile strength, but also improving fatigue properties essentially required for a rotor material rotating at high speed.
(D) Major alloy components that are normally added for the purpose of reducing iron loss by increasing the electrical resistance of an electrical steel sheet are Si, Al and Mn. These three substitutional alloy elements also have an effect of implementing solid solution strengthening of steel. Accordingly, the balance between high strength and low iron loss is effectively ensured on the basis of the solid solution strengthening by these elements. However, there is a limit in adding these elements since excessive addition leads to embrittlement of steel and poses difficulty in manufacturing steel. Si-based addition is desirable for satisfying the requirements of solid solution strengthening, lower iron loss and productivity in most efficient way.

**[0015]** Based on these findings, the inventors of the present invention found that a properly balanced utilization of solid solution strengthening with the use of the substitutional alloy elements mainly composed of Si, crystal grain refinement with Ti carbides, and solid solution strengthening with an interstitial element of C may provide a non-oriented electrical steel sheet that has high strength, excellent fatigue properties under the conditions of use, and furthermore, excellent magnetic properties and quality of steel sheet, without substantially adding extra constraints on manufacture of steel sheets or additional steps to the normal production of non-oriented electrical steel sheets, and also found a method necessary for manufacturing the same. As a result, the inventors accomplished the present invention.
**[0016]** That is, the primary features of the present invention are as follows.

(i) A non-oriented electrical steel sheet comprising, by mass%:

Si: 5.0 % or less;
Mn: 2.0 % or less;
Al: 2.0 % or less; and
P: 0.05 % or less,
in a range satisfying formula (1), and the steel sheet further comprising, by mass%:
C: 0.008 % or more and 0.040 % or less;
N: 0.003 % or less; and
Ti: 0.04 % or less,
in a range satisfying formula (2), the balance being composed of Fe and incidental impurities:

$$300 \le 85[Si\%] + 16[Mn\%] + 40[Al\%] + 490[P\%] \le 430 \cdots (1)$$

$$0.008 \le Ti^* < 1.2[C\%] \cdots (2)$$

where Ti* = Ti - 3.4[N%], and
the [Si%], [Mn%], [Al%], [P%], [C%] and [N%] represent the contents (mass%) of the indicated elements, respectively.

**[0017]** (ii) The non-oriented electrical steel sheet according to (i) above, wherein the Si, Mn, Al and P contents are, by mass%,
Si: more than 3.5 % but not more than 5.0 %,
Mn: 0.3 % or less,
Al: 0.1 % or less, and
P: 0.05 % or less.

**[0018]** (iii) The non-oriented electrical steel sheet according to (i) or (ii) above, further comprising, by mass%, at least one of:

Sb: 0.0005 % or more and 0.1 % or less;
Sn: 0.0005 % or more and 0.1 % or less;
B: 0.0005 % or more and 0.01 % or less;
Ca: 0.001 % or more and 0.01 % or less;
REM: 0.001 % or more and 0.01 % or less;
Co: 0.05 % or more and 5 % or less;
Ni: 0.05 % or more and 5 % or less; and
Cu: 0.2 % or more and 4 % or less.

**[0019]** (iv) A method for manufacturing a non-oriented electrical steel sheet, comprising:

subjecting a steel slab to soaking, where the steel slab is retained at a soaking temperature of 1000 °C to 1200 °C, the steel slab containing, by mass%,
Si: 5.0 % or less,
Mn: 2.0 % or less,
Al: 2.0 % or less, and
P: 0.05 % or less,
in a range satisfying formula (1), and the steel slab further containing, by mass%,
C: 0.008 % or more and 0.040 % or less,
N: 0.003 % or less, and
Ti: 0.04 % or less,
in a range satisfying formula (2);
subjecting the steel slab to subsequent hot rolling to obtain a hot-rolled steel material;
then subjecting the steel material to cold rolling or warm rolling once, or twice or more with intermediate annealing performed therebetween, to be finished to a final sheet thickness; and
subjecting the steel material to final annealing, wherein prior to the final annealing, the steel material is subjected to heat treatment at least once where the steel material is retained at temperatures of 800 °C or higher and 950 °C or lower for 30 seconds or more, and subsequently to the final annealing at 700 °C or higher and 850 °C or lower:

$$300 \leq 85[\mathrm{Si\%}] + 16[\mathrm{Mn\%}] + 40[\mathrm{Al\%}] + 490[\mathrm{P\%}] \leq 430 \cdots\cdots (1)$$

$$0.008 \leq \mathrm{Ti}^* < 1.2[\mathrm{C\%}] \cdots\cdots (2)$$

, where Ti* = Ti - 3.4[N%].

**[0020]** (v) The method for manufacturing a non-oriented electrical steel sheet according to (iv) above, wherein the Si, Mn, Al and P contents are, by mass%,
Si: more than 3.5 % but not more than 5.0 %,
Mn: 0.3 % or less,
Al: 0.1 % or less, and
P: 0.05 % or less.

**[0021]** (vi) The method for manufacturing a non-oriented electrical steel sheet according to (iv) or (v) above, wherein the steel slab further contains, by mass%, at least one of:

Sb: 0.0005 % or more and 0.1 % or less;
Sn: 0.0005 % or more and 0.1 % or less;
B: 0.0005 % or more and 0.01 % or less;
Ca: 0.001 % or more and 0.01 % or less;
REM: 0.001 % or more and 0.01 % or less;
Co: 0.05 % or more and 5 % or less;
Ni: 0.05 % or more and 5 % or less; and
Cu: 0.2 % or more and 4 % or less.

(Advantageous Effect of Invention)

**[0022]** According to the present invention, a non-oriented electrical steel sheet may be provided that is excellent in both mechanical properties and magnetic properties required for a rotor material of motors rotating at high speed, and that has excellent quality of steel sheet in terms of scab, sheet shape, and so on. The present invention also allows stable production of such non-oriented electrical steel sheets with high yield, without incurring a significant increase in cost or imposing severe constraints on manufacture or requiring extra steps, as compared to the normal production of non-oriented electrical steel sheets. Therefore, the present invention is applicable in the field of motors, such as drive motors of electric vehicles and hybrid vehicles or servo motors of robots and machine tools, where demand for higher rotational speed is expected to grow in the future. Thus, the present invention has a high industrial value and makes a significant contribution to the industry.

