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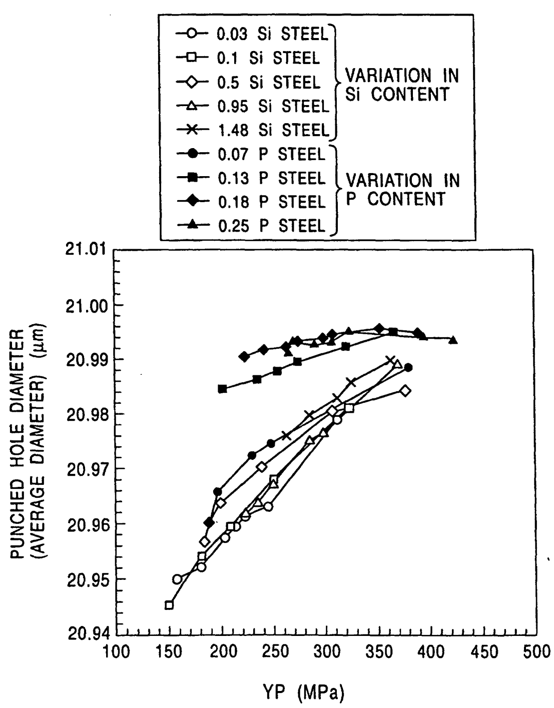
(54) **NONORIENTED ELECTROMAGNETIC STEEL SHEET**

(57) The present invention provides a non-oriented electrical steel sheet containing:

0-0.010% of C;
at least one of Si and Al in a total amount of 0.03% to 0.5%, or more than 0.5% to 2.5%;
0.5% or less of Mn;
0.10% or more to 0.26% or less of P;
0.015% or less of S; and
0.010% or less of N, on a mass percentage basis,

wherein the non-oriented electrical steel sheet has excellent dimensional accuracy during a punching step. When the Si content is low, the non-oriented electrical steel sheet has the excellent balance between high magnetic flux density and low core loss. When the Si content is medium or high, the non-oriented electrical steel sheet has the excellent balance between high magnetic flux density and high strength.

FIG. 1

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## Description

Technical Field

**[0001]** The present invention relates to non-oriented electrical steel sheets used for iron core materials for electric apparatus. In particular, the present invention relates to a non-oriented electrical steel sheet suitable for an iron core material for reluctance motors, IPM-type DC brushless motors, and the like, and relates to a method for manufacturing the non-oriented electrical steel sheet, wherein the reluctance and DC brushless motors need to have high dimensional accuracy in punching together with high magnetic flux density, and the DC brushless motors further need to have high strength.

Background Art

**[0002]** The non-oriented electrical steel sheet is of a soft magnetic material mainly used for iron cores of electric apparatus such as motors and transformers. In order to improve the efficiency and in order to miniaturize the electric apparatus, the non-oriented electrical steel sheet needs to have a small core loss and a high magnetic flux density. In the field of electric motors, magnetic characteristics of the non-oriented electrical steel sheet for iron cores are being improved, that is, the core loss is being lowered and the magnetic flux density is being increased. Conventional AC induction motors, which are of an asynchronous type, are being replaced with synchronous motors having high efficiency, and high-performance motors are being increased, rapidly.
**[0003]** Generally, a synchronous motor is classified into a DC brushless motor type and a reluctance motor type, wherein the DC brushless motor includes a surface permanent magnet (SPM) type and an interior permanent magnet (IPM) type, and the reluctance motor uses reluctance torque generated by the magnetic saliency of the rotor and the stator. Particularly, in the reluctance motor, the magnitude of the torque depends on the shapes of the rotor and the stator, the gap between the rotor and the stator, and the magnetic flux density of the materials. Accordingly, it is important for the iron core material for the reluctance motor to have high magnetic flux density and high dimensional accuracy in punching than other motors.
**[0004]** As motors having an inverter have been increasing, the rotational speed and the number of poles have been increasing in order to improve the motor efficiency and the torque. Since these factors raise the operating frequency, the non-oriented electrical steel sheet, which is a motor material, needs to be improved in magnetic characteristic not only at a conventional commercial frequency (50-60 Hz) but also at a high frequency of 400 Hz or higher.
**[0005]** In regard to the improvement of the magnetic flux density and the core loss, various efforts have been made.
**[0006]** In order to reduce the core loss of the non-oriented electrical steel sheet, the Si content is generally increased. For example, top-grade non-oriented electrical steel sheets have an Si content of about 3.5% by mass in some cases. However, when the Si content is increased, the core loss is lowered but the magnetic flux density is caused to decrease simultaneously.
**[0007]** On the other hand, since low-grade non-oriented electrical steel sheets have a small Si content, a relatively high magnetic flux density can be obtained. However, there is a problem in that the core loss is large.
**[0008]** In order to improve the core loss of such low-Si steel, the following technique is disclosed in Japanese Unexamined Patent Application Publication No. 62-267421: In a non-oriented electrical steel sheet having an Si content of 0.6% by mass or less and an Al content of 0.15-0.60% by mass, the content of impurities such as C, S, N, and O is lowered to reduce the quantity and the inhibition factors of inclusions inhibiting the crystal grain growth to promote the grain growth, thereby obtaining a small core loss. However, in the grain growth of such low-Si steel, since a decrease in strength arises, shear drop part and burr height of a punched sheet become large at a punching step. Therefore, there is a problem in that the punching properties such as the dimensional accuracy are significantly lowered.
**[0009]** In order to adjust the hardness of the low-Si steel to improve the punching properties, the following technique is proposed: the P content is controlled in a range of about 0.08-0.1% by mass. For example, the following technique is disclosed in Japanese Unexamined Patent Application Publication No. 56-130425: the punching properties are improved by adding P in an amount of less than 0.2% by mass. Among techniques in which P is aggressively added to low-Si steel, the following technique is disclosed in Japanese Unexamined Patent Application Publication No. 2-66138: P is added to Al-containing steel to improve the magnetic characteristics with the combined effects of Al and P, wherein the Si content in the steel is limited to 0.1% by mass or less and the Al content is in the range of 0.1-1.0% by mass.
**[0010]** However, among the above techniques, the technique for improving the punching properties by adding P is focused on reducing the burrs by adjusting the hardness but does not make any consideration for the dimensional accuracy in punching.
**[0011]** On the other hand, the interior permanent magnet-type DC brushless motor needs to have high punching accuracy and magnetic flux density in order to increase the torque and in order to downsize the motor constitution. Furthermore, the electrical steel sheet needs to have high strength in order to become possible to rotate in higher

speed of the rotor and in order to prevent the interior permanent magnet from being detached. As described above, high Si steel is advantageous from the point of view of the strength but low Si content steel is preferred from the point of view of the magnetic flux density. Thus, it is conventionally difficult to obtain high strength together with high magnetic flux density.

Disclosure of Invention

[Problems to be Solved by the Invention]

**[0012]** As described above, high magnetic flux density and low core loss are characteristics that are commonly preferred for all the applications of non-oriented electrical steel sheets, such as various motors and transformers. Among the characteristics, for a non-oriented electrical steel sheet used for reluctance motors, the high magnetic flux density and high dimensional accuracy are particularly important from the point of view of the operating principle.

**[0013]** However, a non-oriented electrical steel sheet having the following characteristics has not been found: excellent magnetic characteristics such as high magnetic flux density and low core loss, and superior punching properties that is, particularly high dimensional accuracy. In addition to these characteristics, another non-oriented electrical steel sheet further having the following characteristic has also not been found: high strength required for the interior permanent magnet-type DC brushless motor and the like.

**[0014]** In addition to these magnetic characteristics and punching properties, another non-oriented electrical steel sheet further having the following characteristics has also not been found: high-frequency characteristics adapted to the high-speed rotation of recent motors and to multipolar motors.

**[0015]** The present invention has been developed in view of the above situation, and it is an object of the present invention to provide non-oriented electrical steel sheets suitable for iron cores of motors and transformers and the like, and particularly to provide the following non-oriented electrical steel sheets:

- a non-oriented electrical steel sheet having superior magnetic characteristics, that is, high magnetic flux density together with low core loss more than ever, which are preferred for iron core materials, used for reluctance motors and the like, that need to have particularly high magnetic flux density and dimensional accuracy and further having high dimensional accuracy punching; and
- another non-oriented electrical steel sheet having high magnetic flux density and strength that is important to obtain high-speed rotation and to prevent interior permanent magnets from being detached and further having high dimensional accuracy in punching.

It is another object of the present invention to provide a method for manufacturing such non-oriented electrical steel sheets.

**[0016]** Hereinafter, steel having a total Si and Al content of 0.03 to 0.5% by mass is referred to as low-Si steel, and steel having a total Si and Al content of more than 0.5% by mass is referred to as medium-to-high Si steel for convenience.

[Means for Solving the Problems]

**[0017]** As a result of the intensive research conducted in order to obtain the above objects, the inventors have found that not only excellent magnetic characteristics such as high magnetic flux density and low core loss can be obtained but also dimensional accuracy in punching is significantly improved when steel having a small Si and Al content the same as that of low-Si steel and thus essentially having high magnetic flux density is manufactured to adjust the average crystal grain diameter within a predetermined range and to add P to the resulting steel in an appropriate amount. The inventors have also found that the addition of P in an appropriate amount in addition to the adjustment of the total Si and Al content within a range of more than 0.05% by mass to about 2.5% by mass provides a greatly increased strength without reducing the magnetic flux density, that is, unprecedented well-balanced magnetic and strength characteristics can be obtained, in addition to high dimensional accuracy in punching.

**[0018]** The present invention is based on the above findings.

**[0019]** The outline of the present invention is as follows.

1. A non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching containing:

 0-0.010% of C;
 at least one of Si and Al in a total amount of 0.03% to 0.5%;

0.5% or less of Mn;
0.10% or more to 0.26% or less of P;
0.015% or less of S; and
0.010% or less of N, on a mass percentage basis, the remainder being Fe and unavoidable impurities, and having:
an average crystal grain diameter of 30 µm or more to 80 µm or less.

2. In the above item 1, the non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching further containing:

at least one of Sb and Sn in a total amount of 0.40% or less on a mass percentage basis.

3. In the above item 1 or 2, the non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching further containing:

2.3% or less of Ni on a mass percentage basis.

4. In the above item 1, 2, or 3, the non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching further having a thickness of 0.35 mm or less.

5. A non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching containing:

0-0.010% of C;
at least one of Si and Al in a total amount of more than 0.5% to 2.5%;
0.5% or less of Mn;
0.10% or more to 0.26% or less of P;
0.015% or less of S;
0.010% or less of N; and
2.3% or less of Ni according to needs,

on a mass percentage basis, the remainder being Fe and unavoidable impurities, and satisfying:

at least one of the formula $P \leq P_A$ and the formula $P_F \leq 0.26$,

wherein

$$P_A = -0.2Si + 0.12Mn - 0.32Al + 0.05Ni^2 + 0.10Ni + 0.36 \quad (1);$$

and

$$P_F = -0.34Si + 0.20Mn - 0.54Al + 0.24Ni^2 + 0.28Ni + 0.76 \quad (2),$$

where the unit of each element content is mass%.

6. In the above item 5, the non-oriented electrical steel sheet having excellent magnetic properties and dimensional. accuracy in punching further containing:

at least one of Sb and/or Sn in a total amount of 0.40% or less on a mass percentage basis.

The above steels may further contain at least one selected from the group consisting of 0.01% or less of Ca, 0.005% or less of B, 0.1% or less of Cr, 0.1% or less of Cu, and 0.1% or less of Mo as an auxiliary component.

7. A method for manufacturing a non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching including the steps of:

hot-rolling a steel slab having the composition described in any one of the above items 1-3 under the conditions of a heating temperature in the single-phase austenite region and a coiling temperature of 650°C or less; and then
descaling the hot-rolled sheet to cold-roll the descaled sheet once or twice or more with an intermediate annealing therebetween to finish-anneal the cold-rolled sheet at a temperature of 700°C or more in the single-phase ferrite region.

8. A method for manufacturing a non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching including the steps of:

hot-rolling a steel slab having composition described in any one of the above items 1-3 under the conditions of a heating temperature in the single-phase austenite region and a coiling temperature of 650°C or less;
annealing the hot-rolled sheet at a temperature of 900°C or more in the single-phase ferrite region or at a temperature of more than the Ac3 transformation point in the single-phase austenite region if Ni is not contained (0%) or the Ni content is 1.0% by mass or less;
annealing the hot-rolled sheet at a temperature of more than the Ac3 transformation temperature in the single-phase austenite region if the Ni content is more than 1.0% to 2.3% by mass or less;
descaling the annealed sheet to cold-roll the descaled sheet once or twice or more with an intermediate annealing therebetween; and then
finish-annealing the cold-rolled sheet at a temperature of 700°C or more in the single-phase ferrite region.

9. A method for manufacturing a non-oriented electrical steel sheet having excellent magnetic properties and dimensional accuracy in punching including the steps of:

hot-rolling a steel slab having composition described in the above item 5 or 6 under the conditions of a heating temperature of 1000 to 1200°C and a coiling temperature of 650°C or less;
descaling the hot-rolled sheet to cold-roll the descaled sheet once or twice or more with an intermediate annealing therebetween; and then
finish-annealing the cold-rolled sheet.

**[0020]** In the method for manufacturing the electrical steel sheet recited in the above item 9, hot rolled steel sheets may be annealed after hot rolling.
**[0021]** In a method for manufacturing the electrical steel sheet recited in any one of the above items 7,8 and 9, treatment for providing an insulating coating may be performed after finish-annealing.

Brief Description of the Drawings

**[0022]**

FIG. 1 is a graph showing the effects of the Si content and the P content on the relationship between the yield strength and the punched hole diameter.
FIG. 2 is a graph showing the effects of the Si content and the P content on the relationship between the yield strength and the punching anisotropy.
FIG. 3 is a graph showing the effects of the Si content and the P content on the relationship between the average grain size and the punched hole diameter.
FIG. 4 is a graph showing the effects of the Si content and the P content on the relationship between the average grain size and the punching anisotropy.
FIG. 5 is a graph showing the effects of the Si content and the P content on the relationship between the average grain size and the core loss.
FIG. 6 is a graph showing the effects of the Si content and the P content on the relationship between the average grain size and the magnetic flux density.
FIG. 7 is a graph showing the effects of the Si content and the P content on the relationship between the core loss and the magnetic flux density.
FIG. 8 is a graph showing the effects of the Si content and the P content on the occurrence of a delamination crack.
FIG. 9 is a graph showing the effects of the Si content and the Ni content on the occurrence of the delamination

crack.

FIG. 10 is a graph showing the effects of the Si content and the Ni content on the relationship between the P content and the punched hole diameter.

FIG. 11 is a graph showing the effects of the Si content and the Ni content on the relationship between the P content and the punching anisotropy.

FIG. 12 is a graph showing the effect of the P content on the relationship between the tensile strength and the magnetic flux density.

FIG. 13 is a graph showing the relationship between the sheet thickness and the high-frequency core loss.

FIG. 14 is a graph showing the relationship between the sheet thickness and the magnetic flux density.

Best Mode for Carrying Out the Invention

**[0023]** The result of the experiments conducted in order to make the present invention will now be described. The unit % of the content described below means the unit "mass%".

[EXPERIMENT 1]

**[0024]** In order to clarify the relationship between the composition and the dimensional accuracy, during a punching process, of non-oriented electrical steel sheets, the following steel ingots were experimentally prepared: steel ingots having basic composition including a C content of 0.0016-0.0028%, an Mn content of 0.20-0.22%, an Al content of 0.0007-0.0014%, an N content of 0.0012-0.0022%, and an Sb content of 0.03%, which are approximately constant, and containing 0.02% of P and 0.03-1.49% of Si, wherein the P content is constant and the Si content is varied; and steel products having the above basic composition and containing 0.10-0.11% of Si and 0.02-0.29% of P, wherein the Si content is approximately constant and the P content is varied. These steel products were heated to 1100°C for 60 minutes and then hot-rolled so as to have a thickness of 2 mm. The hot-rolled sheets were treated in a soaking process under the conditions of a temperature of 600°C and a time of two hours, which correspond to the coiling conditions, and then air cooled. The resulting hot-rolled sheets were annealed at 900°C for 60 seconds, pickled, and cold-rolled so as to have a thickness of 0.5 mm. The cold-rolled sheets were finish-annealed at different temperatures of 700-900°C to form recrystallized crystal grains having different diameters. A semi-organic insulating coating having an average thickness of 0.6 μm was provided onto each finish-annealed sheet and then baked, and the baked sheets were used as samples for a punching test.

**[0025]** In each resulting sheet, a cross section in the thickness direction and parallel to the rolling direction was observed to obtain the average grain size corresponding to the diameter of a circle, determined by the Jeffries method.

**[0026]** In the punching test, a circular die having a diameter of 21 mm was used and the clearance was set to 8% of the thickness. The diameter (inner diameter) of a punched hole was measured in four directions that make angles of 0°, 45°, 90°, and 135° with respect to the rolling direction to determine the average of the four obtained diameters. The difference between the maximum and the minimum of the four diameters was determined to be used as the index of punching anisotropy.

**[0027]** FIGS. 1 and 2 show the relationship between the result of the above test and the yield strength (YP) obtained using tensile specimens (JIS No. 5) obtained by cutting the above steel sheets in the rolling direction.

**[0028]** As shown in FIGS. 1 and 2, as a whole, the soft samples having low YP each have a large difference between the die diameter and the punched hole diameter, and as YP increases, the punched hole diameter becomes closer to the die diameter, that is, the dimensional accuracy tends to improved. This tendency is considered to be due to the effect that shear drop deformation arising during the punching process is suppressed when the strength is large, as conventionally known.

**[0029]** However, it is worthy to note that the samples of which the strength is adjusted by changing the P content have superior dimensional accuracy as compared with the conventional electrical steel sheets of which the strength is adjusted by changing the Si content, when both have substantially the same strength. Furthermore, the above samples have a small difference between the die diameter and the punched hole diameter, even in the relatively low YP range (FIG. 1).