BRIEF DESCRIPTION OF THE DRAWING

**[0023]** The present invention will be further described below with reference to the accompanying drawings, wherein:

FIG. 1 is a graph illustrating the relationship between Ti content and tensile strength;
FIG. 2 is a graph illustrating the relationship between Ti content and iron loss; and
FIG. 3 is a graph illustrating the relationship between Ti content and surface scab defect rate.

DESCRIPTION OF EMBODIMENTS

**[0024]** The experimental results underlying the present invention will be described in detail below.
That is, the inventors of the present invention investigated in detail how Ti, which is a major carbonitride forming element, affects the quality of steel sheet in terms of strengthening by precipitation, recrystallization, grain growth behavior, scabs, and so on. As a result, it was found that Ti has significantly different effects, in particular, when added so that the resulting Ti content is equal to or less than a total content of C and N in atomic fraction, and has an optimum range of addition for satisfying the requirements at a high level regarding high strength as well as magnetic properties and quality of steel sheet. The major experimental results will be described below. The percentage "%" of each steel component represents "mass%," unless otherwise specified.

<Experiment 1>

**[0025]** Steel samples, which have steel compositions mainly composed of silicon (Si): 4.0 % to 4.1 %, manganese (Mn): 0.03 % to 0.05 %, aluminum (Al): 0.001 % or less, phosphorus (P): 0.007 % to 0.009 %, and sulfur (S): 0.001 % to 0.002 %, containing substantially constant amounts of carbon (C): 0.024 % to 0.026 % and nitrogen (N): 0.001 % to 0.002 %, and different amounts of titanium (Ti) in the range of 0.001 % to 0.36 %, were obtained by steelmaking in a vacuum melting furnace. These steel samples were heated to 1100 °C and then subjected to hot rolling to be finished to a thickness of 2.1 mm, respectively. Then, the steel samples were subjected to hot band annealing at 900 °C for 90 seconds and further to cold rolling to be finished to a thickness of 0.35 mm, after which the occurrence of scab defects on the surfaces of the steel sheets (scab size per unit area) was determined. Subsequently, the steel samples were subjected to final annealing at 800 °C for 30 seconds and evaluated for their mechanical properties (by using JIS No. 5 tensile test specimens cut parallel to the rolling direction) and magnetic properties (by using Epstein test specimens cut in the rolling direction and transverse direction, measuring iron loss $W_{10/400}$ with a magnetizing flux density of 1.0 T and frequency of 400 Hz). The research results of tensile strength, magnetic property and occurrence of surface scab defect are depicted in FIGS. 1, 2 and 3 as a function of Ti content, respectively.
**[0026]** Firstly, as illustrated in FIG. 1, tensile strength increases with addition of Ti. However, it was found that this effect is less pronounced within a Ti content range indicated by "A" (Range A) in FIG. 1 where Ti content is smaller, while stable improvements in strength are observed within a Ti content range indicated by "B" (Range B) in the figure.

Additionally, even further improvements in strength are achieved within a range indicated by "C" (Range C) in the figure where Ti content is higher. Upon observation of steel structure in these regions, it was found that in Range B, the steel structure contains homogeneous microstructures with a crystal grain size of 10 μm or less, whereas in Range A, it involves crystal grains grown more than in Range B, particularly, mixed-grain-size microstructures with partial grain growth. On the other hand, in Range C, the steel structure assumes a multi-phase of non-recrystallized grains and recrystallized grains.

**[0027]** FIG. 2 illustrates the relationship between Ti content and iron loss $W_{10/400}$. While good iron loss properties are obtained in Range A with the lowest iron loss, as illustrated in FIG. 1, Range A shows lower strength levels. On the other hand, while high strength materials are obtained in Range C and D in FIG. 2, iron loss is also high in these ranges. In contrast, Range B offers materials that have iron loss properties almost as good as in Range A, while yielding strength results comparable to those obtained in Range C.

**[0028]** On the other hand, as illustrated in FIG. 3, the scab defect rate starts to increase when Ti content exceeds 0.04 %, and continues to rise up to around a point at which the equivalent ratio of elements of Ti to C and N is equal to 1, where a substantially constant rate of scab generation is reached. Assuming constant C and N contents, the amount of Ti carbonitride precipitates continues to increase up to around a point at which this equivalent ratio of elements is equal to 1, and then remains constant. Thus, it is considered that the amount of Ti carbonitride precipitates is related to the amount of scab generation.

These results revealed that by controlling Ti content within range B, it becomes possible to balance high strength and low iron loss, while reducing scab defects that would otherwise cause a reduction in yield and a sheet fracture trouble and be directly linked to an increase in manufacturing cost. That is, it is advantageous to contain Ti in an amount of 0.04 % or less in terms of reducing scab defects, provided that it is sufficient for forming a certain amount of Ti carbonitrides.

**[0029]** In addition, as a result of further studies conducted with the same components except for the above-described steel and N content and with varying N contents, it was also found that the lower limit of Ti content to which high strength can be obtained increases with increasing N contents. Still further studies revealed that it is necessary to satisfy a relation of $0.008 \le Ti^*$ (where $Ti^* = Ti - 3.4[N\%]$). From this, it is believed that since Ti carbides make a large contribution to enhancement of strength while Ti nitrides contribute less, control of Ti carbides is more important.

**[0030]** These results revealed that by controlling Ti content at a level of Range B, it becomes possible to balance high strength and low iron loss, while reducing scab defects that would otherwise cause a reduction in yield and a sheet fracture trouble and be directly linked to an increase in manufacturing cost.

<Experiment 2>

**[0031]** Then, to investigate details of the influence of Ti carbonitrides, steel samples having compositions shown in Table 1 were prepared by steelmaking in a vacuum melting furnace to obtain steel sheets, each having a sheet thickness of 0.35 mm, following the same procedure as in Experiment 1. C and N contents of steel samples were varied using steel sample "a," which has small C and N contents, as a reference. Steel samples "c" and "d" contain C and N so that the total content thereof is within a predetermined range. The surface scab defect rate, iron loss and tensile strength of the resulting samples are shown in Table 2. While steel samples "b," "c" and "d" show an increase in strength in relation to steel sample "a," comparing steel samples "c" and "d" having substantially the same total amount of C and N to evaluate the effect of addition of C and N, it can be seen that steel sample "c" having a lower N content has higher strength. Upon observation of microstructures, it was found that the steel samples are listed as a > d > b > c in descending order of crystal grain size, as is the case with in descending order of tensile strength.