**[0030]** As shown in FIG. 2, in the steel sheets of which the strength is adjusted by changing the Si content, as the strength increases, the punched hole diameter becomes close to the die diameter, however the anisotropy that is a difference between the maximum diameter and the minimum diameter remains large. In contrast, in the steel sheets of which the strength is adjusted by changing the P content, the anisotropy of the shape of punched holes is remedied.

**[0031]** FIG. 3 shows the relationship between the punched hole diameter and the average crystal grain diameter of the finish-annealed steel sheets, and FIG. 4 shows the relationship between the anisotropy and the average crystal grain diameter (average grain size).

**[0032]** As shown in FIGS. 3 and 4, in the steel sheets of which the Si content is varied, the dimensional accuracy in punching and the punching anisotropy are deteriorated when the grain diameter is large. In contrast, in the steel sheet containing 0.13% or more of P, the dimensional accuracy in punching and the punching anisotropy are superior when the crystal grain diameter is large.

**[0033]** The phenomenon that the dimensional accuracy in punching and the punching anisotropy are remedied when the P content is a certain value or more is considered to be caused by the following effects functioning in cooperation, even though the detail is not clear:

(1) the effect that the strength is increased by adding P to suppress the shear drop deformation arising during the punching process;
(2) the effect that the punching fracture limit is lowered by adding P, known to function as an element that makes steel brittle, in a proper amount; and
(3) the effect that the grains having the {100} <uvw> orientation in the texture of the finish-annealed sheets tend to increase by adding P to remedy the anisotropy.

**[0034]** The result of studying the magnetic characteristics will now be described.

**[0035]** The inventors have studied the relationship between the manufacturing conditions and the magnetic characteristics using the steel sheets essentially having high magnetic flux density by minimizing the content of Si and Al, as much as possible, improving the core loss but lowering the saturation magnetic flux density.

**[0036]** FIG. 5 shows the relationship between the crystal grain diameter and the core loss ($W_{15/50}$: a value at a frequency of 50 Hz and a maximum magnetic flux density of 1.5 T) of the finish-annealed sheets for the samples having a thickness of 0.5 mm, wherein the core loss is measured at a commercial frequency band.

**[0037]** As shown in the figure, when the Si content is small, the core loss is large because the electrical resistance is decreased. However, since the core loss greatly changes depending on the crystal grain diameter, the core loss is stable and small when the crystal grain diameter is about 30 μm or more. It is also confirmed that the core loss is small when the grain diameter is about 30 μm or more in the case that the electrical resistance is lowered by reducing the Al content.

**[0038]** However, in the case of a non-oriented electrical steel sheet of the present invention, which is of a low grade in which the Si and Al content is small, it has been customary that the average crystal grain diameter of a finish-annealed sheet is limited to 15-25 μm. The reason is that the punching properties are deteriorated due to the low strength when grain grows, as indicated by the steel sheet sample (the symbol • in the figure) having an Si content of 0.11% and a P content of 0.07% shown in FIGS. 3 and 4.

**[0039]** In contrast, the steel sheets having a high P content have superior dimensional accuracy in punching even when the grain size is about 30 μm or more.

**[0040]** FIG. 6 shows the relationship between the average crystal grain diameter and the magnetic flux density of the steel sheets, and FIG. 7 shows the relationship between the core loss and the magnetic flux density. Herein, $B_{50}$ represents the magnetic flux density at a magnetizing force of 5000 A/m.

**[0041]** In the Si-containing samples, the core loss is improved but the magnetic flux density is significantly decreased. In contrast, in the P-containing samples, the magnetic flux density remains large when the core loss is improved due to the growth of the crystal grains.

**[0042]** Since P is an embrittling element, defects such as edge cracks and delamination cracks mainly arise during a cold-rolling process in some cases when the P content is large in the same manner as for the present invention. The inventors have intensively studied this phenomenon to obtain the following findings: when a slab is heated to a temperature in the ferrite-austenite coexisting region during a hot-rolling process, redistribution of P between austenite grains and ferrite grains to cause the significant segregation of P in the ferrite grains, thereby promoting the embrittlement of the slab. In order to prevent such embrittlement, the heating temperature of slabs during a hot-rolling step must be in the single-phase austenite region (or the single-phase ferrite region, if possible).

**[0043]** Since P is a ferrite-forming element, P has a function of reducing the single-phase austenite area at around the heating temperature of slabs. However, single-phase austenite can be obtained when the Si content is small and the heating temperature of slabs is 1000-1200°C.

**[0044]** As described above, it is clear that the addition of P to the low-Si steel sheets in an amount of about 0.1% or more is extremely effective. Therefore, the positive addition of P to steel sheets containing 0.5% or more of Si was investigated.

[EXPERIMENT 2]

**[0045]** Various types of steel products having the following composition were prepared: a C content of 0.0013-0.0026, an Mn content of 0.18-0.23%, an Al content of 0.0001-0.0011%, and an N content of 0.0020-0.0029%, which are approximately constant, and an Si content of 0.60-2.42 and a P content of 0.04-0.29%, wherein the P and Si content are varied. These steel products were heated to 1100°C for 60 minutes and then hot-rolled so as to have a thickness of 2 mm. The hot-rolled sheets were descaled, and then cold-rolled so as to have a thickness of 0.50 mm. The following defect arose depending on the steel composition: delamination cracks which are in the hot-rolled steel sheets and are parallel to the surfaces thereof. The result is shown in FIG. 8.

**[0046]** The mapping analysis of delamination crack portions was performed using EPMA. As a result, it was observed that P is segregated or concentrated at the delamination crack portions. The segregation conditions of P were investigated in detail, and it then became clear that a steel piece (slab) is reheated at a temperature in the ferrite-austenite double phase region under a soaking condition during a hot-rolling step, thereby causing P to be distributed to the ferrite phase to be concentrated.

**[0047]** That is, it became clear that the single austenite phase area is reduced since the content of Si and Al, which are ferrite-forming elements, is large in a medium-to-high Si range and therefore the ferrite-austenite double phase are readily formed at a heating temperature conventionally applied.

**[0048]** The steel sheets containing more than 0.26% of P had delamination cracks even if the steel sheets had any composition.

**[0049]** Steel products having a various Si, Mn, Al, P content were prepared in a laboratory to investigate the conditions of suppressing the segregation of P at a temperature range of about 1000-1200°C to the extent not to cause the rolling defect. The above slab-reheating temperature is preferable in view of the stable precipitation of carbides, nitrides, and sulfides contained in the steel products.

**[0050]** Since the segregation due to phase distribution does not arise under the condition that the slab-reheating temperature is in the single-phase austenite region or in the single-phase ferrite region, it is assumed that the formation of the delamination cracks can be avoided if the P content is smaller than a certain value. According to the above experiment, the P content needs to be 0.26% or less.

**[0051]** The conditions for obtaining single-phase austenite in the medium-to-high Si steel products were investigated.

**[0052]** As a result, in the steel products having an Si and Al total content of more than 0.5%, it became clear that single-phase austenite can be obtained when the P content satisfies the following formula:

$$P \leq P_A'$$

wherein

$$P_A' = -0.2Si + 0.12Mn - 0.32Al + 0.36 \qquad (1)'$$

(the unit of the content of Si, Mn, Al, and P is mass%). Accordingly, when the above condition is satisfied and the condition P ≤ about 0.26% is also satisfied, the embrittlement due to P can be suppressed.

**[0053]** The conditions for obtaining single-phase ferrite in the medium-to-high Si steel products were investigated in the same manner as the above. It then became clear that single-phase ferrite can be obtained when the P content satisfies the following formula:

$$P \geq P_F'$$

wherein

$$P_F' = -0.34Si + 0.20Mn - 0.54Al + 0.76 \qquad (2)'$$

(the unit of the content of Si, Mn, Al, and P is mass%). Accordingly, when this condition is satisfied and the condition P ≤ about 0.26% is also satisfied, the embrittlement due to P can be suppressed, too.

**[0054]** The conditions for achieving the following purpose were investigated: to suppress the segregation of P when it is difficult to heat a slab at a temperature in the single-phase austenite region or in the single-phase ferrite region. When the redistribution of P between the ferrite and austenite phases arises, the P content in the ferrite phase corresponds to the above $P_F'$. As a result of the above investigation, it became clear that the embrittlement due to P can be avoided when the above $P_F'$ is about 0.26 or less.

**[0055]** The conditions for avoiding the embrittlement in the double phase coexistent region and the conditions for avoiding the embrittlement in the single-phase ferrite region can be combined into the condition P ≤ about 0.26% and the condition $P_F' \leq$ about 0.26.

**[0056]** In summary, the conditions for avoiding the embrittlement due to P are as follows: P ≤ about 0.26%, and $P \leq P_A'$ or $P_F' \leq$ about 0.26.

**[0057]** According to the above results, the following findings can be obtained: steel sheets can be manufactured without causing defects such as delamination cracks after a cold rolling step when the steel sheets are heated at a temperature in the single-phase austenite region or in the single-phase ferrite region during a hot rolling step, and steel sheets can be manufactured when the Si content and the Al content are relatively large, that is, the quantity of P distributed to the ferrite phase is small, even if the steel sheets are heated at a temperature in the ferrite-austenite double phase region.

**[0058]** Furthermore, the inventors investigated such steel composition that the single-phase austenite or single-phase ferrite structure is formed in a slab-reheating temperature range (about 1000-1200°C) during a hot rolling step even if the P content is about 0.1% or more.

**[0059]** As a result, it became clear that the addition of Ni is effective in enhancing the austenite area at the hot-rolling temperature of P-containing steel, wherein Ni is an element suitable for improving the magnetic characteristics and suitable for maintaining the strength.

[EXPERIMENT 3]

**[0060]** The following steel samples were prepared: steel products having the basic composition including a C content of 0.0013-0.0026%, an Mn content of 0.18-0.23%, an Al content of 0.0007-0.0013%, an N content of 0.0014-0.0025%, and an P content of 0.16-0.18%, which are approximately constant, and containing 0.95-2.44% of Si and 0-2.20% of Ni, wherein the Si content and the Ni content are varied. The steel samples were rolled so as to have a thickness of 0.50 mm in the similar prosess as EXPERIMENT 2, and the delamination cracks in the obtained cold-rolled sheets were investigated. The results are shown in FIG. 9.

**[0061]** The steel sheets containing 1.1-1.5% of Si and no Ni have cracks, but the steel sheets containing 1.1-1.5% of Si and Ni have no cracks and thus the hot rolling is possible. On the other hand, the steel sheets containing 1.95% of Si and no Ni and the steel sheets containing 2.4% of Si and no Ni can be hot-rolled without cracks. However, when such steel sheets contains Ni in a large amount, the steel sheets have cracks in some cases. Thus, it is clear that there is an appropriate range of the Ni content in order to obtain the effect of Ni.

**[0062]** According to the above formulae, in consideration of the effect of Ni, it became clear that the embrittlement due to P can be avoided for the steel sheets having an Si and Al total content of more than 0.5% in the following cases: the P content is about 0.26% or less and $P \leq P_A$, wherein

$$P_A = -0.2Si + 0.12Mn - 0.32Al + 0.05Ni^2 + 0.10Ni + 0.36 \quad (1);$$

and the P content is about 0.26% or less and $P_F \leq$ about 0.26, wherein

$$P_F = -0.34Si + 0.20Mn - 0.54Al + 0.24Ni^2 + 0.28Ni + 0.76 \leq P \quad (2).$$

In the former case, the slab-reheating temperature, which is 1000-1200°C, is in the single-phase austenite region, and in the latter case, the degree of the concentration of P is small when the slab-reheating temperature is in the double phase region or in the single-phase ferrite region.

**[0063]** In the above formulae, the unit of the content of Si, Mn, Al, P, and Ni is mass%. The technical meanings of $P_F$ and $P_A$ are the same as those of $P_F'$ and $P_A'$ described above.

[EXPERIMENT 4]

**[0064]** The cold-rolled steel sheets, having a thickness of 0.50 mm, prepared in Experiments 2 and 3 were finish-annealed, and a semi-organic insulating coating having an average thickness of 0.6 μm was provided onto each resulting steel sheet and then baked. These samples were provided to the punching test according to the procedure described in Experiment 1 to investigate the punched hole diameters and the anisotropy thereof. The results are shown in FIGS. 10 and 11. As shown in the figures, among the steel sheets having an Si and Al total content of more than

0.5%, the steel sheets satisfying the condition P ≥ 0.10% have superior dimensional accuracy in punching. In the Ni-containing steel sheets, the Ni content varies for 0.38% to 2.20%.

**[0065]** FIG. 12 shows the relationship between the magnetic flux density $B_{50}$ and the tensile strength TS of these samples. The tensile strength was obtained from the same tensile test as in the Experiment 1, and the magnetic flux density was also obtained according to the procedure in the Experiment 1.

**[0066]** The steel sheets containing about 0.1% or more of P have good balance between the magnetic flux density $B_{50}$ and the tensile strength TS, as compared with conventional electrical steel sheets having a medium-to-high Si content (that is, Si + Al > 0.5%). Particularly, as the P content is increased, the tensile strength is increased and the magnetic flux density is not decreased but tended to increase. This is characteristic of the steel sheets as compared with conventional electrical steel sheets to which alloy elements such as Si and Al, which are not of a ferromagnetic material, are added to increase the strength thereof, wherein such a method causes a decrease in magnetic flux density.

**[0067]** These characteristics are suitable for rotor materials for various rotary machines (motors and generators) such as DC brushless motors and reluctance motors that need to have higher motor torque, smaller size, and higher-speed rotation.

**[0068]** According to the above findings, in order to obtain superior magnetic flux density together with dimensional accuracy in punching, the Si, Al, P, and Ni content of steel are limited to the following range. In addition, in case of low-Si steel, the average grain size of finish-annealed sheets are limited to the following range.

Total content of one or two of Si and Al in low-Si steel: about 0.03-0.5%

**[0069]** Since Si and Al in steel have a deoxidizing function, Si and Al are used as deoxidizing agents alone or in combination. In order to exert the function, the alone Si or Al content or the Si and Al total content must be about 0.03% or more. Si and Al have a function of increasing the resistivity and a function of improving the core loss. However, Si and Al decrease the saturation magnetic flux density. Thus, the upper limit of the content thereof is limited to 0.5%.

Total content of one or two of Si and Al in medium-to-high Si steel: more than 0.5% to about 2.5%

**[0070]** When steel needs to have high mechanical strength and low core loss together with superior dimensional accuracy, the Si and Al total content may exceed 0.5%. As described above, the medium-to-high Si steel having a large P content has high dimensional accuracy in punching and good balance between the strength and the magnetic flux density, as compared with conventional medium-to-high Si steel having a small P content. However, when the Si and Al total content exceeds 2.5%, it is difficult to cold-roll such steel by a method of the present invention. Thus, the content is limited to the range from more than 0.5% to about 2.5%.

P content: about 0.10% to about 0.26%

**[0071]** P is an especially important element in the present invention. P has high ability to promote the formation of a solid solution and therefore has a function of adjusting the steel strength, as previously known. In low-Si and low-Al steel sheets, which are relatively soft originally, since the average crystal grain diameter must be about 30 μm or more in order to obtain low core loss in the present invention, there is a problem in that the hardness is further decreased. P is essential to improve the punching accuracy, that is, to suppress the increase of shear drops and burrs caused by the insufficient strength of the steel sheets. In addition to such an ability to increase the steel strength, P has ability to decrease the rupture limit during a punching process to reduce the total quantity of the punching deformation and ability to increase the {100} <uvw> orientation in the texture of finish-annealed sheets. Therefore, P can improve the dimensional accuracy in punching with these effects.

**[0072]** Furthermore, P has the property of being able to increase the strength of steel sheets and not to decrease the magnetic flux density. In the medium-to-high Si steel, such effects can also be obtained.

**[0073]** In order to obtain such effects, the P content must be about 0.10% or more. In contrast, P is originally an element that makes steel brittle. Therefore, when the P content is excessively high, edge cracks and delamination cracks are readily formed, thereby lowering the productivity. In the present invention, high-P steel can be manufactured by improving a manufacturing method thereof and by adding Ni, wherein the production of such steel is conventionally thought to be difficult. However, when the P content exceeds 0.26%, the production of the high-P steel is difficult even if a manufacturing method according to the present invention is used. Thus, the P content is limited to the range from about 0.10% to about 0.26%.

Ni content: about 2.3% or less (Ni can be optionally contained)

**[0074]** Ni has not only a function of improving the texture of steel to increase the magnetic flux density but also functions such as a function of increasing the electrical resistance to decrease the core loss and a function of increasing the strength of steel by solid solution strengthening to reduce shear drops during a punching process or so. Therefore, Ni can be positively added to steel.

**[0075]** Since Ni is an element that contributes to form an austenite phase, Ni has a function of extending the austenite region (the $\gamma$-loop in the phase diagram) at about 1000-1200°C, wherein such a temperature range is suitable for heating a slab. Particularly, for steel having an Si and Al total content of more than 0.5%, Ni is effective in increasing the manufactural stability. When this effect is used, low manufactural stability during a hot-rolling step can be greatly improved, wherein such low manufactural stability arises when the P content is high. That is, in order to improve the manufactural stability of a high-P steel sheet, the excessive segregation of P must be suppressed during a hot-rolling step, and therefore the slab-reheating temperature must avoid the ferrite-austenite. double phase region, which is a key point. When the Si and Al total content exceeds 0.5%, the ferrite-austenite double phase is readily formed at the slab-reheating temperature. However, because Ni has an effect of extending the $\gamma$ region, the single austenite phase can be obtained during a slab-reheating step even if the Si and Al total content is in the above range.

**[0076]** However, when the Ni content exceeds about 2.3%, there is a risk that the magnetic flux density is lowered because the temperature at which transformation from the ferrite ($\alpha$) phase to the austenite ($\gamma$) phase starts is decreased to cause the austenite transformation to arise. Furthermore, in case of low-Si steel sheet, it is difficult to obtain an average crystal grain diameter of about 30 μm or more at a finish-annealing temperature lower than the transformation temperature, and thus, the core loss is decreased. Thus, the Ni content should be about 2.3% or less. When Ni is added to steel, the Ni content is preferably about 0.50% or more.