**[0032]** [Table 1]

Table 1

| (mass%) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Steel | Si | Mn | Al | P | C | N | Ti |
| a | 4.33 | 0.07 | 0.0005 | 0.010 | 0.0019 | 0.0021 | 0.0302 |
| b | 4.32 | 0.05 | 0.0010 | 0.010 | 0.0240 | 0.0009 | 0.0295 |
| c | 4.29 | 0.03 | 0.0007 | 0.010 | 0.0293 | 0.0009 | 0.0298 |
| d | 4.25 | 0.08 | 0.0018 | 0.020 | 0.0249 | 0.0052 | 0.0301 |

**[0033]** [Table 2]

Table 2

| Steel | $W_{10/400}$ (W/kg) | Tensile Strength TS (MPa) | Fatigue Limit Strength FS (MPa) | Strength Ratio FS/TS | Surface Scab Defect Rate (m/m$^2$) |
|---|---|---|---|---|---|
| a | 26.9 | 641 | 535 | 0.83 | 0.000 |
| b | 33.0 | 722 | 630 | 0.87 | 0.003 |
| c | 32.5 | 730 | 665 | 0.91 | 0.003 |
| d | 31.0 | 676 | 540 | 0.80 | 0.004 |

**[0034]** These samples were further investigated for their fatigue properties. Tests were conducted in a tension-to-tension mode with a stress ratio of 0.1 at a frequency of 20 Hz, where the fatigue limit strength is defined as a stress which allows a sample to survive 10 million stress amplitude cycles. The results thereof are also shown in Table 2. While a tendency is observed that materials having a higher tensile strength TS possess a higher fatigue limit strength FS, the strength ratio FS/TS differs for different materials. In this case, steel sample "c" gave the best result. On the other hand, steel sample "d" does not improve so much in fatigue limit strength for its high tensile strength. Given these circumstances, and as a result of our detailed investigations of the microstructures of steel sample "d," many precipitates, presumably TiN precipitates having a grain size of greater than 5 $\mu$m were scattered over the microstructures, and these precipitates were estimated as contributing to origins of fatigue fracture. It should be noted here that nitrogen reacts with titanium at relatively high temperatures of 1100 °C or higher and tends to precipitate as TiN coarsely. It was thus believed that TiN tends to provide origins of fatigue fracture and is less effective as compared to Ti carbides for inhibiting the growth of crystal grains, which is one of the goals of the present invention.

**[0035]** On the other hand, when comparing steel samples "b" and "c," it was also found that steel sample "c" gives better results in terms of tensile strength and fatigue limit strength, and is particularly characterized by its relatively high fatigue limit strength and high strength ratio FS/TS. Since steel samples "b" and "c" have substantially the same Ti and N contents, they exhibit similar precipitation behavior of Ti nitrides and Ti carbides. It is thus believed that the difference between them is attributed to the difference in the amount of solute carbon. Accordingly, it is estimated that the presence of solute carbon reduced the occurrence and propagation of cracks and increased fatigue limit strength by locking dislocations introduced during repeated stress cycles such as found in fatigue test. Therefore, it is also important to ensure formation of solute carbon.

**[0036]** Based on the above-described experimental results, the inventors of the present invention made further studies on how these factors including Ti carbides, Ti nitrides and solute carbon, with the addition of a relatively small amount of Ti, affect the steel structure, quality of steel sheet surface, as well as mechanical properties and magnetic properties of steel sheets. As a result, the inventors discovered the rules comprehensively applicable to these factors and accomplished the present invention.

**[0037]** The present invention will now be described in detail below for each requirement.

Firstly, the grounds for the limitations with regard to the major steel components are described.

Steel of the present invention contains Si: 5.0 % or less, Mn: 2.0 % or less, Al: 2.0 % or less, and P: 0.05 % or less in a range satisfying formula (1):

$$300 \leq 85[\mathrm{Si}\%] + 16[\mathrm{Mn}\%] + 40[\mathrm{Al}\%] + 490[\mathrm{P}\%] \leq 430 \cdots\cdots (1)$$

**[0038]** An object of the present invention is to provide an electrical steel sheet having high strength and excellent magnetic properties at low cost. To this end, it is necessary to achieve solid solution strengthening above a certain level by means of the above-described four major alloy components. Thus, it is important to specify the contents of the four major alloy components as described later, and to add these components to the steel so that the total amount of these alloy components is within a range satisfying the above formula (1), considering individual contributions to solid solution strengthening. That is, if formula (1) gives a result less than 300, the strength of the resulting material is insufficient, whereas if formula (1) gives a result more than 430, there are more troubles with sheet cracking at the time of manufacture of steel sheets, leading to a deterioration in productivity and a significant increase in manufacturing cost.

**[0039]** Next, the grounds for the limitations on the individual contents of the four major alloy components are described.

**Si ≤ 5.0 %**

**[0040]** Silicon (Si) is generally used as a deoxidizer and one of the major elements that are contained in a non-oriented electrical steel sheet and have an effect of increasing the electrical resistance of steel to reduce its iron loss. Further, Si has high solid solution strengthening ability. That is, Si is an element that is positively added to the non-oriented electrical steel sheet because it is capable of achieving higher tensile strength, higher fatigue strength and lower iron loss at the same time in a most balanced manner as compared to other solid-solution-strengthening elements, such as Mn, Al or Ni, that are added to the non-oriented electrical steel sheet. To this end, it is advantageous to contain Si in steel in an amount of 3.0 % or more, more preferably exceeding 3.5 %. However, above 5.0 %, toughness degradation will be pronounced, which should necessitate highly-sophisticated control during sheet passage and rolling processes, resulting in lower productivity. Therefore, the upper limit of the Si content is to be 5.0 % or less.

**Mn ≤ 2.0 %**

**[0041]** Manganese (Mn) is effective in improving hot shortness properties, and also has effects of increasing the electrical resistance of steel to reduce its iron loss and enhancing the strength of steel by solid solution strengthening. Thus, Mn is preferably contained in steel in an amount of 0.01 % or more. However, addition of Mn is less effective in improving the strength of steel as compared to Si and excessive addition thereof leads to embrittlement of the resulting steel. Therefore, the Mn content is to be 2.0 % or less.