Average crystal grain diameter of finish-annealed sheet made of low-Si steel: from about 30 μm to about 80 μm

**[0077]** In a low-Si and low-Al non-oriented electrical steel sheet, in order to obtain superior core loss property, a finish-annealed sheet needs to have an average crystal grain diameter of 30 μm or more, as shown in FIG. 5. However, when the crystal grain diameter exceeds about 80 μm, further improved core loss cannot be obtained. furthermore, steel products according to the present invention are of transformable steel, and the single-phase ferrite region suitable for recrystallization-annealing is in a range of 700-900°C. Such a temperature range is relatively low as compared with that of ferrite steel having a high Si content, and therefore the excessive growth of crystal grains is disadvantageous to the productivity of a continuous short-time annealing facility. Thus, the upper limit of the crystal grain diameter is limited to about 80 μm.

**[0078]** In the medium-to-high Si steel, since the electrical resistance is improved due to alloy, relatively low core loss can be readily obtained. Thus, the crystal grain diameter is not particularly limited and may be in an ordinary range. Generally, the crystal grain diameter is about 20-200 μm.

**[0079]** The inventors have studied a method for improving the magnetic characteristics at a high frequency. Such characteristics have recently become important because the high-speed rotation and the increase of poles of motors have been advancing. As a result, it became clear that reducing the thickness is effective and the effect is particularly significant for low-Si steel. The experiment that provides the above result will now be described.

[EXPERIMENT 5]

**[0080]** FIG. 13 shows the dependency of the coreless with the sheet thickness, at 400 Hz, of the steel sheet containing 0.11% of Si and 0.18% of P, the steel sheet containing 0.95% of Si and 0.02% of P and the steel sheet containing 2.0% of Si and 0.5% of Al.

**[0081]** As shown in the figure, in all the samples, it is clear that the core loss at high frequency is improved because the eddy-current loss is decreased when the thickness is reduced, and that the effect of improving the core loss at high frequency by reducing the thickness is more significant than that in the low-Si steel.

**[0082]** However, conventionally, major non-oriented electrical steel sheets have a thickness of 0.50 mm. Only some of the high-grade non-oriented electrical steel sheets having a large content of Si and Al, which are elements increasing the resistivity, have a thickness smaller than 0.50 mm. There are no examples of such a thinner non-oriented electrical steel sheets having a small content of Si and Al.

**[0083]** FIG. 14 shows the dependency of the magnetic flux density with the thickness of these steel sheets.

**[0084]** As shown in the figure, when the thickness is reduced, the magnetic flux density is slightly decreased, wherein the degree of the decrease is very small. The steel sheet having a smaller Si content has a significantly larger magnetic flux density than that of the other steel sheets all over the thickness range. For applications such as driving motors for electric vehicles (EV) and hybrid electric vehicles (HEV) in particular, a high-speed rotation - type reluctance motor is being studied. In such an application, high magnetic flux density and low core loss at high frequency are important. Such characteristics can be obtained by reducing the thickness of a low-Si and low-Al steel sheet, essentially having high magnetic flux density, according to the present invention.

**[0085]** As shown in FIG. 13, when the thickness is about 0.35 mm or less, the effect of a reduction in thickness is significant. When the thickness is about 0.30 mm or less, the effect is further significant. Since the smaller thickness is more advantageous in order to reduce the eddy-current loss, the lower limit of the thickness is not particularly limited. However, when the thickness is excessively lowered, the number of man-hours needed to stack the cores is increased to raise the manufacturing cost and there is a problem in that it is difficult to interlock the stacked cores. Thus, the lower limit of the thickness is preferably about 0.10 mm for general applications.

**[0086]** The reason for limiting the upper and lower limits of the content of components other than Si, Al, and P in a steel sheet of the present invention will now be described. C content: 0 to about 0.010%

**[0087]** Element C having an age-hardening function deteriorates the magnetic characteristic (core loss) with the passage of time after the production of the steel sheet. Since the degree of the deterioration becomes significant when the C content exceeds about 0.010%, the C content is limited to 0.010% or less. In consideration of the deterioration due to the age-hardening function, smaller C content is more preferable. Thus, in the present invention, the C content may include substantially zero (below the lower limit of analysis).

Mn content: about 0.5% or less

**[0088]** Mn has a function of fixing S by reacting with S to form MnS, thereby preventing the embrittlement caused by FeS during a hot-rolling step. As the Mn content is increased, the resistivity is increased to improve the core loss. In contrast, the increase of the Mn content causes the decrease of the magnetic flux density. Thus, the upper limit of the Mn content is limited to about 0.5%.

S content: about 0.015% or less

**[0089]** S is an unavoidable impurity. When FeS is precipitated, S causes the embrittlement during a hot-rolling step, as described above and fine particles made of precipitated FeS prevent grain growth. In order to reduce the core loss, it is advantageous to minimize the S content as much as possible. Since the deterioration of the core loss becomes significant when the S content exceeds 0.015%, the upper limit thereof is limited to 0.015%. On the other hand, S has a function of improving the shape of a sheared surface during a punching step. Therefore, the extent of redusing S is determined depending on the applications.

N content: about 0.010% or less

**[0090]** N is also an unavoidable impurity. Fine particles made of precipitated AlN prevent crystal grain growth to increase the core loss. Thus, the N content is limited to 0.010% or less.

**[0091]** In the above description, the essential components and the components to be reduced are illustrated. In the present invention, the following elements may be further contained in an appropriate amount in order to improve the magnetic characteristics.

Sb and/or Sn content: in a total amount of about 0.40% or less

**[0092]** Sb and Sn are located at the grain boundaries and have a function of improving magnetic flux density and core loss by preventing {111}-oriented recrystallized nucleus from being formed at the grain boundaries during the recrystallization of steel. In order to obtain this effect, the total content is preferably 0.01% or more when these elements are contained alone or in combination. However, if the content is excessively increased, the effect is not greatly increased. When the content exceeds 0.40%, the embrittlement arises to cause cracks during a cold-rolling step. The total content is preferably 0.40% or less when the elements are contained alone or in combination.

**[0093]** Other auxiliary components will now be described.

**[0094]** In the present invention, Ca can be contained in an amount of about 0.01% or less, wherein Ca functions as a deoxidizing agent and effectively captures S, which is an impurity, together with Mn. Furthermore, B can be contained in an amount of about 0.005% or less and Cr can be contained in an amount of about 0.1% or less in order to suppress the oxidation and nitridation during stress relief annealing.

**[0095]** Known elements such as Cu and Mo that do not deteriorate the magnetic characteristics may be further contained, other than the above-mentioned elements. In such a case, the effects of the present invention are not deteriorated. In consideration of the manufacturing cost, the content of each element is preferably about 0.1% or less.

**[0096]** Other elements such as Ti, Nb, and V that form carbonitrides may be contained in a small amount and the content is preferably as small as possible in order to assure low core loss.

**[0097]** As described above, in the medium-to-high content range of Si, the excessive local segregation of P is suppressed to produce steel having high P content in a reproducible manner by performing the design for obtaining the following composition: the composition in which either one of the single ferrite or austenite phase can be obtained at a slab-reheating temperature; or the composition in which the concentration of P distributed into the ferrite phase, in which P is more readily concentrated, is suppressed when there is the austenite-ferrite duplex phase.

**[0098]** Specifically, in order to suppress the excessive local segregation of P at a slab-reheating temperature (about 1000-1200°C) which is suitable for allowing carbides, nitrides, and sulfides, which are contained in the steel, to stably precipitate, the following condition is satisfied:

the index $P_A$ expressed by the following formula:

$$P_A = -0.2Si + 0.12Mn - 0.32Al + 0.05Ni^2 + 0.10Ni + 0.36 \quad (1)$$

and
the P content satisfy the following condition:

$$P \leq P_A;$$

or
the index $P_F$ expressed by the following formula:

$$P_F = -0.34Si + 0.20Mn - 0.54Al + 0.24Ni^2 + 0.28Ni + 0.76 \quad (2),$$

satisfies the following condition:
$P_F \leq$ about 0.26
where the unit of Si, Mn, Al, Ni, and P is mass%. In the above formulae, the index $P_A$ corresponds to the upper limit of the P content experimentally determined using various steel products having a different content of Si, Mn, Al, and Ni so as to obtain the single austenite phase at a temperature of about 1000-1200.°C. The index $P_F$ corresponds to the lower limit of the P content experimentally determined so as to obtain the single ferrite phase.

**[0099]** Next, production conditions of the present invention will now be described.

**[0100]** Molten steel having the above preferable composition is prepared by a converter-refining method, an electric furnace-melting method or the like to manufacture a slab by a continuous casting method or an ingot-blooming method.

**[0101]** The slab is then heated and then hot-rolled. In order to allow carbides, nitrides, and sulfides in the slab to stably precipitate, the preferable temperature is about 1000-1200°C. As described above, the state of the phase is important in order to suppress the excessive local segregation of P.

**[0102]** Since P is an element that contributes to form the ferrite phase, P has a function of reducing the single-phase austenite region close to the slab-reheating temperature. In the case of low-Si steel, however, when the composition is within the scope of the present invention, the single austenite phase can be obtained at a slab-reheating temperature of about 1000-1200°C. Furthermore, in the case of medium-to-high Si steel, when the composition satisfies the condition $P \leq P_A$, the single austenite phase can be obtained at a slab-reheating temperature of about 1000-1200°C. Furthermore, in the case of medium-to-high Si steel, when the composition satisfies the condition $P_F \leq$ about 0.26, the degree of the segregation of P in the ferrite phase is in such a range that the embrittlement can be avoided, even if the ferrite-austenite coexisting phase is formed. When the slab is heated at a temperature in the single-phase ferrite region, a steel sheet can be made without forming delamination cracks if the P content is about 0.26% or less.

**[0103]** In the present invention, the coiling temperature is also an important factor in order to manufacture a high-P steel sheet. That is, when the coiling temperature is high, iron phosphide ($Fe_3P$) is formed to deteriorate the bending properties and the rolling properties of the hot-rolled sheet. Therefore, the coiling temperature is about 650°C or less, preferably about 600°C or less, and more preferably about 550°C or less. That is, the winding is preferably performed at a temperature as low as possible. It is effective that the coil is acceleratingly cooled by such a method that the coil is soaked in a water bath or water is sprayed on the coil.

**[0104]** The hot-rolled coil is descaled by a pickling method or the like and then subjected to a cold-rolling step. In order to further increase the magnetic characteristics, the resulting hot-rolled coil may be annealed.

**[0105]** In low-Si steel having an Si and Al total content of 0.5% or less, the hot-rolled sheet is preferably annealed at a temperature outside the ferrite-austenite coexisting region (two-phase coexisting region). The reason is that the magnetic characteristics such as the magnetic flux density are not improved because the crystal grains cannot sufficiently grow at an annealing temperature in the two-phase coexisting region. The suitable annealing temperature of the hot-rolled sheets made of the low-Si steel will now be described on an Ni content basis.

**[0106]** A steel sheet containing no Ni or a steel sheet having a relatively small Ni content of 1.0% or less can be annealed at such a temperature that is about 900°C and is within the single-phase ferrite region in the same manner as that a hot-rolled non-oriented electrical steel sheet is usually annealed. The annealing temperature can be increased to such a temperature that is higher than the Ac3 transformation point and in the single-phase austenite region (preferably about 1050-1100°C): It is important to avoid an annealing temperature (particularly about 950°C) in the duplex region, which is the intermediate region between the two regions.

**[0107]** On the other hand, when the Ni content is more than 1.0% to 2.3%, which is relatively high, an annealing temperature of about 900°C corresponds to the duplex region since the austenite-forming temperature is lowered, thereby decreasing the magnetic flux density. However, since the crystal grains cannot sufficiently grow at an annealing temperature is 900°C or less, single-phase ferrite region, high magnetic flux density cannot be achieved. Thus, the annealing temperature of the hot-rolled sheet having this content is limited to such a temperature that is in the single-phase austenite region (preferably about 1050-1100°C) which is the Ac3 transformation point or more.

**[0108]** In the medium-to-high Si steel sheet, the grain growth during an annealing step is not an important factor as compared with the low-Si steel sheet because low core loss can be achieved if the grain diameter is small. Thus, the annealing temperature of the hot-rolled sheet is not particularly limited and is preferably 700-1100°C usually.

**[0109]** Subsequently, the obtained coil is descaled and then cold or warm-rolled once, or cold-rolled (or warm-rolled) twice or more with an intermediate annealing step therebetween so as to have a predetermined thickness.

**[0110]** The finish-annealing is then performed. In the case of the low-Si steel sheet, the finish-annealing is preferably performed at such a temperature that is 700°C or more and is in the single-phase ferrite region. The reason is as follows: it is difficult to make the crystal grains to uniformly grow so as to have an average diameter of about 30 μm or more when the annealing temperature is less than 700°C, and the texture is deteriorated to decrease the magnetic flux density and to increase the core loss when the annealing temperature exceeds the single-phase ferrite region to form austenite grains.

**[0111]** In the medium-to-high Si steel sheet, the grain growth during an annealing step is not an important factor as compared with the low-Si steel sheet, as described above. Thus, the finish-annealing temperature is not particularly limited and is preferably 700-1100°C usually.

**[0112]** In the hot-rolled sheets and the cold-rolled sheets, the temperature region in which single-phase ferrite or single-phase austenite is formed can be obtained by observing samples with an optical microscope, wherein the samples are prepared by heating and then water-cooling the pieces of each steel sheet having certain composition. Alternatively, the temperature region can be estimated using a computational phase diagram obtained with a softwear for thermodynamic calculation, for example, Thermo-Calc™.

**[0113]** After the finish-annealing, an insulating coating may be provided onto the steel sheet in the same manner as for ordinary non-oriented electrical steel sheets. The providing method is not particularly limited. The following procedure is preferable: the application of a coating solution and the baking treatment are performed in that order.

**[0114]** The obtained coil is slit into strips having a desired width and length. The strips are punched into pieces having shapes of motor stators and rotors, and the resulting pieces are then stacked to form products, by users. In some cases, stress relief annealing will be carried out to these stacked cores (usually at 750°C for 1-2 hours), and then used for manufacturing products.

[EXAMPLES]

[Example 1]

**[0115]** Each molten steels having the composition shown in Table 1 were experimentally casted. The obtained ingots were hot-rolled into a sheet bar having a thickness of 30 mm. The sheet bar was heated at 1100°C for 60 minutes and then hot-rolled so as to have a thickness of 2 mm. The hot-rolled sheet was maintained at 600°C for two hours in a soaking step and was then air cooled, wherein such conditions correspond to coiling conditions. The hot-rolled sheet was annealed at 950°C for 60 second, pickled, and then cold-rolled (once) so as to have a thickness of 0.50 mm. The cold-rolled sheet was finish-annealed at various temperatures of 700-900°C to obtain different recrystallized grain diameters. During the cold-rolling step, since many delamination-cracks parallel to a sheet surface were formed in the sample steel J in which P content exceeded invention range, subsequent treatment and the evaluation were not performed.

**[0116]** The samples No. 56-59 were each prepared by the following procedure: a sheet bar was hot-rolled and then cold-rolled twice with an intermediate annealing step therebetween at 800°C, without annealing the hot-rolled sheet.

**[0117]** A semi-organic insulating coating was provided onto the finish-annealed sheet so as to have an average thickness of 0.6 μm to form samples, which were used in various tests.

**[0118]** In a punching test, a circular die having a diameter of 21 mm was used and the clearance was set to 8% of the thickness. The diameter (inner diameter) of a punched hole was measured in four directions that make angles of 0°, 45°, 90°, and 135° with respect to the rolling direction to determine the average of the four obtained diameters. The difference between the maximum and the minimum of the four diameters was measured to use as the index of punching anisotropy.

**[0119]** The magnetic properties were measured by the Epstein method, using rectangular specimens having a length of 180 mm and a width of 30 mm, wherein the rolling direction makes an angle of 0° with respect to the longitudinal direction of one of the specimens and makes an angle of 90° with respect to the longitudinal direction of another.

**[0120]** The yield point (YP) was measured by a tensile test method at a crosshead speed of 10 mm/min. using a JIS No. 5 specimen of which the longitudinal direction is parallel to the rolling direction, and the upper yield stress was employed.