**Al ≤ 2.0 %**

**[0042]** Aluminum (Al) is an element that is generally used in steel refining as a strong deoxidizer. Further, as is the case with Si and Mn, Al also has effects of increasing the electrical resistance of steel to reduce its iron loss and enhancing the strength of steel by solid solution strengthening. Therefore, Al is preferably contained in steel in an amount of 0.0001 % or more. However, addition of Al is less effective in improving the strength of steel as compared to Si and excessive addition thereof leads to embrittlement of the resulting steel. Therefore, the Al content is to be 2.0 % or less.

**P ≤ 0.05 %**

**[0043]** Phosphorus (P) is extremely effective in enhancing the strength of steel because it offers a significantly high solid solution strengthening ability even when added in relatively small amounts. Thus, P is preferably contained in steel in an amount of 0.005 % or more. However, excessive addition of P leads to embrittlement of steel due to segregation, causing intergranular cracking or a reduction in rollability. Therefore, the P content is limited to 0.05 % or less.

**[0044]** Additionally, among these major alloy elements Si, Mn, Al and P, a Si-based alloy design is advantageous for balancing solid solution strengthening/low iron loss and productivity in a most efficient way. That is, it is advantageous to contain Si in steel in an amount of more than 3.5 % for optimizing the balance of properties of the non-oriented electrical steel sheet, where the contents of the remaining three elements are preferably controlled as follows: Mn: 0.3 % or less, Al: 0.1 % or less, and P: 0.05 % or less. The grounds for the limitations on the upper limit are as described above.

**[0045]** In addition, C, N and Ti are also important elements in the present invention. This is because it is important to inhibit the growth of crystal grains during steel sheet annealing with the use of a proper amount of fine Ti carbides and to develop an ability of reinforcing crystal grain refinement. For this purpose, it is necessary to contain C: 0.008 % or more and 0.040 % or less, N: 0.003 % or less, and Ti: 0.04 % or less in steel, in a range satisfying formula (2):

$$0.008 \leq \mathrm{Ti}^* < 1.2[\mathrm{C}\%] \cdots\cdots (2)$$

where Ti* = Ti - 3.4[N%].

**0.008 % ≤ C ≤ 0.040 %**

**[0046]** Carbon (C) needs to be contained in steel in an amount of 0.008 % or more. That is, a carbon content of less than 0.008 % makes it difficult to provide stable precipitation of fine Ti carbides and results in an insufficient amount of solute C, in which case a further improvement in fatigue strength is no longer possible. On the other hand, excessive addition of C leads to a deterioration in magnetic properties, while becoming a factor responsible for an increase in cost, such as making work hardening more pronounced during cold rolling and causing sheet fracture, forcing more rolling cycles due to an increased rolling load, and so on. Therefore, the upper limit of C is limited to 0.04 %.

**N ≤ 0.003 %**

**[0047]** Nitrogen (N) forms nitrides with Ti, which are, however, formed at higher temperatures than Ti carbides. Thus, N is less effective in inhibiting the growth of crystal grains and not effective so much in refining crystal grains. Rather, N sometimes causes adverse effects such as providing origins of fatigue fracture. Therefore, N content is limited to 0.003 % or less. Additionally, without limitation, the lower limit is preferably about 0.0005 % in terms of steelmaking degassing ability and for avoiding a deterioration in productivity due to a long refining duration.

**Ti ≤ 0.04 %**

**[0048]** Control of titanium (Ti) carbides is important in the present invention. Ti tends to form nitrides rather than carbides at high temperatures. Thus, it is necessary to control the amount of Ti forming carbides. If the amount of Ti that is capable of forming carbides is denoted as Ti*, Ti* is represented as the Ti content minus the atom equivalent with N, namely:

$$\mathrm{Ti}^* = \mathrm{Ti} - 3.4[\mathrm{N}\%]$$

To allow the added Ti to precipitate as Ti carbides for enhancing the strength of steel, while inhibiting the growth of crystal grains for preventing an increase in iron loss of the steel, it is necessary to use a proper amount of C and satisfy $\mathrm{Ti}^* \geq 0.008$. On the other hand, if Ti content is increased in relation to C content, there is a reduction in the amount of solute C, in which case a further improvement in fatigue strength is no longer possible. Therefore, it is also necessary to satisfy $\mathrm{Ti}^* < 1.2[\mathrm{C}\%]$ at the same time.

**[0049]** In addition, if Ti content exceeds 0.04 %, as previously described with reference to FIG. 3, more scab defects will occur and the quality of steel sheet and yield will be reduced, resulting in an increase in cost. Therefore, the upper limit of Ti content is to be 0.04 %.

**[0050]** The present invention may also contain elements other than the aforementioned elements without impairing the effects of the invention. For example, the present invention may contain: antimony (Sb) and tin (Sn), each of which has an effect of improving magnetic properties of steel, in the range of 0.0005 % to 0.1 %; boron (B), which has an effect of enhancing grain boundary strength of steel, in the range of 0.0005 % to 0.01 %; Ca and REM, each of which has an effect of controlling the form of oxide and sulfide and improving magnetic properties of steel, in the range of 0.001 % to 0.01 %; Co and Ni, each of which has an effect of improving magnetic flux density of steel, in the range of 0.05 % to 5 %; and Cu, which is expected to provide strengthening by precipitation by means of aging precipitation, in the range of 0.2 % to 4 %, respectively.

**[0051]** The grounds for the limitations with regard to a manufacturing method according to the present invention will now be described below. In the present invention, the manufacturing process from steelmaking to cold rolling may be performed in accordance with methods commonly used for manufacturing general non-oriented electrical steel sheets. For example, steel, which was prepared by steelmaking and refined with predetermined components in a converter or electric furnace, may be subjected to continuous casting or blooming after ingot casting to obtain steel slabs, which in turn may be subjected to process steps, including hot rolling, optional hot band annealing, cold rolling, final annealing, insulating coating application and baking, and so on to manufacture steel sheets. In these steps, the conditions for properly controlling the precipitation state will be described below. It should be noted that hot band annealing may optionally be carried out after the hot rolling, and that the cold rolling may be performed once, or twice or more with intermediate annealing performed therebetween.