**[0121]** The obtained result is shown in Tables 2 and 3.

Table 1

| Steel ID | Composition (mass%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Al | Mn | S | P | N | Sb | Sn |
| A | 0.0027 | 0.03 | 0.0008 | 0.21 | 0.0040 | 0.02 | 0.0015 | 0.030 | <0.001 |
| B | 0.0026 | 0.10 | 0.0008 | 0.22 | 0.0035 | 0.02 | 0.0020 | 0.032 | <0.001 |
| C | 0.0019 | 0.53 | 0.0012 | 0.22 | 0.0023 | 0.02 | 0.0018 | 0.030 | <0.001 |
| D | 0.0019 | 0.95 | 0.0007 | 0.20 | 0.0033 | 0.02 | 0.0012 | 0.030 | <0.001 |
| E | 0.0022 | 1.48 | 0.0014 | 0.21 | 0.0041 | 0.02 | 0.0022 | 0.033 | <0.001 |
| F | 0.0016 | 0.11 | 0.0015 | 0.20 | 0.0074 | 0.07 | 0.0019 | 0.030 | <0.001 |
| G | 0.0017 | 0.11 | 0.0008 | 0.21 | 0.0036 | 0.13 | 0.0022 | 0.031 | <0.001 |
| H | 0.0023 | 0.11 | 0.0011 | 0.22 | 0.0022 | 0.18 | 0.0014 | 0.030 | <0.001 |
| I | 0.0028 | 0.11 | 0.0006 | 0.22 | 0.0075 | 0.25 | 0.0018 | 0.031 | <0.001 |
| J | 0.0016 | 0.11 | 0.0014 | 0.21 | 0.0060 | 0.29 | 0.0016 | 0.032 | <0.001 |

Table 2

| No. | Steel ID | Grain Diame ter (μm) | $B_{50}$ (T) | $W_{15/50}$ (W/kg) | YP (MPa) | Punched Hole Diameter (mm) | Punched hole diameter Max - min (μm) | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1 | A | 11.3 | 1.818 | 9.79 | 311 | 20.979 | 17 | CE*1 |
| 2 | A | 20.5 | 1.811 | 6.85 | 243 | 20.963 | 21 | CE*1 |
| 3 | A | 28.2 | 1.807 | 5.90 | 214 | 20.959 | 28 | CE*1 |
| 4 | A | 31.9 | 1.804 | 5.45 | 204 | 20.957 | 29 | CE*1 |
| 5 | A | 42.8 | 1.797 | 5.09 | 182 | 20.952 | 25 | CE*1 |
| 6 | A | 61.3 | 1.785 | 4.62 | 160 | 20.950 | 34 | CE*1 |
| 7 | B | 10.8 | 1.808 | 10.23 | 322 | 20.981 | 16 | CE*1 |
| 8 | B | 20.3 | 1.806 | 6.85 | 249 | 20.968 | 14 | CE*1 |
| 9 | B | 26.8 | 1.801 | 5.99 | 223 | 20.961 | 18 | CE*1 |
| 10 | B | 31.5 | 1.796 | 5.52 | 210 | 20.959 | 19 | CE*1 |
| 11 | B | 46.2 | 1.786 | 4.94 | 183 | 20.954 | 23 | CE*1 |
| 12 | B | 78.2 | 1.775 | 4.50 | 152 | 20.945 | 26 | CE*1 |

(1*) CE represents the term "Comparative Example".

Table 2 (continued)

| No. | Steel ID | Grain Diame ter (μm) | $B_{50}$ (T) | $W_{15/50}$ (W/kg) | YP (MPa) | Punched Hole Diameter (mm) | Punched hole diameter Max - min (μm) | Remarks |
|---|---|---|---|---|---|---|---|---|
| 13 | C | 9.3 | 1.786 | 10.95 | 375 | 20.985 | 9 | CE*1 |
| 14 | C | 16.0 | 1.782 | 7.57 | 305 | 20.980 | 14 | CE*1 |
| 15 | C | 33.6 | 1.771 | 5.22 | 236 | 20.970 | 13 | CE*1 |
| 16 | C | 59.4 | 1.764 | 4.43 | 198 | 20.964 | 17 | CE*1 |
| 17 | C | 78.9 | 1.757 | 4.25 | 183 | 20.957 | 31 | CE*1 |
| 18 | D | 12.2 | 1.772 | 8.57 | 368 | 20.990 | 15 | CE*1 |
| 19 | D | 23.5 | 1.767 | 5.88 | 297 | 20.977 | 12 | CE*1 |
| 20 | D | 27.2 | 1.764 | 5.54 | 284 | 20.976 | 14 | CE*1 |
| 21 | D | 42.8 | 1.758 | 4.56 | 249 | 20.968 | 12 | CE*1 |
| 22 | D | 55.5 | 1.754 | 4.25 | 233 | 20.964 | is | CE*1 |
| 23 | D | 64.9 | 1.746 | 4.20 | 224 | 20.962 | 16 | CE*1 |
| 24 | E | 18.2 | 1.755 | 6.48 | 361 | 20.990 | 16 | CE*1 |
| 25 | E | 26.8 | 1.752 | 5.20 | 324 | 20.986 | 15 | CE*1 |
| 26 | E | 31.7 | 1.749 | 4.68 | 310 | 20.983 | 13 | CE*1 |
| 27 | E | 45.6 | 1.741 | 4.18 | 284 | 20.980 | 14 | CE*1 |
| 28 | E | 66.8 | 1.726 | 3.90 | 261 | 20.976 | 17 | CE*1 |

(1*) CE represents the term "Comparative Example".

Table 3

| No. | Steel ID | Grain Diame ter (μm) | $B_{50}$ (T) | $W_{15/50}$ (W/kg) | YP (MPa) | Punched Hole Diameter (mm) | Punched hole diameter Max - min (μm) | Remarks |
|---|---|---|---|---|---|---|---|---|
| 29 | F | 8.6 | 1.813 | 11.80 | 377 | 20.989 | 7 | CE*1 |
| 30 | F | 26.5 | 1.811 | 5.99 | 246 | 20.975 | 11 | CE*1 |
| 31 | F | 33.4 | 1.809 | 5.45 | 227 | 20.973 | 10 | CE*1 |
| 32 | F | 52.0 | 1.802 | 4.77 | 196 | 20.966 | 14 | CE*1 |
| 33 | F | 59.7 | 1.797 | 4.75 | 188 | 20.960 | 16 | CE*1 |
| 34 | G | 11.3 | 1.817 | 9.69 | 363 | 20.995 | 6 | CE*1 |
| 35 | G | 16.2 | 1.815 | 7.70 | 320 | 20.993 | 5 | CE*1 |
| 36 | G | 26.5 | 1.814 | 5.95 | 271 | 20.989 | 6 | CE*1 |
| 37 | G | 33.6 | 1.812 | 5.40 | 252 | 20.988 | 4 | IE*2 |
| 38 | G | 43.8 | 1.808 | 4.95 | 233 | 20.986 | 5 | IE*2 |
| 39 | G | 75.2 | 1.804 | 4.45 | 201 | 20.984 | 7 | IE*2 |
| 40 | H | 11.3 | 1.822 | 9.66 | 384 | 20.995 | 3 | CE*1 |
| 41 | H | 14.8 | 1.819 | 8.10 | 351 | 20.996 | 4 | CE*1 |
| 42 | H | 23.0 | 1.819 | 6.34 | 305 | 20.995 | 5 | CE*1 |
| 43 | H | 25.6 | 1.819 | 6.02 | 295 | 20.994 | 6 | CE*1 |
| 44 | H | 35.6 | 1.816 | 5.26 | 269 | 20.993 | 4 | IE*2 |

(1*) CE represents the term "Comparative Example".
(2*) IE represents the term "Inventive Example".

Table 3 (continued)

| No. | Steel ID | Grain Diame ter (µm) | $B_{50}$ (T) | $W_{15/50}$ (W/kg) | YP (MPa) | Punched Hole Diameter (mm) | Punched hole diameter Max - min (µm) | Remarks |
|---|---|---|---|---|---|---|---|---|
| 45 | H | 40.2 | 1.814 | 5.05 | 260 | 20.933 | 4 | IE*2 |
| 46 | H | 56.8 | 1.813 | 4.62 | 237 | 20.992 | 3 | IE*2 |
| 47 | H | 77.6 | 1.811 | 4.41 | 220 | 20.991 | 6 | IE*2 |
| 48 | I | 10.8 | 1.826 | 9.93 | 420 | 20.994 | 3 | CE*1 |
| 49 | I | 13.5 | 1.824 | 8.55 | 391 | 20.995 | 4 | CE*1 |
| 50 | I | 26.8 | 1.821 | 5.77 | 321 | 20.996 | 5 | CE*1 |
| 51 | I | 32.5 | 1.820 | 5.15 | 305 | 20.994 | 4 | IE*2 |
| 52 | I | 40.8 | 1.818 | 4.94 | 288 | 20.993 | 5 | IE*2 |
| 53 | I | 56.4 | 1.817 | 4.59 | 267 | 20.994 | 4 | IE*2 |
| 54 | I | 60.5 | 1.816 | 4.53 | 263 | 20.992 | 4 | IE*2 |
| 55 | J | Not evaluated due to cracks caused during a cold-rolled step | | | | | | CE*1 |
| 56 | B | 19.8 | 1.784 | 7.98 | 260 | 20.965 | 16 | CE*1 |
| 57 | B | 39.4 | 1.761 | 5.22 | 199 | 20.953 | 21 | CE*1 |
| 58 | H | 18.2 | 1.795 | 7.81 | 335 | 20.993 | 6 | CE*1 |
| 59 | H | 35.6 | 1.816 | 5.26 | 269 | 20.993 | 4 | IE*2 |

(1*) CE represents the term "Comparative Example".
(2*) IE represents the term "Inventive Example".

**[0122]** In the steel products A-F (Sample No. 1-33, 56, and 57), the P content does not satisfies the condition of the present invention, and the strength varies depending on the Si content and the crystal grain diameter. In such steel products, as the yield stress YP increases, the punched hole diameter tends to become close to the die diameter. However, the punching anisotropy remains relatively large, that is, the anisotropy is about 10-20 µm, wherein the anisotropy corresponds to the difference between the maximum and the minimum of the punched hole diameter. Furthermore, there is a problem in that the magnetic flux density decreases as the Si content increases.

**[0123]** In contrast, the steel products G-H according to the present invention have low Si and Al content and contain a 0.10% of P or more. Such steel products have a good punched hole shape and a small punching anisotropy even if yield point YP is 350 MPa or less, that is, the yield point YP is relatively small. Among them, the steel products having an average crystal grain diameter of 30 µm or more (Samples No. 37, 38, 39, 44, 45, 46, 47, 51, 52, 53, 54, and 59) are excellent in magnetic characteristic, that is, such steel products stably have low core loss and high magnetic flux density.

[Example 2]

**[0124]** Each steel having the composition shown in Table 4, was experimentally casted. Obtained ingot was hot-rolled so as to have a thickness of 2 mm in the same manner as that of Example 1. The hot-rolled sheet was annealed at 1100°C for 30 seconds, pickled, and then cold-rolled so as to have a thickness of 0.5 mm. The cold-rolled sheet was finish-annealed at various temperatures to obtain different recrystallized grain diameters, wherein the various temperatures are 700°C or more and are in the single-phase ferrite region.

**[0125]** Then, samples having a semi-organic insulating coating were prepared in the same manner as that of Example 1. The samples were used in various tests.

**[0126]** The obtained result is shown in Table 5.

**[0127]** The steel IDs K-M are such samples that the deoxidization was performed by the Al content and decreasing the Si content. The pair of the steel IDs N and O and the pair of the steel IDs Q and R are samples prepared in order to evaluate the effect of Ni.

Table 4

| Steel ID | Composition (mass%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Al | Mn | S | Ni | P | N | Sb | Sn |
| K | 0.0011 | 0.01 | 0.32 | 0.25 | 0.0032 | - | 0.05 | 0.0020 | <0.001 | 0.044 |
| L | 0.0009 | 0.01 | 0.33 | 0.24 | 0.0039 | - | 0.16 | 0.0021 | <0.001 | 0.046 |
| M | 0.0019 | 0.02 | 0.31 | 0.22 | 0.0018 | - | 0.24 | 0.0024 | <0.001 | <0.001 |
| N | 0.0033 | 0.21 | 0.23 | 0.15 | 0.0028 | - | 0.16 | 0.0012 | 0.060 | <0.001 |
| O | 0.0024 | 0.21 | 0.24 | 0.18 | 0.0016 | 1.23 | 0.16 | 0.0018 | 0.055 | <0.001 |
| P | 0.0088 | 0.35 | 0.0011 | 0.35 | 0.0046 | - | 0.05 | 0.0031 | <0.001 | <0.001 |
| Q | 0.0082 | 0.34 | 0.0007 | 0.33 | 0.0040 | - | 0.19 | 0.0019 | <0.001 | <0.001 |
| R | 0.0080 | 0.35 | 0.0011 | 0.33 | 0.0051 | 0.95 | 0.19 | 0.0018 | <0.001 | <0.001 |

Table 5

| No. | Steel ID | Grain Diame ter (μm) | $B_{50}$ (T) | $W_{15/50}$ (W/kg) | YP (MPa) | Punched Hole Diameter (mm) | Punched hole diameter Max - min (μm) | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1 | K | 36.1 | 1.777 | 4.95 | 211 | 20.959 | 18 | CE*1 |
| 2 | K | 61.3 | 1.769 | 4.27 | 177 | 20.950 | 26 | CE*1 |
| 3 | L | 26.5 | 1.789 | 5.57 | 283 | 20.982 | 8 | CE*1 |
| 4 | L | 34.2 | 1.785 | 4.98 | 262 | 20.985 | 7 | IE*2 |
| 5 | L | 47.0 | 1.785 | 4.47 | 240 | 20.982 | 9 | IE*2 |
| 6 | M | 12.5 | 1.777 | 8.63 | 396 | 20.995 | 6 | CE *1 |
| 7 | M | 35.2 | 1.774 | 4.88 | 294 | 20.991 | 8 | IE*2 |
| 8 | M | 70.2 | 1.768 | 4.06 | 250 | 20.992 | 9 | IE*2 |
| 9 | N | 28.7 | 1.786 | 5.38 | 289 | 20.990 | 8 | CE *1 |
| 10 | N | 36.2 | 1.785 | 4.89 | 270 | 20.989 | 9 | IE*2 |
| 11 | N | 58.1 | 1.779 | 4.26 | 239 | 20.989 | 9 | IE*2 |
| 12 | O | 6.8 | 1.807 | 12.96 | 484 | 20.995 | 2 | CE *1 |
| 13 | O | 22.7 | 1.803 | 5.28 | 329 | 20.992 | 2 | CE *1 |
| 14 | O | 32.1 | 1.803 | 4.37 | 299 | 20.992 | 3 | IE*2 |
| 15 | O | 48.2 | 1.797 | 3.70 | 270 | 20.995 | 7 | IE*2 |
| 16 | P | 43.0 | 1.768 | 4.88 | 218 | 20.966 | 16 | CE *1 |
| 17 | P | 60.4 | 1.766 | 4.50 | 197 | 20.959 | 18 | CE *1 |
| 18 | P | 72.0 | 1.769 | 4.38 | 187 | 20.961 | 21 | CE *1 |
| 19 | Q | 18.4 | 1.766 | 6.99 | 348 | 20.987 | 7 | CE *1 |
| 20 | Q | 44.8 | 1.766 | 4.76 | 273 | 20.977 | 8 | IE*2 |
| 21 | Q | 75.1 | 1.775 | 4.29 | 243 | 20.984 | 8 | IE*2 |
| 22 | R | 22.6 | 1.778 | 5.07 | 359 | 20.990 | 4 | CE *1 |
| 23 | R | 39.7 | 1.784 | 3.75 | 313 | 20.992 | 5 | IE*2 |
| 24 | R | 56.8 | 1.781 | 3.30 | 290 | 20.991 | 5 | IE*2 |

(1*) CE represents the term "Comparative Example".

(2*) IE represents the term "Inventive Example".

**[0128]** Such samples that have composition within the scope of the present invention and have an average crystal grain diameter of 30 µm or more, which is a proper value, have superior dimensional accuracy in punching, low punching anisotropy, and further excellent magnetic characteristics. From the comparison of the steel products N and O and the comparison of the steel products Q and R respectively, it is clear that the steel products O and R containing Ni have a greatly increased magnetic flux density.

[Example 3]

**[0129]** The steel ID F having the composition shown in Table 1 and the steel ID N and O having the composition shown in Table 4 were experimentally hot-rolled to have a thickness of 2 mm in the same manner as that of Example 1. Each obtained hot-rolled sheet was annealed at 1100°C for 30 seconds; pickled, and then cold-rolled so as to have a thickness of 0.50-0.2 mm. The obtained cold-rolled sheet was finish-annealed at various temperatures that is 700°C or more and is in the single-phase ferrite region to control the recrystallized grain diameter in a range of 35-45 µm.

**[0130]** Samples having a semi-organic insulating coating were prepared in the same manner as that of Example 1. The samples were used in various tests. For these samples, the core loss at high frequency, that is, at 400 Hz, was measured.

**[0131]** The obtained result is shown in Table 6.

Table 6

| No. | Steel ID | Thickness (mm) | Grain Diameter (µm) | $B_{50}$ (T) | $W_{15/50}$ (W/kg) | $W_{15/400}$ (W/kg) | YP (MPa) | Punched Hole Diameter (mm) | Punched hole diameter Max - min (µm) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | F | 0.50 | 38.2 | 1.807 | 4.84 | 171 | 217 | 20.968 | 14 | Comparative Example |
| 2 | F | 0.35 | 37.1 | 1.804 | 3.78 | 98 | 219 | 20.983 | 12 | Comparative Example |
| 3 | F | 0.20 | 42.8 | 1.803 | 3.41 | 58 | 209 | 20.989 | 11 | Comparative Example |
| 4 | N | 0.50 | 42.0 | 1.785 | 4.48 | 141 | 259 | 20.988 | 8 | Inventive Example |
| 5 | N | 0.35 | 37.9 | 1.783 | 3.39 | 71 | 267 | 20.993 | 7 | Inventive Example |
| 6 | N | 0.20 | 41.3 | 1.783 | 3.08 | 42 | 261 | 20.995 | 5 | Inventive Example |
| 7 | O | 0.50 | 37.4 | 1.802 | 3.86 | 89 | 288 | 20.992 | 4 | Inventive Example |
| 8 | O | 0.35 | 43.5 | 1.797 | 3.05 | 48 | 277 | 20.995 | 3 | Inventive Example |
| 9 | O | 0.20 | 35.2 | 1.798 | 2.78 | 29 | 292 | 20.995 | 3 | Inventive Example |

**[0132]** It is clear that the core loss tends to decrease particularly at high frequency as the thickness decreases. Furthermore, the dimensional accuracy in punching tends to improve when the thickness is reduced. The steel products

N and O, of which the composition is within the scope of the present invention, are superior to the steel product F, which is a comparative example, in such a tendency. Furthermore, the examples of the present invention are superior in punching anisotropy at any thickness.

[Example 4]

**[0133]** Each steel having the composition shown in Table 7 was experimentally casted to form an ingot. The obtained ingots were treated at 1150 °C for one hour in a soaking step and then hot-rolled to form a sheet bar having a thickness of 30 mm.

**[0134]** The obtained sheet bar was heated at a temperature (SRT) shown in Table 8 and held for one hour and then hot-rolled so as to have a thickness of 2.0 mm. The hot-rolled sheet was treated under the condition of a temperature of 580°C and a time of one hour, which corresponds to the coiling condition, and then air cooled. With some exception, the resulting hot-rolled sheets were annealed under the conditions shown in Table 8. The annealed sheets were pickled and then cold-rolled so as to have a thickness of 0.50 mm.

**[0135]** The machinability during a cold-rolling step was evaluated by observing the state of each sheet that is being cold-rolled and the texture in the cross section of the cold-rolled sheet during the cold-rolling step. Many delamination cracks parallel to a sheet surface were observed in the following steel products and samples: the steel products (W, Z, a, c, d, k, and 1) that have a high P content (0.10% or more) and composition which is outside the scope of the present invention, and the samples (No. 25 and 26) having composition within the scope of the invention but having slab-reheating temperature (SRT) or hot rolled sheet-coiling temperature (CT) that are outside the scope of the present invention. In some samples (No. 5, 19, and 25), separation by delamination arose during the cold-rolling step, so that the cold rolling could not proceed. The steel products and samples having the above evaluations, are difficult to manufacture stably. Therefore, for such steel products and samples, the subsequent treatment and the evaluation were not conducted.

**[0136]** The cold-rolled sheets were finish-rolled at various temperatures which are 700°C or more. A semi-organic insulating coating was provided onto each cold-rolled sheet, and the resulting cold-rolled sheets were provided to various tests. JIS No. 5 specimens prepared by slitting the cold-rolled sheets in parallel to the rolling direction were used for measuring the strength. The specimens were tested at a crosshead speed of 10 mm/s to obtain tensile strength (TS), which was evaluated. The result is shown also in Table 8.

Table 7

| Steel ID | Steel Composition | C % | Si % | Al % | Mn % | S % | Ni % | P % | N % | Sb % | Sn % | $P_A$ | Condition $P_A \geq P$ | $P_F$ | Condition $P_F \leq 0.26$ | Result *5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S | CS*1 | 0.0018 | 0.60 | 0.0010 | 0.18 | 0.0041 | 0.00 | 0.05 | 0.0022 | <0.001 | <0.001 | 0.261 | S*3 | 0.591 | NS*4 | Good |
| T | IS*2 | 0.0011 | 0.60 | 0.0011 | 0.19 | 0.0033 | 0.00 | 0.13 | 0.0032 | <0.001 | <0.001 | 0.262 | S*3 | 0.593 | NS*4 | Good |
| U | IS*2 | 0.0014 | 0.60 | 0.0006 | 0.22 | 0.0028 | 0.00 | 0.19 | 0.0015 | <0.001 | <0.001 | 0.266 | S*3 | 0.600 | NS*4 | Good |
| V | IS*2 | 0.0032 | 0.60 | 0.0005 | 0.18 | 0.0032 | 0.00 | 0.26 | 0.0018 | <0.001 | <0.001 | 0.261 | S*3 | 0.592 | NS*4 | Good |
| W | CS*1 | 0.0031 | 0.63 | 0.0006 | 0.19 | 0.0041 | 0.00 | 0.29 | 0.0021 | <0.001 | <0.001 | 0.257 | NS*4 | 0.585 | NS*4 | No good |
| X | CS*1 | 0.0011 | 1.02 | 0.0010 | 0.19 | 0.0032 | 0.00 | 0.04 | 0.0018 | <0.001 | 0.023 | 0.178 | S*3 | 0.451 | NS*4 | Good |
| Y | IS*2 | 0.0011 | 1.00 | 0.0011 | 0.21 | 0.0032 | 0.00 | 0.15 | 0.0020 | <0.001 | 0.036 | 0.185 | S*3 | 0.461 | NS*4 | Good |
| Z | CS*1 | 0.0011 | 0.98 | 0.0004 | 0.19 | 0.0032 | 0.00 | 0.21 | 0.0022 | <0.001 | 0.025 | 0.187 | NS*4 | 0.465 | NS*4 | No good |
| a | CS*1 | 0.0011 | 1.01 | 0.0006 | 0.18 | 0.0032 | 0.00 | 0.25 | 0.0025 | <0.001 | 0.032 | 0.179 | NS*4 | 0.452 | NS*4 | No good |
| b | CS*1 | 0.0019 | 1.52 | 0.0009 | 0.20 | 0.0050 | 0.00 | 0.04 | 0.0019 | 0.018 | 0.002 | 0.080 | S*3 | 0.283 | NS*4 | Good |
| c | CS*1 | 0.0025 | 1.54 | 0.0011 | 0.19 | 0.0041 | 0.00 | 0.12 | 0.0012 | 0.022 | <0.001 | 0.074 | NS*4 | 0.274 | NS*4 | No good |
| d | CS*1 | 0.0016 | 1.48 | 0.0008 | 0.22 | 0.0028 | 0.00 | 0.17 | 0.0031 | 0.023 | <0.001 | 0.090 | NS*4 | 0.300 | NS*4 | No good |
| e | IS*2 | 0.0018 | 1.63 | 0.0007 | 0.18 | 0.0019 | 0.00 | 0.19 | 0.0026 | 0.019 | <0.001 | 0.056 | NS*4 | 0.242 | S*3 | Good |
| f | IS*2 | 0.0024 | 1.60 | 0.0006 | 0.18 | 0.0032 | 0.00 | 0.25 | 0.0014 | 0.022 | <0.001 | 0.061 | NS*4 | 0.252 | S*3 | Good |
| g | CS*1 | 0.0008 | 2.18 | 0.25 | 0.20 | 0.0008 | 0.00 | 0.03 | 0.0018 | <0.001 | 0.035 | -0.132 | NS*4 | -0.076 | S*3 | Good |
| h | IS*2 | 0.0011 | 2.20 | 0.26 | 0.18 | 0.0004 | 0.00 | 0.13 | 0.0022 | 0.002 | 0.036 | -0.142 | NS*4 | -0.092 | S*3 | Good |
| i | IS*2 | 0.0016 | 2.11 | 0.25 | 0.18 | 0.0013 | 0.00 | 0.19 | 0.0021 | <0.001 | 0.034 | -0.120 | NS*4 | -0.056 | S*3 | Good |
| j | IS*2 | 0.0017 | 2.08 | 0.27 | 0.19 | 0.0017 | 0.00 | 0.24 | 0.0035 | <0.001 | 0.032 | -0.120 | NS*4 | -0.055 | S*3 | Good |
| k | CS*1 | 0.0024 | 2.11 | 0.27 | 0.22 | 0.0023 | 0.00 | 0.29 | 0.0028 | <0.001 | 0.035 | -0.122 | NS*4 | -0.059 | S*3 | Good |
| l | CS*1 | 0.0026 | 1.50 | 0.0010 | 0.20 | 0.0032 | 0.50 | 0.18 | 0.0026 | <0.001 | 0.022 | 0.146 | NS*4 | 0.489 | NS*4 | No good |
| m | IS*2 | 0.0033 | 1.45 | 0.0005 | 0.19 | 0.0015 | 1.09 | 0.16 | 0.0021 | 0.002 | 0.021 | 0.261 | S*3 | 0.894 | NS*4 | Good |
| n | IS*2 | 0.0036 | 1.56 | 0.0010 | 0.19 | 0.0032 | 1.57 | 0.17 | 0.0019 | <0.001 | 0.021 | 0.351 | S*3 | 1.296 | NS*4 | Good |
| o | IS*2 | 0.0038 | 1.50 | 0.0006 | 0.21 | 0.0022 | 2.13 | 0.19 | 0.0025 | <0.001 | 0.026 | 0.525 | S*3 | 1.978 | NS*4 | Good |

(*1) The symbol CS (Comparative steel) means that the composition is outside the scope of the present invention.

(*2) The symbol IS (Inventive steel) means that the composition is within the scope of the present invention.

(*3) The symbol S means that the condition is satisfied.

(*4) The symbol NS means that the condition is not satisfied.

(*5) Result of the estimation by the formulae.

Table 8-1

| No. | Steel ID | Steel Composition | Remarks | SRT (°C) | CT (°C) | HSAT*7 (°C) | B50 (T) | YP (MPa) | TS (MPa) | PHD*8 (mm) | PHD*8 max-min (μm) | Producibility | $P_A$ | Condition $P_A \geq P$ | $P_F$ | Condition $P_F \leq 0.26$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | S | CS*1 | CE*5 | 1150 | 520 | 900 | 1.775 | 227 | 348 | 20.969 | 16 | Possible | 0.261 | S*3 | 0.591 | NS*4 |
| 2 | T | IS*2 | IE*6 | 1150 | 520 | 900 | 1.774 | 260 | 382 | 20.988 | 5 | Possible | 0.262 | S*3 | 0.593 | NS*4 |
| 3 | U | IS*2 | IE*6 | 1150 | 520 | 900 | 1.776 | 286 | 410 | 20.991 | 6 | Possible | 0.266 | S*3 | 0.600 | NS*4 |
| 4 | V | IS*2 | IE*6 | 1150 | 520 | 900 | 1.777 | 315 | 439 | 20.993 | 5 | Possible | 0.261 | S*3 | 0.592 | NS*4 |
| 5 | W | CS*1 | CE*5 | 1150 | 520 | 900 | - | - | - | - | - | NP*9 | 0.257 | NS*4 | 0.585 | NS*4 |
| 6 | X | CS*1 | CE*5 | 1150 | 550 | 900 | 1.762 | 255 | 370 | 20.968 | 12 | Possible | 0.178 | S*3 | 0.451 | NS*4 |
| 7 | Y | IS*2 | IE*6 | 1150 | 550 | 900 | 1.764 | 297 | 415 | 20.992 | 5 | Possible | 0.185 | S*3 | 0.461 | NS*4 |
| 8 | Z | CS*1 | CE*5 | 1150 | 550 | 900 | - | - | - | - | - | NP*9 | 0.187 | NS*4 | 0.465 | NS*4 |
| 9 | a | CS*1 | CE*5 | 1150 | 550 | 900 | - | - | - | - | - | NP*9 | 0.179 | NS*4 | 0.452 | NS*4 |
| 10 | b | CS*1 | CE*5 | 1150 | 550 | 1100 | 1.733 | 291 | 400 | 20.974 | 15 | Possible | 0.080 | S*3 | 0.283 | NS*4 |
| 11 | c | CS*1 | CE*5 | 1150 | 550 | 1100 | - | - | - | - | - | NP*9 | 0.074 | NS*4 | 0.274 | NS*4 |
| 12 | d | CS*1 | CE*5 | 1150 | 550 | 1100 | - | - | - | - | - | NP*9 | 0.090 | NS*4 | 0.300 | NS*4 |
| 13 | e | IS*2 | IE*6 | 1150 | 550 | 1100 | 1.735 | 360 | 470 | 20.993 | 4 | Possible | 0.056 | NS*4 | 0.242 | S*3 |
| 14 | f | IS*2 | IE*6 | 1150 | 550 | 1100 | 1.733 | 383 | 494 | 20.992 | 3 | Possible | 0.061 | NS*4 | 0.252 | S*3 |
| 15 | g | CS*1 | CE*5 | 1150 | 580 | 1000 | 1.703 | 338 | 444 | 20.990 | 15 | Possible | -0.132 | NS*4 | -0.076 | S*3 |
| 16 | h | IS*2 | IE*6 | 1150 | 580 | 1000 | 1.708 | 382 | 489 | 20.995 | 5 | Possible | -0.142 | NS*4 | -0.092 | S*3 |
| 17 | i | IS*2 | IE*6 | 1150 | 580 | 1000 | 1.709 | 400 | 509 | 20.996 | 3 | Possible | -0.120 | NS*4 | -0.056 | S*3 |
| 18 | j | IS*2 | IE*6 | 1150 | 580 | 1000 | 1.704 | 419 | 530 | 20.994 | 3 | Possible | -0.120 | NS*4 | -0.055 | S*3 |

(*1) The symbol CS (Comparative Steel) means that the composition is outside the scope of the present invention.

(*2) The symbol IS (Inventive Steel) means that the composition is within the scope of the present invention.

(*3) The symbol S means that the condition is satisfied.

(*4) The symbol NS means that the condition is not satisfied.

(*5) The symbol CE represents the term "Comparative Example".

(*6) The symbol IE represents the term "Inventive Example".

(*7) The symbol HSAT represents the hot-rolled sheet annealing temperature.

(*8) The symbol PHD represents the punched hole diameter.

(*9) The symbol NP means that the production is not possible due to delamination cracks.

Table 8-2

| No. | Steel ID | Steel Composition | Remarks | SRT (°C) | CT (°C) | HSAT*7 (°C) | B50 (T) | YP (MPa) | TS (MPa) | PHD*8 (mm) | PHD*8 max-min (μm) | Producibility | $P_A$ | Condition $P_A≥P$ | $P_F$ | Condition $P_F≤0.26$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | k | CS*1 | CE*5 | 1150 | 580 | 1000 | - | - | - | - | - | NP*9 | -0.122 | NS*4 | -0.059 | S*3 |
| 20 | l | CS*1 | CE*5 | 1150 | 550 | 1100 | - | - | - | - | - | NP*9 | 0.146 | NS*4 | 0.489 | NS*4 |
| 21 | m | IS*2 | IE*6 | 1150 | 550 | 1100 | 1.742 | 353 | 465 | 20.996 | 3 | Possible | 0.261 | S*3 | 0.894 | NS*4 |
| 22 | n | IS*2 | IE*6 | 1150 | 550 | 1100 | 1.748 | 372 | 483 | 20.995 | 4 | Possible | 0.351 | S*3 | 1.296 | NS*4 |
| 23 | O | IS*2 | IE*6 | 1150 | 550 | 1100 | 1.751 | 383 | 495 | 20.996 | 4 | Possible | 0.525 | S*3 | 1.978 | NS*4 |
| 24 | Y | IS*2 | IE*6 | 1100 | 550 | - | 1.754 | 312 | 416 | 20.990 | 6 | Possible | 0.185 | S*3 | 0.461 | NS*4 |
| 25 | Y | IS*2 | CE*5 | 1250 | 550 | 550 | - | - | - | - | - | NP*9 | 0.185 | S*3 | 0.461 | NS*4 |
| 26 | Y | IS*2 | CE*5 | 1150 | 700 | 700 | - | - | - | - | - | NP*9 | 0.185 | S*3 | 0.461 | NS*4 |

(*1) The symbol CS (Comparative Steel) means that the composition is outside the scope of the present invention.

(*2) The symbol IS (Inventive Steel) means that the composition is within the scope of the present invention.

(*3) The symbol S means that the condition is satisfied.

(*4) The symbol NS means that the condition is not satisfied.

(*5) The symbol CE represents the term "Comparative Example".

(*6) The symbol IE represents the term "Inventive Example".

(*7) The symbol HSAT represents the hot-rolled sheet annealing temperature.

(*8) The symbol PHD represents the punched hole diameter.

(*9) The symbol NP means that the production is not possible due to delamination cracks.

**[0137]** The samples (No. 2-4, 7, 13, 14, 16-18, and 21-24) having composition that is within the scope of the present invention and containing 0.1% or more of P have excellent dimensional accuracy in punching in particular. That is, in the samples (No. 1, 6, 10, and 15) containing less than 0.1% of P, as the Si and Al total content increases, the dimensional accuracy in punching tends to increase but the punching anisotropy remains high. In contrast, it is clear that the examples of the present invention are excellent in both dimensional accuracy and punching anisotropy. Furthermore, the examples of the present invention have magnetic flux density that is the same as that or more than that of the comparative examples having a P content of less than 0.1%. Even more, the examples have high strength. That is, the examples have the excellent balance of the strength and the magnetic flux density.

[Example 5]

**[0138]** The steel IDs M, N, and O having the composition shown in Table 4 were experimentally prepared. After the casting, sheet bars having a thickness of 30 mm were obtained by hot rolling. The sheet bars were heated at each temperature (SRT) shown in Table 9 for 60 minutes and hot-rolled so as to have a thickness of 2 mm. The hot-rolled sheets were treated in a soaking process under the conditions of each temperature (CT) and a time of one hour, which correspond to the coiling conditions, and then air cooled. With some exception, the hot-rolled sheets were then annealed at each temperature shown in Table 9 for 60 seconds.

**[0139]** For the obtained hot-rolled sheets, the bending test was conducted at room temperature (23°C). A specimen prepared from hot-rolled sheet having a length of 100 mm and a width of 30 mm was used in the bending test, wherein the longitudinal direction of the specimen is parallel to the rolling direction. The repetitive bending test was conducted according to the method defined in JIS-C 2550. In the bending test, the bending radius was 15 mm. Table 9 shows the number of times each specimen was bent until cracks are formed on a surface.

**[0140]** Microstructures (phase) of each slab during the heating step and each hot-rolled sheet during the annealing step were investigated by the following procedure: each sheet bar and each hot-rolled sheet are separately maintained at a predetermined temperature (shown in Table 9) for a predetermined time (for one hour when the slab is heated or for 60 seconds when the hot-rolled sheet is annealed) and then quenched with water to fix the microstructure during the heating step. The obtained microstructure was observed with an optical microscope to determine the phase. The result is also shown in Table 9.

**[0141]** The above hot-rolled sheets were pickled and then cold-rolled (once) so as to have a thickness of 0.50 mm. The cold-rolled sheets were checked if there are defects (delamination cracks) due to the embrittlement arising during the cold-rolling step. The cold-rolled sheets having no delamination cracks were finish-annealed at various temperatures shown in Table 9. A semi-organic insulating coating was then provided onto each finish-annealed sheet in the same manner as that of Example 1 to form samples, which were used in various tests. The obtained result is shown in Table 9.