**[0052]** The steel slabs composed of the aforementioned chemical compositions are to be subjected to hot rolling at a slab heating temperature of 1000 °C or higher to 1200 °C or lower. That is, if the slab heating temperature is below 1000 °C, it is not possible to achieve an effect of inhibiting the growth of crystal grains during final annealing in a sufficient manner due to the precipitation and growth of Ti carbides during slab heating. Alternatively, if the slab heating temperature is above 1200 °C, this is not only disadvantageous in terms of cost, but also causes slab deformation due to a reduction in strength at high temperature, which interferes with, e.g., extraction of the steel slabs from the heating furnace, resulting in lower operability. Therefore, the slab heating temperature is to be within the range of 1000 °C to 1200 °C. Additionally, the hot rolling itself is not limited to a particular type and may be performed under the conditions of, for example, hot rolling finishing temperature in the range of 700 °C to 950 °C and coiling temperature of 750 °C or lower.

**[0053]** Then, the resulting hot rolled steel materials are subjected to optional hot band annealing and cold rolling or warm rolling once, or twice or more with intermediate annealing performed therebetween to be finished to a final sheet thickness before final annealing. Prior to the final annealing, it is important to subject the steel materials to heat treatment at least once where the steel materials are retained at temperatures of 800 °C or higher and 950 °C or lower for 30 seconds or more. This heat treatment may allow precipitation of Ti carbides in microstructures prior to the final annealing and thereby inhibit the growth of crystal grains during final annealing.

**[0054]** That is, if the above-described heat treatment is performed at temperatures below 800 °C, the resulting precipitation may be insufficient, while above 950 °C, the effect of inhibiting the growth of crystal grains during final annealing would be insufficient due to the growth of precipitates.

**[0055]** Additionally, the aforementioned heat treatment is preferably performed in combination with either hot band annealing or intermediate annealing prior to the final annealing.

**[0056]** The subsequent final annealing may be performed at 700 °C or higher and 850 °C or lower to thereby control the microstructure of recrystallized grains into a homogeneous and fine state, providing an electrical steel sheet having high strength and excellent magnetic properties. If the final annealing is performed at temperatures below 700 °C, the resulting recrystallization is insufficient, while above 850 °C, crystal grains are prone to grow even when applying the present invention, resulting in a reduction in strength of the products. Following this final annealing, the steel materials are subjected to processes for applying and baking insulating coating thereon to obtain final products.

[Example 1]

**[0057]** Steel samples having compositions shown in Table 3 were obtained by steelmaking in a vacuum melting furnace, heated to 1100 °C, and then subjected to hot rolling to be a thickness of 2.1 mm. Then, the samples were subjected to hot band annealing at 900 °C for 90 seconds and further to cold rolling to be finished to a thickness of 0.35 mm. At this moment, an evaluation was made of the occurrence of scab defects on the surfaces of the steel sheets, using the scab size per unit area as a reference. Subsequently, the samples were subjected to final annealing for 30 seconds under two different conditions at 750 °C and 800 °C, respectively. Then, test specimens were cut parallel to the rolling direction from the steel sheet samples thus obtained for tensile test and fatigue test. In addition, the magnetic properties were evaluated based on the iron loss with a magnetizing flux density of 1.0 T and frequency of 400 Hz of the Epstein test specimens that were cut from the samples in the rolling direction and transverse direction, respectively. The evaluation results are shown in Table 4.

**[0058]** [Table 3]

Table 3

| (mass %) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Steel | Si | Mn | Al | P | C | N | Ti | Formula (1) | Ti* | Remarks |
| 1 | 4.08 | 0.08 | 0.0010 | 0.012 | 0.0250 | 0.0015 | 0.0010 | 354 | -0.0041 | Comparative Example |
| 2 | 4.10 | 0.05 | 0.0010 | 0.010 | 0.0247 | 0.0013 | 0.0189 | 354 | 0.0145 | Inventive Example |
| 3 | 4.05 | 0.04 | 0.0004 | 0.018 | 0.0251 | 0.0016 | 0.0349 | 354 | 0.0295 | Inventive Example |
| 4 | 4.08 | 0.05 | 0.0015 | 0.011 | 0.0245 | 0.0012 | 0.0641 | 353 | 0.0600 | Comparative Example |
| 5 | 4.02 | 0.04 | 0.0020 | 0.017 | 0.0258 | 0.0017 | 0.1164 | 351 | 0.1106 | Comparative Example |
| 6 | 4.07 | 0.08 | 0.0019 | 0.014 | 0.0260 | 0.0019 | 0.1630 | 354 | 0.1565 | Comparative Example |

**[0059]** [Table 4]

Table 4

| Steel | Surface Scab Defect Rate ($m/m^2$) | 800 °C Annealing | | | | 750 °C Annealing | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $W_{10/400}$ (W/kg) | Tensile Strength TS (MPa) | Fatigue Limit Strength FS (MPa) | Strength Ratio FS/TS | $W_{10/400}$ (W/kg) | Tensile Strength TS(MPa) | Fatigue Limit Strength FS (MPa) | Strength Ratio FS/TS | |
| 1 | 0.000 | 27.4 | 634 | 540 | 0.85 | 33.4 | 707 | 570 | 0.81 | Comparative Example |
| 2 | 0.000 | 31.5 | 710 | 635 | 0.89 | 33.9 | 727 | 650 | 0.89 | Inventive Example |
| 3 | 0.005 | 33.7 | 715 | 650 | 0.91 | 34.6 | 731 | 665 | 0.91 | Inventive Example |
| 4 | 0.159 | 42.7 | 722 | 600 | 0.83 | 44.4 | 737 | 620 | 0.84 | Comparative Example |
| 5 | 0.189 | 46.5 | 726 | 560 | 0.77 | 48.3 | 744 | 575 | 0.77 | Comparative Example |
| 6 | 0.211 | 48.0 | 734 | 565 | 0.77 | 51.0 | 750 | 580 | 0.77 | Comparative Example |

**[0060]** It can be seen from Table 4 that Steel Sample No. 1, which has a Ti* value out of the scope of the present invention, exhibits significantly different properties depending on the final annealing temperatures, which is considered problematic in terms of quality control. On the other hand, steel samples containing a proper amount of Ti show smaller difference in their properties depending on the final annealing temperatures, yielding high tensile strength in a stable manner. However, as compared to Steel Sample No. 2 and 3 having steel compositions within the range specified by the present invention, Steel Sample No. 4, 5 and 6, each having a Ti content out of the scope of the present invention, exhibit not so high fatigue limit strength for their high tensile strength and have inferior scab rate and magnetic properties.

[Example 2]

**[0061]** Steel samples having compositions shown in Table 5 were obtained by steelmaking in a vacuum melting furnace, heated to 1050 °C, and then subjected to hot rolling to be a thickness of 2.1 mm. Then, the samples were subjected to hot band annealing at 850 °C for 120 seconds and further to cold rolling to be finished to a thickness of 0.35 mm. At this moment, an evaluation was made of the occurrence of scab defects on the surfaces of the steel sheets, using the scab size per unit area as a reference. Subsequently, the steel samples were subjected to final annealing at 800 °C for 30 seconds. Then, test specimens were cut parallel to the rolling direction from the steel sheet samples thus obtained for tensile test and fatigue test. In addition, the magnetic properties were evaluated based on the iron loss with a magnetizing flux density of 1.0 T and frequency of 400 Hz of the Epstein test specimens that were cut from the samples in the rolling direction and transverse direction, respectively. The results thereof are also shown in Table 6.
Additionally, Steel Sample No. 18, which does not satisfy the relation of formula (1) specified by the present invention, experienced sheet fracture during cold rolling, and so was not subjected to the subsequent evaluation process.

**[0062]** [Table 5]

Table 5

(mass%)

| Steel | Si | Mn | Al | P | C | N | Ti | Others | Formula (1) | Ti* | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 3.05 | 0.15 | 0.3500 | 0.018 | 0.0165 | 0.0014 | 0.0174 | - | 284 | 0.0126 | Comparative Example |
| 8 | 3.75 | 0.08 | 0.0010 | 0.019 | 0.0043 | 0.0015 | 0.0172 | - | 329 | 0.0121 | Comparative Example |
| 9 | 3.78 | 0.05 | 0.0008 | 0.014 | 0.0159 | 0.0017 | 0.0166 | - | 329 | 0.0108 | Inventive Example |
| 10 | 4.01 | 0.04 | 0.0001 | 0.015 | 0.0135 | 0.0013 | 0.0154 | - | 349 | 0.0109 | Inventive Example |
| 11 | 4.01 | 0.04 | 0.0004 | 0.015 | 0.0320 | 0.0016 | 0.0148 | - | 349 | 0.0093 | Inventive Example |
| 12 | 4.05 | 0.05 | 0.0004 | 0.013 | 0.0572 | 0.0016 | 0.0166 | - | 351 | 0.0111 | Comparative Example |
| 13 | 4.03 | 0.01 | 0.0004 | 0.001 | 0.0175 | 0.0041 | 0.0168 | - | 343 | 0.0027 | Comparative Example |
| 14 | 4.82 | 0.04 | 1.0300 | 0.018 | 0.0158 | 0.0016 | 0.0188 | - | 419 | 0.0133 | Inventive Example |
| 15 | 3.02 | 0.88 | 0.7000 | 0.010 | 0.0289 | 0.0016 | 0.0333 | - | 317 | 0.0278 | Inventive Example |
| 16 | 3.55 | 0.59 | 1.2100 | 0.010 | 0.0294 | 0.0021 | 0.0328 | - | 344 | 0.0256 | Inventive Example |
| 17 | 4.30 | 0.11 | 0.1800 | 0.012 | 0.0285 | 0.0025 | 0.0322 | - | 380 | 0.0236 | Inventive Example |
| 18 | 4.60 | 0.59 | 1.2100 | 0.010 | 0.0296 | 0.0011 | 0.0311 | - | 454 | 0.0293 | Comparative Example |
| 19 | 4.03 | 0.15 | 0.0005 | 0.010 | 0.0144 | 0.0009 | 0.0244 | Sb: 0.015 | 350 | 0.0213 | Inventive Example |
| 20 | 4.11 | 0.08 | 0.0009 | 0.011 | 0.0167 | 0.0021 | 0.0217 | Sn: 0.043 | 356 | 0.0145 | Inventive Example |
| 21 | 4.30 | 0.18 | 0.2530 | 0.007 | 0.0145 | 0.0009 | 0.0191 | B: 0.003 | 382 | 0.0160 | Inventive Example |
| 22 | 4.25 | 0.09 | 0.2310 | 0.018 | 0.0181 | 0.0011 | 0.0155 | Ca: 0.003 | 381 | 0.0117 | Inventive Example |
| 23 | 4.22 | 0.15 | 0.0830 | 0.015 | 0.0226 | 0.0016 | 0.0185 | REM: 0.004 | 372 | 0.0130 | Inventive Example |
| 24 | 3.98 | 0.25 | 0.2250 | 0.013 | 0.0284 | 0.0018 | 0.0355 | Co: 0.25 | 358 | 0.0293 | Inventive Example |
| 25 | 4.05 | 0.20 | 0.2840 | 0.016 | 0.0133 | 0.0015 | 0.0211 | Ni: 0.15 | 367 | 0.0160 | Inventive Example |
| 26 | 3.87 | 0.18 | 0.2760 | 0.011 | 0.0336 | 0.0013 | 0.0347 | Cu: 0.22 | 348 | 0.0302 | Inventive Example |