Table 9

| No. | Steel ID | Steel Composition | Remarks | SRT (°C) | Ms-slab*4 | CT (°C) | HSAT*5 (°C) | Ms-hrs*6 | N-bend*7 | Producibility | FAT*10 (°C) | Grain size (μm) | B50 (T) | W15/50 (W/kg) | YP (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | M | IS*1 | CE*2 | 1250 | α and γ | 520 | - | - | 4 | NP-c*8 | - | - | - | - | - |
| 2 | M | IS*1 | IE*3 | 1150 | single γ | 520 | - | - | 30 | Possible | 800 | 46.2 | 1.765 | 4.47 | 275 |
| 3 | M | IS*1 | IE*3 | 1050 | single γ | 520 | - | - | 28 | Possible | 800 | 38.2 | 1.762 | 4.75 | 288 |
| 4 | M | IS*1 | CE*2 | 950 | α and γ | 520 | - | - | 5 | NP-c*8 | - | - | - | - | - |
| 5 | M | IS*1 | CE*2 | 1150 | single γ | 720 | 900 | single α | 3 | NP-b*9 | 850 | 45.1 | 1.762 | 6.83 | 288 |
| 6 | N | IS*1 | IE*3 | 1150 | single γ | 620 | 900 | single α | 17 | Possible | 850 | 55.2 | 1.764 | 4.31 | 242 |
| 7 | N | IS*1 | CE*2 | 1150 | single γ | 550 | 960 | α and γ | 20 | Possible | 850 | 53.8 | 1.736 | 4.33 | 244 |
| 8 | N | IS*1 | IE*3 | 1150 | single γ | 550 | 1100 | single γ | 22 | Possible | 850 | 52.1 | 1.768 | 4.36 | 246 |
| 9 | N | IS*1 | CE*2 | 1150 | single γ | 500 | 900 | single α | 27 | Possible | 670 | 16.0 | 1.766 | 7.38 | 345 |
| 10 | O | IS*1 | IE*3 | 1100 | single γ | 600 | 1100 | single γ | 26 | Possible | 800 | 36.5 | 1.777 | 4.12 | 290 |
| 11 | O | IS*1 | IE*3 | 1100 | single γ | 600 | 1000 | single γ | 33 | Possible | 800 | 38.5 | 1.780 | 4.02 | 286 |
| 12 | O | IS*1 | CE*2 | 1100 | single γ | 550 | 900 | α and γ | 28 | Possible | 800 | 32.6 | 1.733 | 4.34 | 298 |
| 13 | O | IS*1 | CE*2 | 1100 | single γ | 550 | 800 | single α | 24 | Possible | 800 | 36.8 | 1.733 | 4.10 | 289 |

(*1) The symbol IS (Inventive Steel) means that the composition is within the scope of the present invention.

(*2) The symbol CE represents the term "Comparative Example".

(*3) The symbol IE represents the term "Inventive Example".

(*4) The symbol Ms-slab represents the microstructure of a slab during a heating step.

(*5) The symbol HSAT represents the hot-rolled sheet annealing temperature.

(*6) The symbol Ms-hrs represents the microstructure of a hot-rolled sheet during an annealing step.

(*7) The symbol N-bend represents the number of times a hot-rolled sheet is bent until cracks are formed on a surface.

(*8) The symbol NP-c means that the production is not possible due to delamination cracks.

(*9) The symbol NP-b means that the production is not possible due to the deterioration of the bending properties.

(*10) The symbol FAT represents the finish-annealing temperature.

**[0142]** In the samples (No. 2, 3, 6, 8, 10, and 11) having composition (low-Si steel) within the scope of the present invention and having manufacturing conditions within the scope of the present invention, steel sheets can be manufactured without causing any problems and the characteristics are superior, even if the P content is high.

**[0143]** In contrast, in the samples (No. 1 and 4) in which the slab-reheating temperature is within duplex region, it is clear that it is difficult to obtain the products because defects due to the embrittlement during the cold-rolled sheet step are readily caused. In the sample (No. 5) in which the coiling temperature is higher than 650°C, the hot-rolled sheet has inferior cold-rolling workability and the electrical steel sheet has also inferior core loss. Furthermore, in the samples (No. 7 and 12) in which the hot-rolled sheet-annealing temperature is in the two-phase coexisting region and the sample (No. 13) in which the hot-rolled sheet containing more than 1.0% by mass of Ni annealed at a temperature in the single-phase alpha region, the obtained electrical steel sheet have low magnetic flux density. Furthermore, in the sample (No. 9) in which the finish-annealing temperature is outside the scope of the present invention and is not sufficient to form recrystallized crystal grains having a diameter of 30 μm or more, the magnetic characteristics are inferior.

Industrial Applicability

**[0144]** The present invention provides a non-oriented electrical steel sheet having excellent magnetic characteristics such as high magnetic flux density and low core loss and further having high dimensional accuracy during a punching step and further provides a non-oriented electrical steel sheet having high strength, with manufactural stablity.

**[0145]** A non-oriented electrical steel sheet of the present invention is suitable for an iron core material for reluctance motors and DC brushless motors that are of an interior permanent magnet type, among iron core materials for various motors, wherein the reluctance motors need to have high dimensional accuracy and high magnetic flux density in combination, and the DC brushless motors need to have high strength.

## Claims

**1.** A non-oriented electrical steel sheet containing:

0-0.010% of C;
at least one of Si and Al in a total amount of 0.03% to 0.5%;
0.5% or less of Mn;
0.10% or more to 0.26% or less of P;
0.015% or less of S; and
0.010% or less of N, on a mass percentage basis, the remainder being Fe and unavoidable impurities, and having:

an average grain size of 30 μm or more to 80 μm or less.

**2.** The non-oriented electrical steel sheet according to Claim 1 further containing:

at least one of Sb and Sn in a total amount of 0.40% or less on a mass percentage basis.

**3.** The non-oriented electrical steel sheet according to Claim 1 or 2 further containing:

2.3% or less of Ni on a mass percentage basis.

**4.** The non-oriented electrical steel sheet according to any one of Claims 1 to 3 further containing at least any one of:

0.01% or less of Ca;
0.005% or less of B;
0.1% or less of Cr;
0.1% or less of Cu; and
0.1% or less of Mo,

on a mass percentage basis.

**5.** The non-oriented electrical steel sheet according to any one of Claims 1 to 4 further having a thickness of 0.35 mm or less.

**6.** A non-oriented electrical steel sheet containing:

0-0.010% of C;
at least one of Si and Al in a total amount of more than 0.5% to 2.5%;
0.5% or less of Mn;
0.10% or more to 0.26% or less of P;
0.015% or less of S;
0.010% or less of N; and
2.3% or less of Ni according to needs,

on a mass percentage basis, the remainder being Fe and unavoidable impurities, and satisfying:

at least one of the formula $P \leq P_A$ and the formula $P_F \leq 0.26$,

wherein

$$P_A = -0.2Si + 0.12Mn - 0.32Al + 0.05Ni^2 + 0.10Ni + 0.36 \quad (1);$$

and

$$P_F = -0.34Si + 0.20Mn - 0.54Al + 0.24Ni^2 + 0.28Ni + 0.76 \quad (2),$$

where the unit of each element content is mass%.

**7.** The non-oriented electrical steel sheet according to Claim 6 further containing:

at least one of Sb and Sn in a total amount of 0.40% or less on a mass percentage basis.

**8.** The non-oriented electrical steel sheet according to Claim 6 or 7 further containing at least any one of:

0.01% or less of Ca;
0.005% or less of B;
0.1% or less of Cr;
0.1% or less of Cu; and
0.1% or less of Mo,

on a mass percentage basis.

**9.** A method for manufacturing a non-oriented electrical steel sheet comprising the steps of:

hot-rolling a steel slab having the composition according to any one of Claims 1 to 4 under the conditions of a heating temperature in the single-phase austenite region and a coiling temperature of 650°C or less; and then descaling the hot-rolled sheet to cold-roll the descaled sheet once or twice or more with an intermediate annealing sub-step therebetween, and then finish-annealing the cold-rolled sheet at a temperature of 700°C or more in the single-phase ferrite region.

**10.** A method for manufacturing a non-oriented electrical steel sheet comprising the steps of:

hot-rolling a steel slab having composition according to any one of Claims 1 to 4 under the conditions of a heating temperature in the single-phase austenite region and a coiling temperature of 650°C or less;
annealing the hot-rolled sheet at a temperature of 900°C or more in the single-phase ferrite region or at a temperature of more than the Ac3 transformation point in the single-phase austenite region if Ni is not contained

or the Ni content is 1.0% by mass or less;
annealing the hot-rolled sheet at a temperature of more than the Ac3 transformation point in the single-phase austenite region if the Ni content is more than 1.0% to 2.3% by mass or less;
descaling the annealed sheet to cold-roll the descaled sheet once or twice or more with an intermediate annealing sub-step therebetween; and then
finish-annealing the cold-rolled sheet at a temperature of 700°C or more in the single-phase ferrite region.

**11.** A method for manufacturing a non-oriented electrical steel sheet comprising the steps of:

hot-rolling a steel slab having composition according to any one of Claims 6 to 8 under the conditions of a heating temperature of 1000-1200°C and a coiling temperature of 650°C or less;
annealing the hot-rolled sheet according to needs;
descaling the hot-rolled or annealed sheet to cold-roll the descaled sheet once or twice or more with an intermediate annealing sub-step therebetween; and then
finish-annealing the cold-rolled sheet.

# FIG. 1

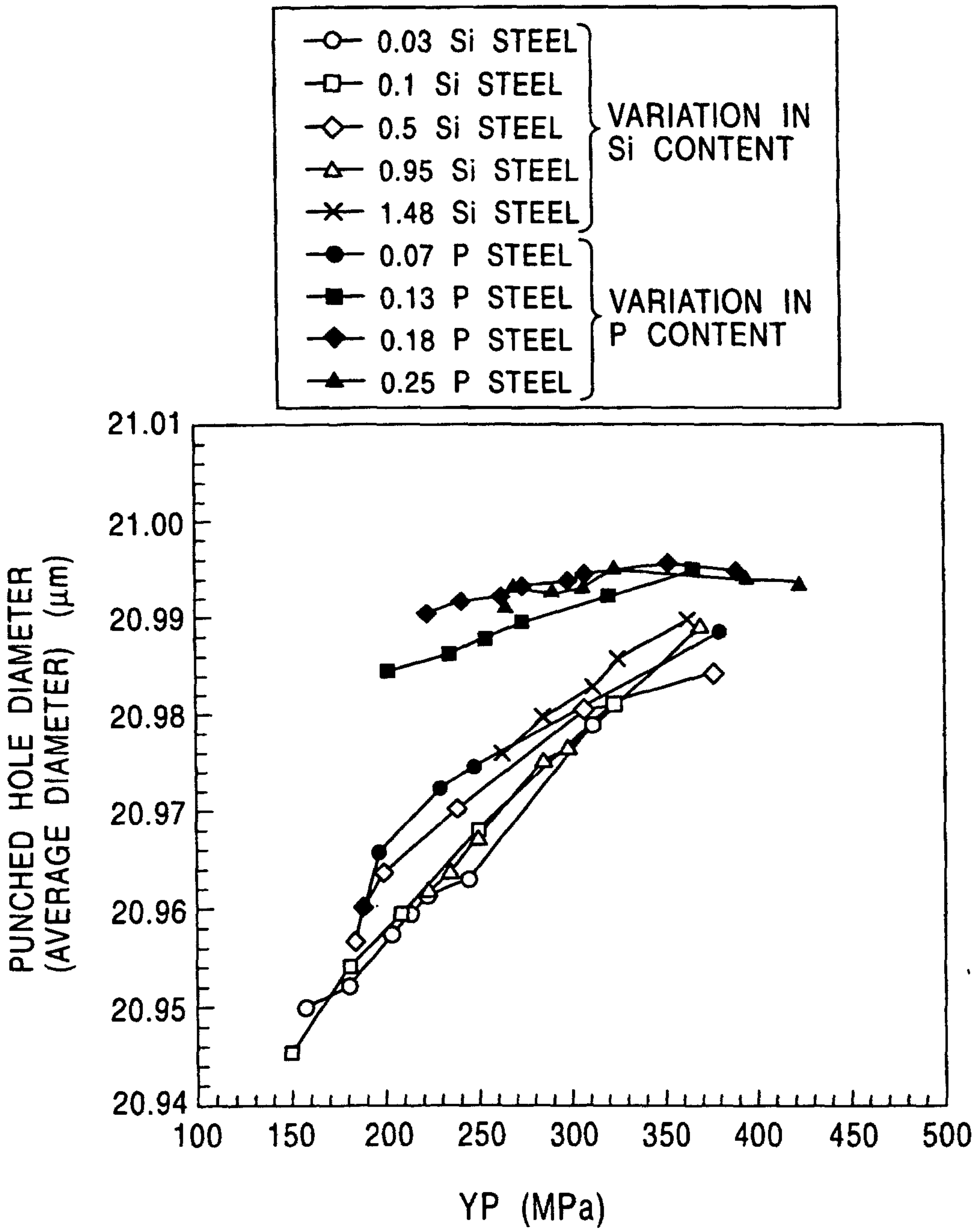

0.03 Si STEEL
0.1 Si STEEL
0.5 Si STEEL
0.95 Si STEEL
1.48 Si STEEL
VARIATION IN Si CONTENT
0.07 P STEEL
0.13 P STEEL
0.18 P STEEL
0.25 P STEEL
VARIATION IN P CONTENT
PUNCHED HOLE DIAMETER (AVERAGE DIAMETER) (μm)
21.01
21.00
20.99
20.98
20.97
20.96
20.95
20.94
100
150
200
250
300
350
400
450
500
YP (MPa)

FIG. 2

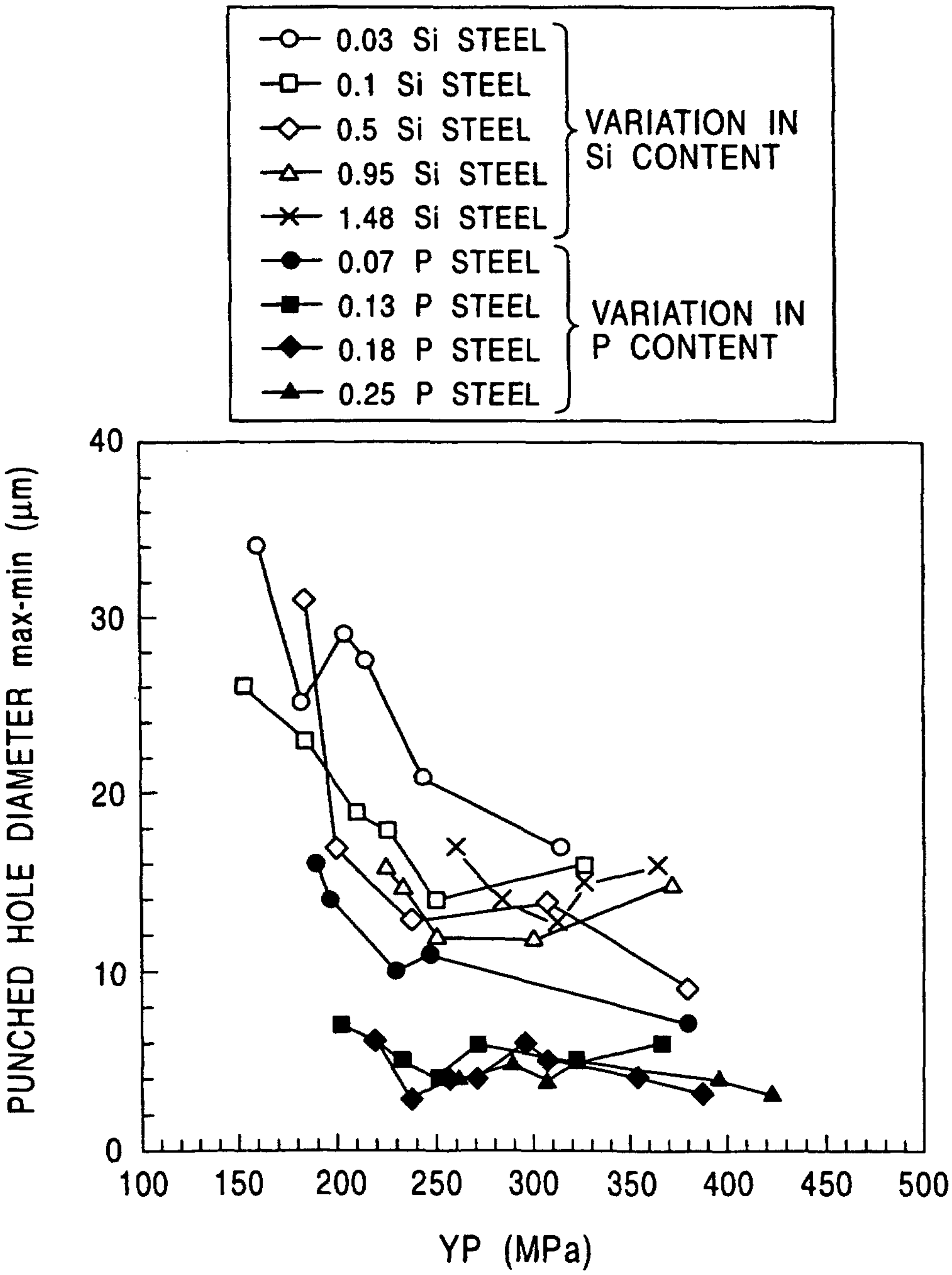
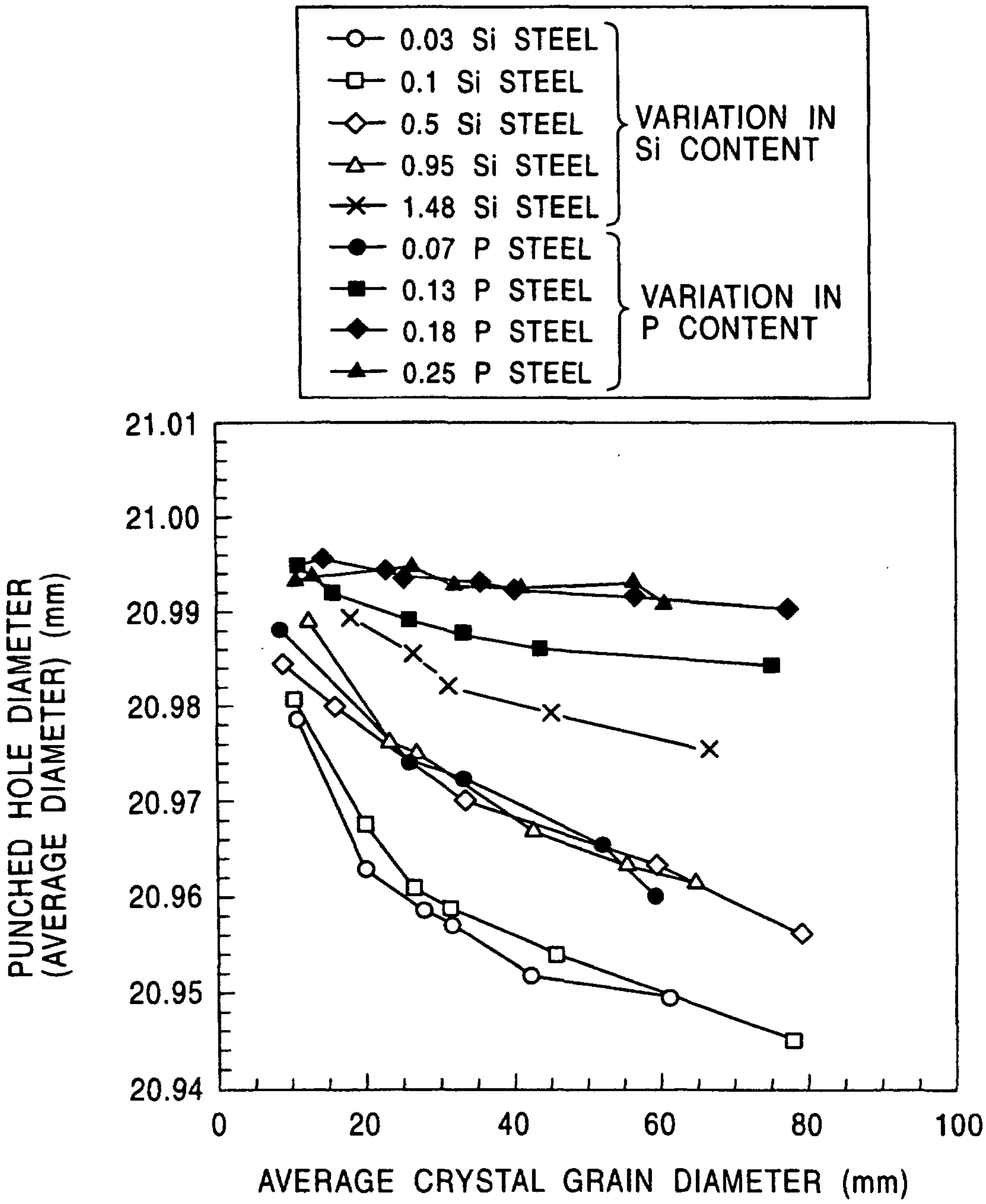