**[0063]** [Table 6]

Table 6

| Steel | Surface Scab Defect Rate ($m/m^2$) | $W_{10/400}$ (W/kg) | Tensile Strength TS (MPa) | Fatigue Limit Strength FS (MPa) | Strength Ratio FS/TS | Remarks |
|---|---|---|---|---|---|---|
| 7 | 0.001 | 28.6 | 625 | 510 | 0.82 | Comparative Example |
| 8 | 0.000 | 32.7 | 673 | 535 | 0.79 | Comparative Example |
| 9 | 0.001 | 34.5 | 685 | 624 | 0.91 | Inventive Example |
| 10 | 0.005 | 32.2 | 708 | 631 | 0.89 | Inventive Example |
| 11 | 0.005 | 31.2 | 705 | 650 | 0.92 | Inventive Example |
| 12 | 0.230 | 38.7 | 694 | 575 | 0.93 | Comparative Example |
| 13 | 0.110 | 36.8 | 701 | 540 | 0.77 | Comparative Example |
| 14 | 0.005 | 28.8 | 779 | 715 | 0.92 | Inventive Example |
| 15 | 0.035 | 34.5 | 668 | 607 | 0.91 | Inventive Example |
| 16 | 0.026 | 33.3 | 703 | 645 | 0.92 | Inventive Example |
| 17 | 0.039 | 33.5 | 735 | 680 | 0.93 | Inventive Example |
| 18 | - | - | - | - | - | Comparative Example |
| 19 | 0.003 | 31.9 | 701 | 620 | 0.88 | Inventive Example |
| 20 | 0.004 | 31.2 | 707 | 635 | 0.90 | Inventive Example |
| 21 | 0.006 | 33.4 | 733 | 640 | 0.87 | Inventive Example |
| 22 | 0.003 | 31.6 | 729 | 640 | 0.88 | Inventive Example |
| 23 | 0.003 | 32.0 | 721 | 633 | 0.88 | Inventive Example |
| 24 | 0.007 | 33.3 | 723 | 645 | 0.89 | Inventive Example |
| 25 | 0.005 | 34.1 | 718 | 625 | 0.87 | Inventive Example |
| 26 | 0.008 | 33.5 | 706 | 608 | 0.86 | Inventive Example |

**[0064]** It can be seen from Table 6 that each of the steel sheets according to the present invention exhibits less scabs, good iron loss properties and high tensile strength, as well as high fatigue limit strength.

## Claims

**1.** A non-oriented electrical steel sheet comprising, by mass%:

Si: 5.0 % or less;
Mn: 2.0 % or less;
Al: 2.0 % or less; and
P: 0.05 % or less,
in a range satisfying formula (1), and the steel sheet further comprising, by mass%:
C: 0.008 % or more and 0.040 % or less;
N: 0.003 % or less; and
Ti: 0.04 % or less,
in a range satisfying formula (2), the balance being composed of Fe and incidental impurities:

$$300 \leq 85[Si\%] + 16[Mn\%] + 40[Al\%] + 490[P\%] \leq 430 \cdots\cdots (1)$$

$$0.008 \leq Ti^* < 1.2[C\%] \cdots\cdots (2)$$

, where Ti* = Ti - 3.4[N%].

**2.** The non-oriented electrical steel sheet according to claim 1, wherein the Si, Mn, Al and P contents are, by mass%,
Si: more than 3.5 % but not more than 5.0 %,
Mn: 0.3 % or less,
Al: 0.1 % or less, and
P: 0.05 % or less.

**3.** The non-oriented electrical steel sheet according to claim 1 or 2, further comprising, by mass%, at least one of:

Sb: 0.0005 % or more and 0.1 % or less;
Sn: 0.0005 % or more and 0.1 % or less;
B: 0.0005 % or more and 0.01 % or less;
Ca: 0.001 % or more and 0.01 % or less;
REM: 0.001 % or more and 0.01 % or less;
Co: 0.05 % or more and 5 % or less;
Ni: 0.05 % or more and 5 % or less; and
Cu: 0.2 % or more and 4 % or less.

**4.** A method for manufacturing a non-oriented electrical steel sheet, comprising:

subjecting a steel slab to soaking, where the steel slab is retained at a soaking temperature of 1000 °C to 1200 °C, the steel slab containing, by mass%,
Si: 5.0 % or less,
Mn: 2.0 % or less,
Al: 2.0 % or less, and
P: 0.05 % or less,
in a range satisfying formula (1), and the steel slab further containing, by mass%,
C: 0.008 % or more and 0.040 % or less,
N: 0.003 % or lees, and
Ti: 0.04 % or less,
in a range satisfying formula (2);
subjecting the steel slab to subsequent hot rolling to obtain a hot-rolled steel material;
then subjecting the steel material to cold rolling or warm rolling once, or twice or more with intermediate annealing

performed therebetween, to be finished to a final sheet thickness; and
subjecting the steel material to final annealing, wherein prior to the final annealing, the steel material is subjected to heat treatment at least once where the steel material is retained at temperatures of 800 °C or higher and 950 °C or lower for 30 seconds or more, and subsequently to the final annealing at 700 °C or higher and 850 °C or lower:

$$300 \leq 85[Si\%] + 16[Mn\%] + 40[Al\%] + 490[P\%] \leq 430 \cdots\cdots (1)$$

$$0.008 \leq Ti^* < 1.2[C\%] \cdots\cdots (2)$$

, where Ti* = Ti - 3.4[N%].

**5.** The method for manufacturing a non-oriented electrical steel sheet according to claim 4, wherein the Si, Mn, Al and P contents are, by mass%,
Si: more than 3.5 % but not more than 5.0 %,
Mn: 0.3 % or less,
Al: 0.1 % or less, and
P: 0.05 % or less.

**6.** The method for manufacturing a non-oriented electrical steel sheet according to claim 4 or 5, wherein the steel slab further contains, by mass%, at least one of:

Sb: 0.0005 % or more and 0.1 % or less,
Sn: 0.0005 % or more and 0.1 % or less,
B: 0.0005 % or more and 0.01 % or less,
Ca: 0.001 % or more and 0.01 % or less,
REM: 0.001 % or more and 0.01 % or less,
Co: 0.05 % or more and 5 % or less,
Ni: 0.05 % or more and 5 % or less, and
Cu: 0.2 % or more and 4 % or less.