0.03 Si STEEL
0.1 Si STEEL
0.5 Si STEEL
0.95 Si STEEL
1.48 Si STEEL
VARIATION IN Si CONTENT
0.07 P STEEL
0.13 P STEEL
0.18 P STEEL
0.25 P STEEL
VARIATION IN P CONTENT
PUNCHED HOLE DIAMETER max-min (µm)
0
10
20
30
40
100
150
200
250
300
350
400
450
500
YP (MPa)

FIG. 3



0.03 Si STEEL
0.1 Si STEEL
0.5 Si STEEL
0.95 Si STEEL
1.48 Si STEEL
VARIATION IN Si CONTENT
0.07 P STEEL
0.13 P STEEL
0.18 P STEEL
0.25 P STEEL
VARIATION IN P CONTENT
PUNCHED HOLE DIAMETER (AVERAGE DIAMETER) (mm)
21.01
21.00
20.99
20.98
20.97
20.96
20.95
20.94
0
20
40
60
80
100
AVERAGE CRYSTAL GRAIN DIAMETER (mm)

FIG. 4

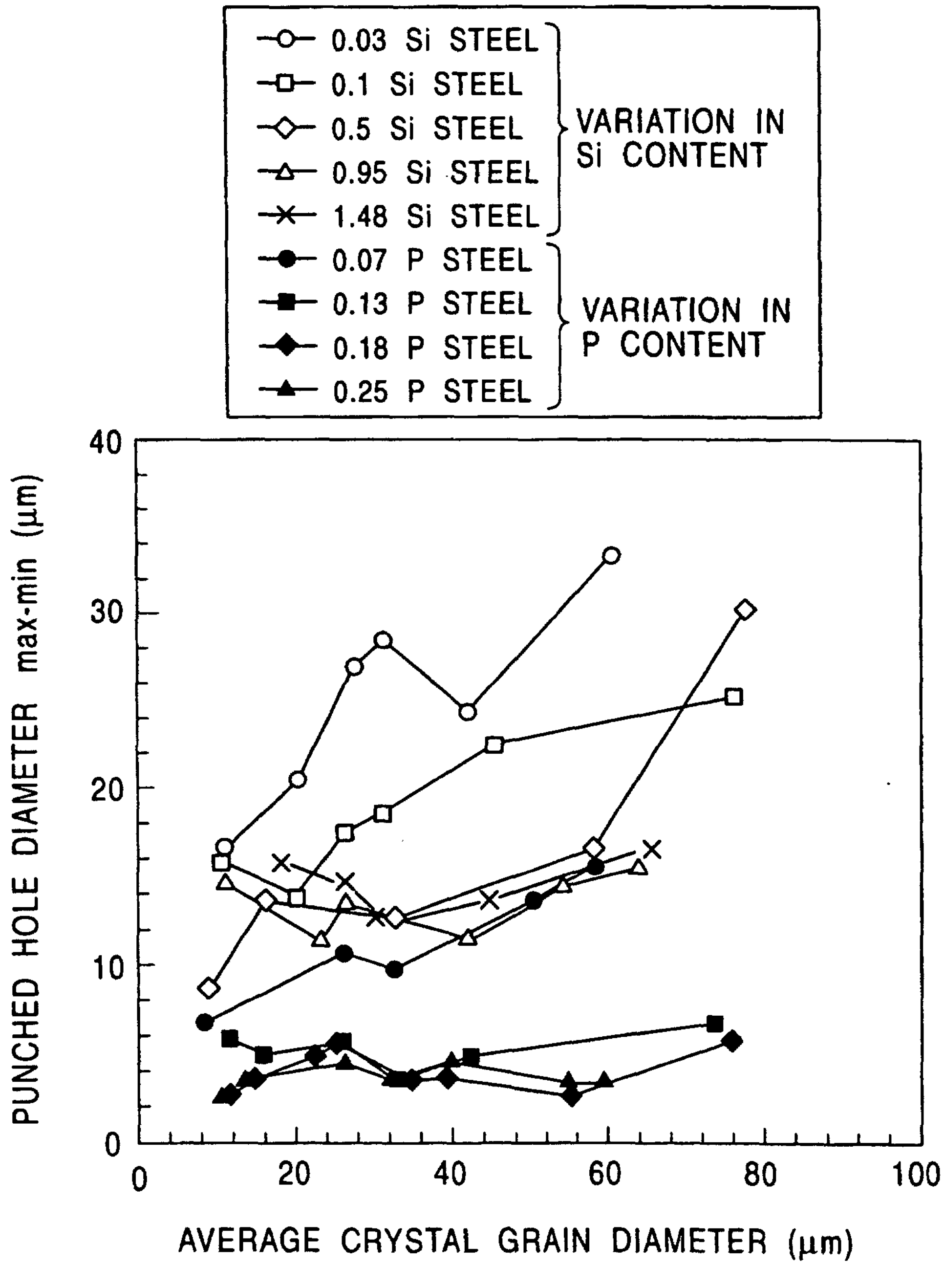

0.03 Si STEEL
0.1 Si STEEL
0.5 Si STEEL
0.95 Si STEEL
1.48 Si STEEL
VARIATION IN Si CONTENT
0.07 P STEEL
0.13 P STEEL
0.18 P STEEL
0.25 P STEEL
VARIATION IN P CONTENT
PUNCHED HOLE DIAMETER max-min (μm)
AVERAGE CRYSTAL GRAIN DIAMETER (μm)
0
10
20
30
40
0
20
40
60
80
100

FIG. 5

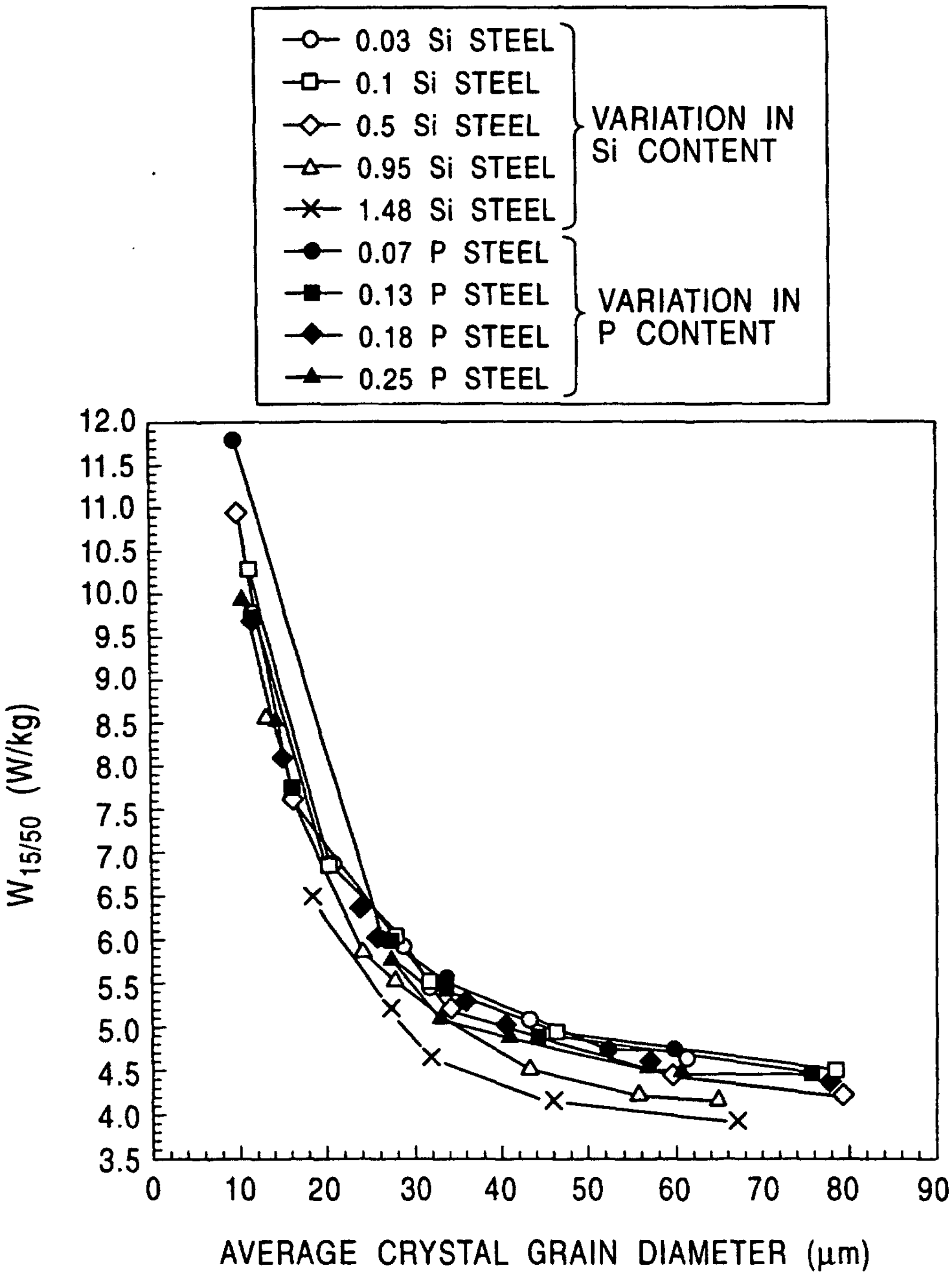
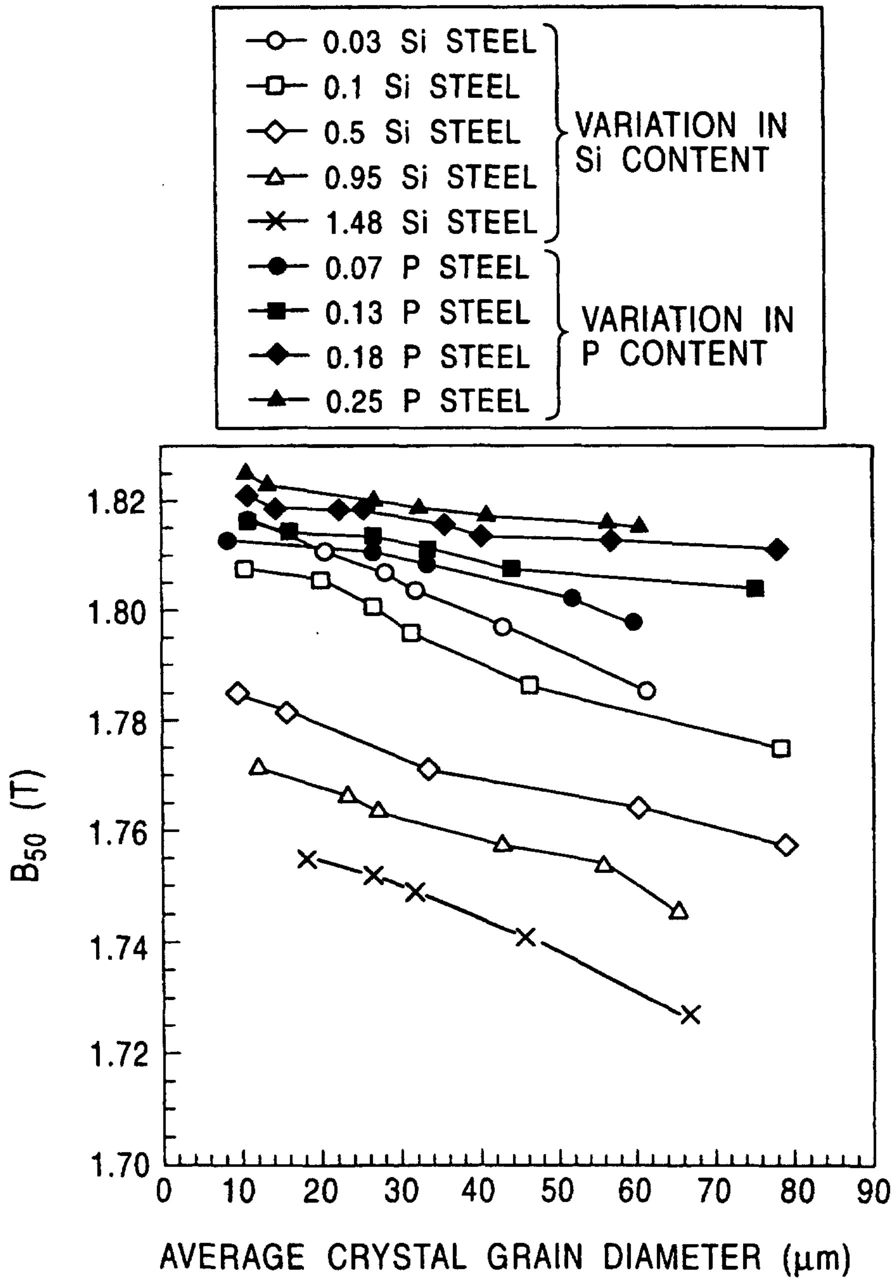

0.03 Si STEEL
0.1 Si STEEL
0.5 Si STEEL
0.95 Si STEEL
1.48 Si STEEL
VARIATION IN Si CONTENT
0.07 P STEEL
0.13 P STEEL
0.18 P STEEL
0.25 P STEEL
VARIATION IN P CONTENT
W15/50 (W/kg)
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0
10
20
30
40
50
60
70
80
90
AVERAGE CRYSTAL GRAIN DIAMETER (μm)

FIG. 6


0.03 Si STEEL
0.1 Si STEEL
0.5 Si STEEL
0.95 Si STEEL
1.48 Si STEEL
VARIATION IN Si CONTENT
0.07 P STEEL
0.13 P STEEL
0.18 P STEEL
0.25 P STEEL
VARIATION IN P CONTENT
B50 (T)
1.70
1.72
1.74
1.76
1.78
1.80
1.82
0
10
20
30
40
50
60
70
80
90
AVERAGE CRYSTAL GRAIN DIAMETER (μm)