FIG. 1

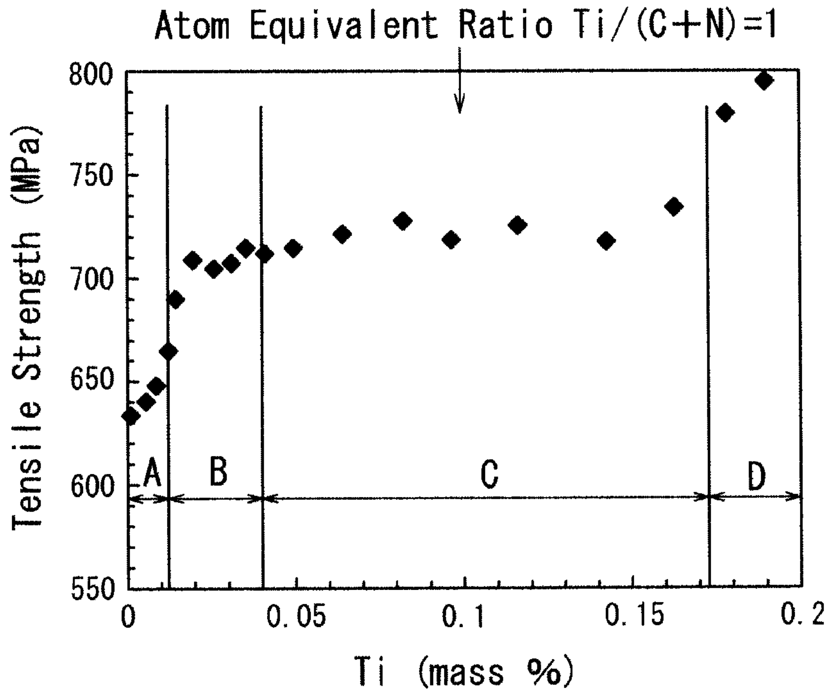

Atom Equivalent Ratio Ti/(C+N)=1
800
750
700
650
600
550
Tensile Strength (MPa)
A
B
C
D
0
0.05
0.1
0.15
0.2
Ti (mass %)

FIG. 2

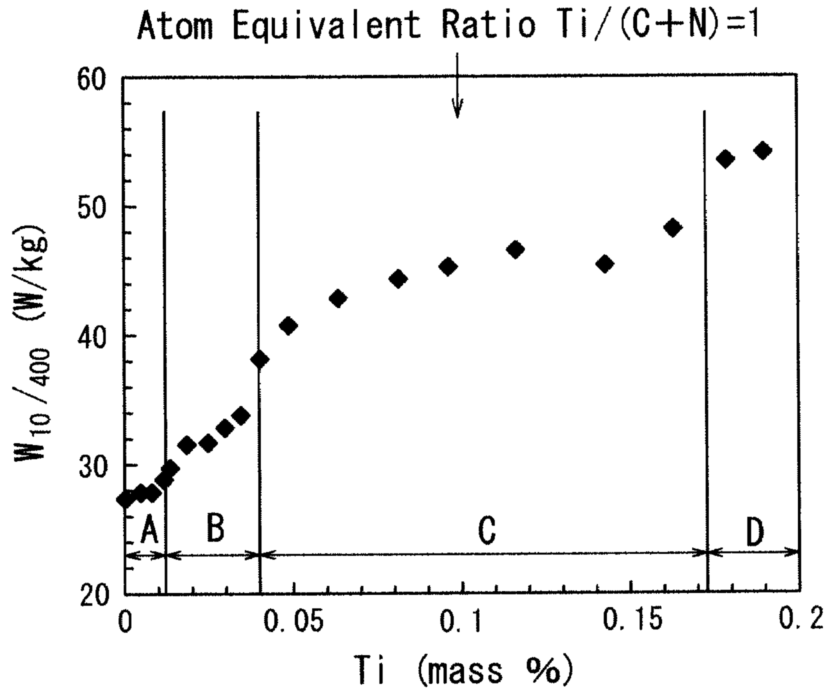
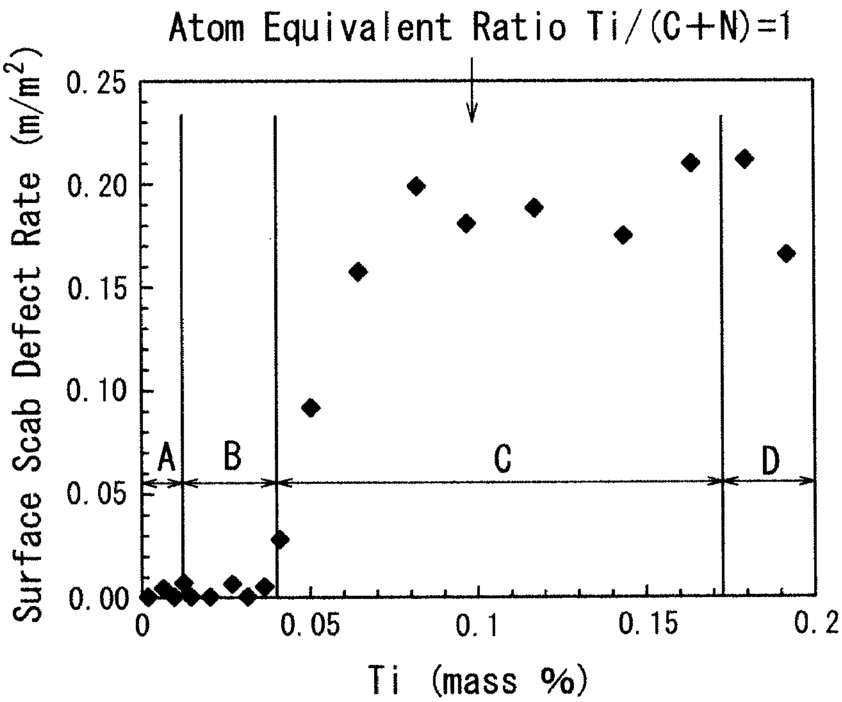

Atom Equivalent Ratio Ti/(C+N)=1
60
50
40
30
20
W10/400 (W/kg)
A
B
C
D
0
0.05
0.1
0.15
0.2
Ti (mass %)

FIG. 3


Atom Equivalent Ratio Ti/(C+N)=1
Surface Scab Defect Rate (m/m²)
0.25
0.20
0.15
0.10
0.05
0.00
A
B
C
D
0
0.05
0.1
0.15
0.2
Ti (mass %)

**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/JP2011/001074

A. CLASSIFICATION OF SUBJECT MATTER
*C22C38/00*(2006.01)i, *C21D8/12*(2006.01)i, *C22C38/60*(2006.01)i, *H01F1/16*
(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)
C22C38/00-38/60, C21D8/12, H01F1/16-1/18

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 | 1996-2011 |
| Kokai Jitsuyo Shinan Koho | 1971-2011 | Toroku Jitsuyo Shinan Koho | 1994-2011 |

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | JP 2008-240104 A (JFE Steel Corp.), 09 October 2008 (09.10.2008), claims 1 to 4 (Family: none) | 1-6 |
| E,X | JP 2011-46997 A (JFE Steel Corp.), 10 March 2011 (10.03.2011), claims 1 to 6 (Family: none) | 1-6 |

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