# FIG. 7

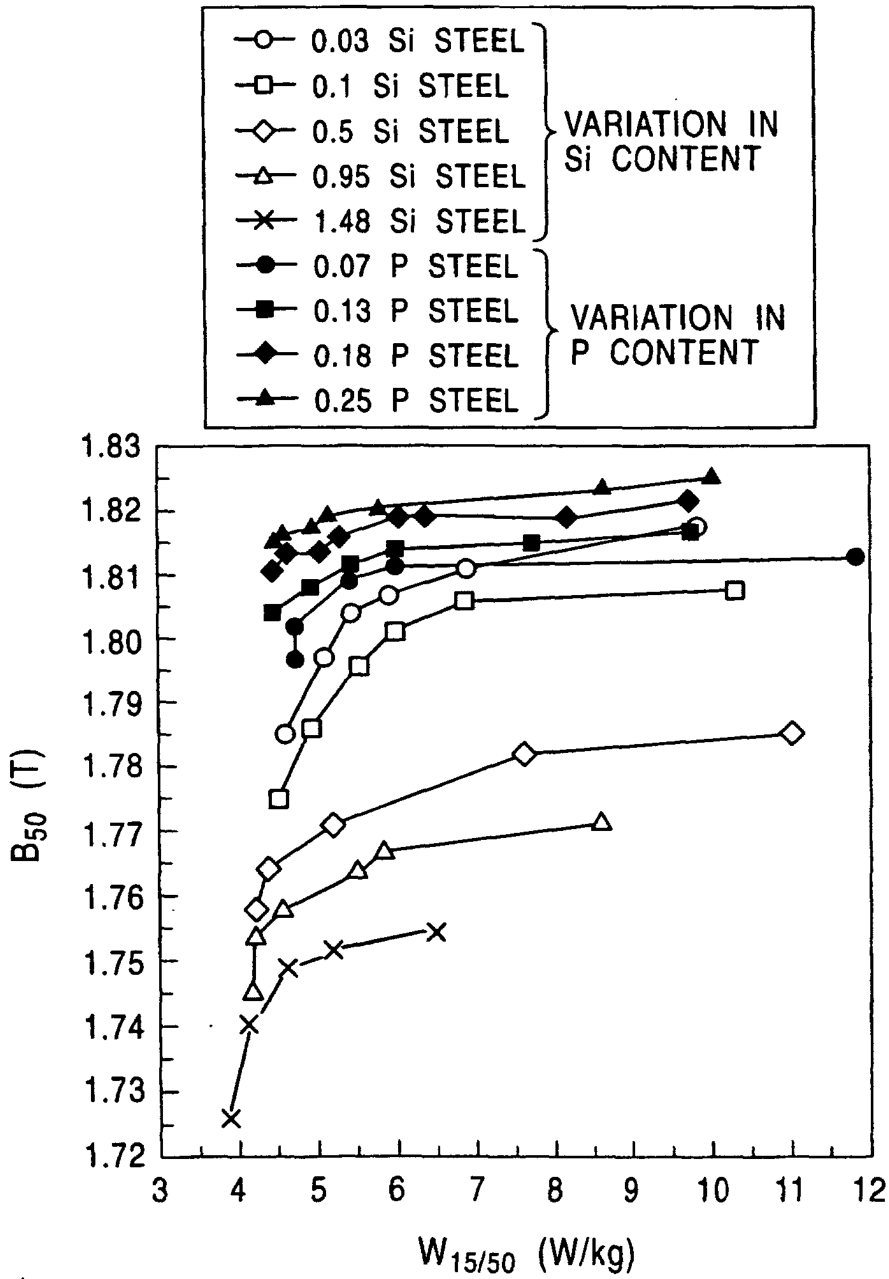

0.03 Si STEEL
0.1 Si STEEL
0.5 Si STEEL
0.95 Si STEEL
1.48 Si STEEL
VARIATION IN Si CONTENT
0.07 P STEEL
0.13 P STEEL
0.18 P STEEL
0.25 P STEEL
VARIATION IN P CONTENT
1.83
1.82
1.81
1.80
1.79
1.78
1.77
1.76
1.75
1.74
1.73
1.72
$B_{50}$ (T)
3 4 5 6 7 8 9 10 11 12
$W_{15/50}$ (W/kg)

FIG. 8

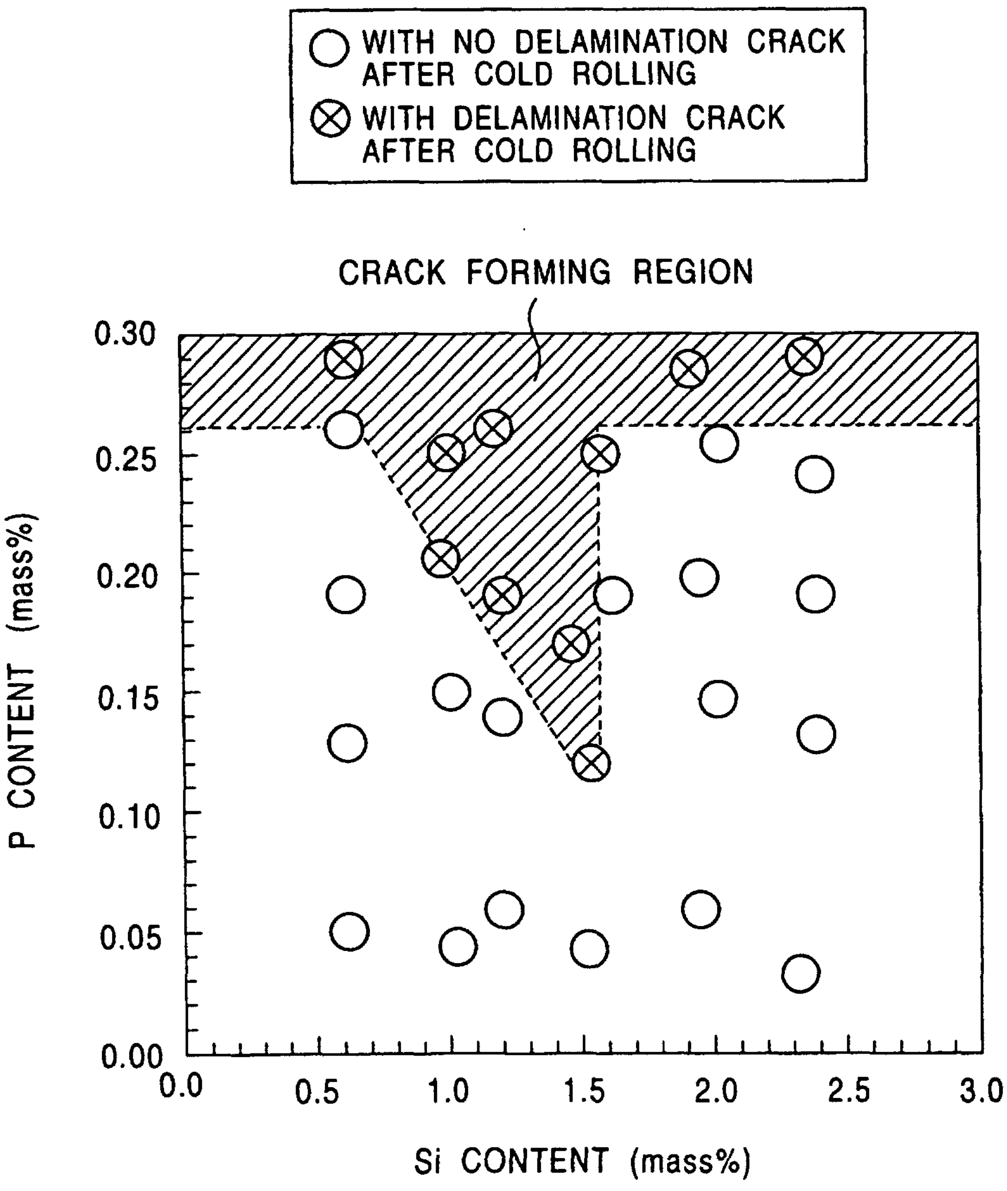
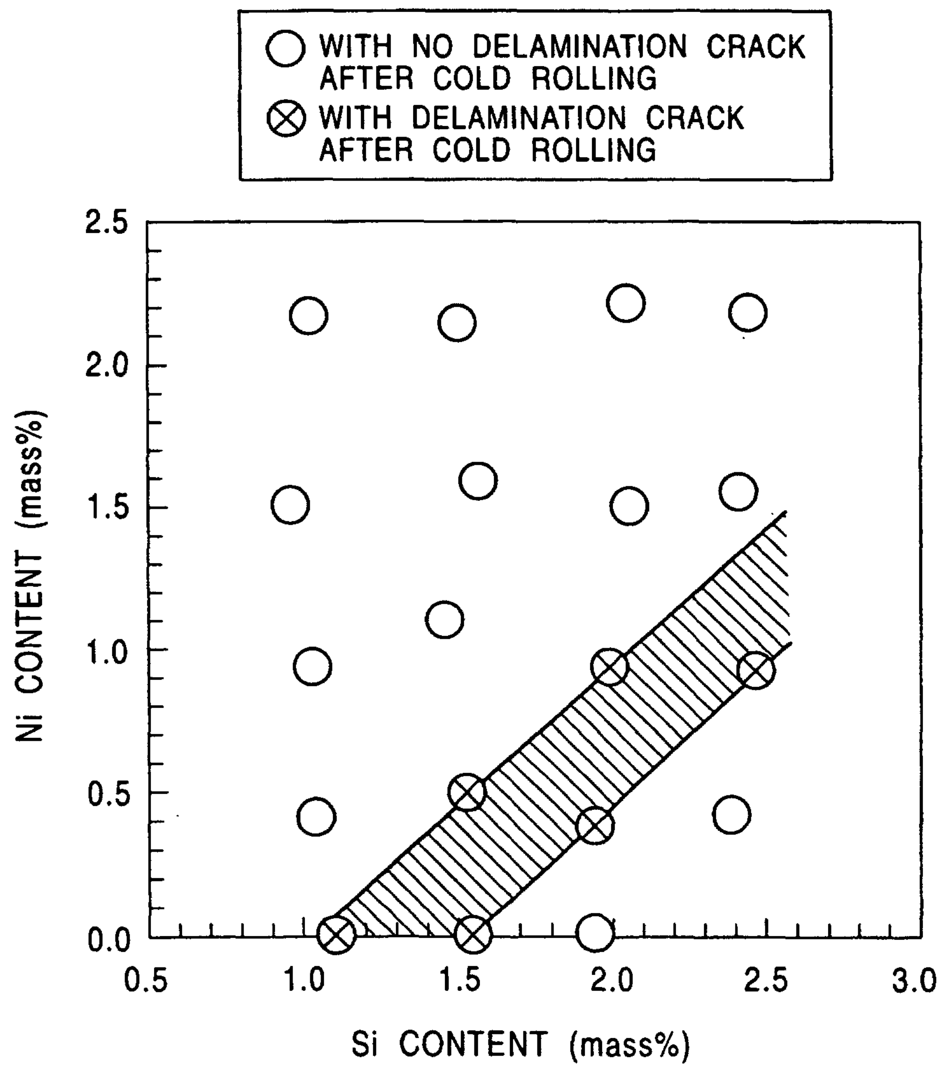
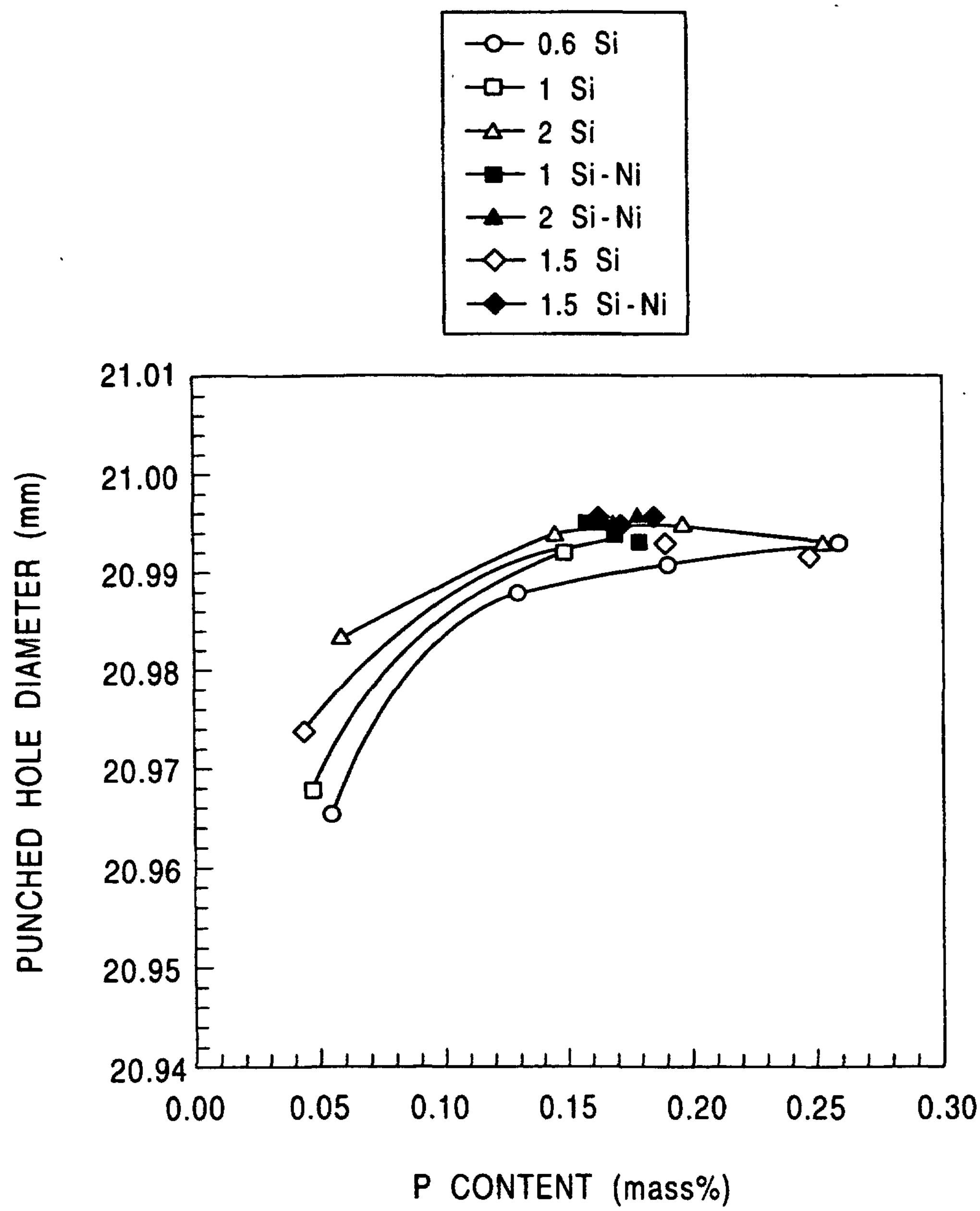

WITH NO DELAMINATION CRACK AFTER COLD ROLLING
WITH DELAMINATION CRACK AFTER COLD ROLLING
CRACK FORMING REGION
0.30
0.25
0.20
0.15
0.10
0.05
0.00
P CONTENT (mass%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Si CONTENT (mass%)

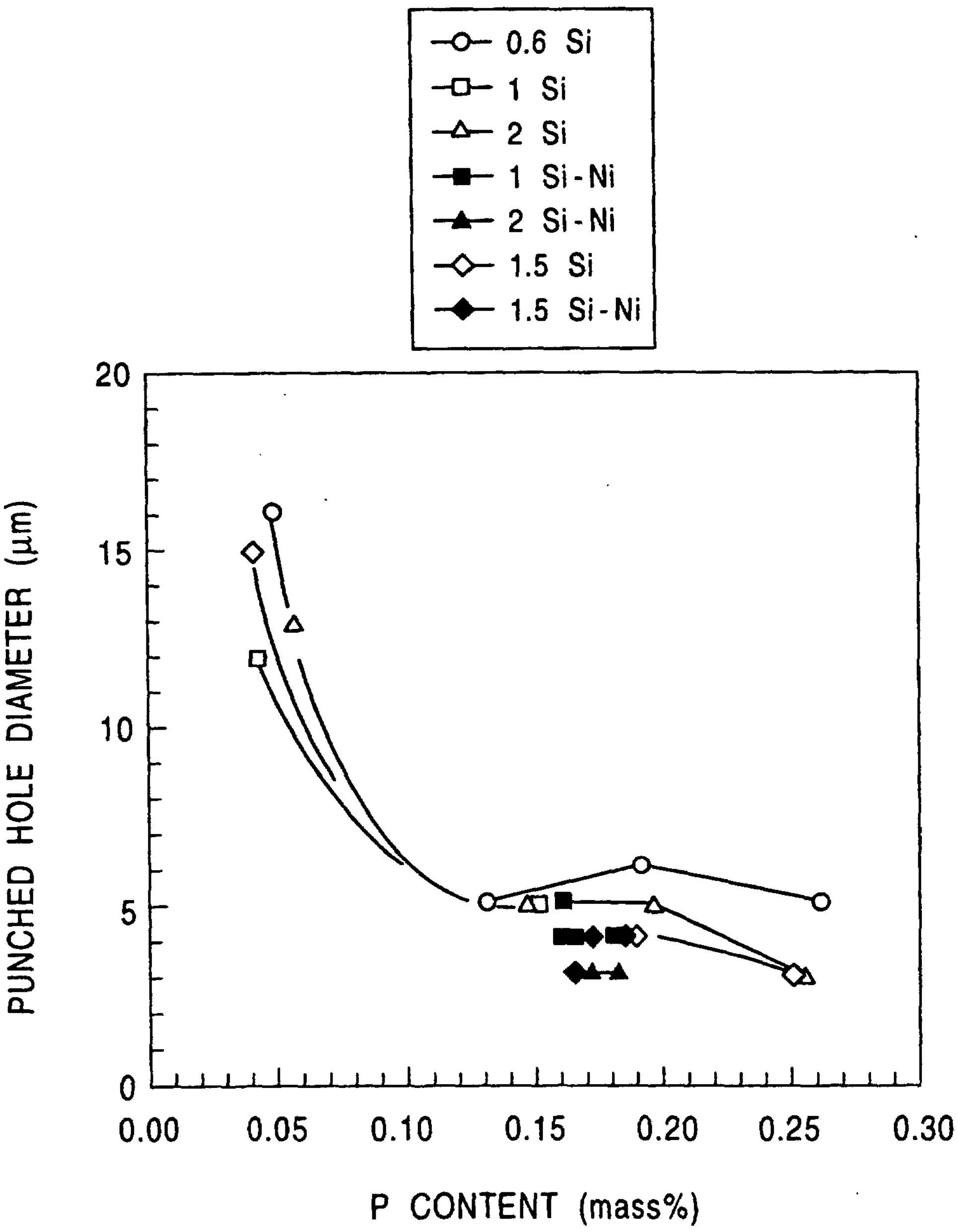
FIG. 9


WITH NO DELAMINATION CRACK AFTER COLD ROLLING
WITH DELAMINATION CRACK AFTER COLD ROLLING
Ni CONTENT (mass%)
Si CONTENT (mass%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

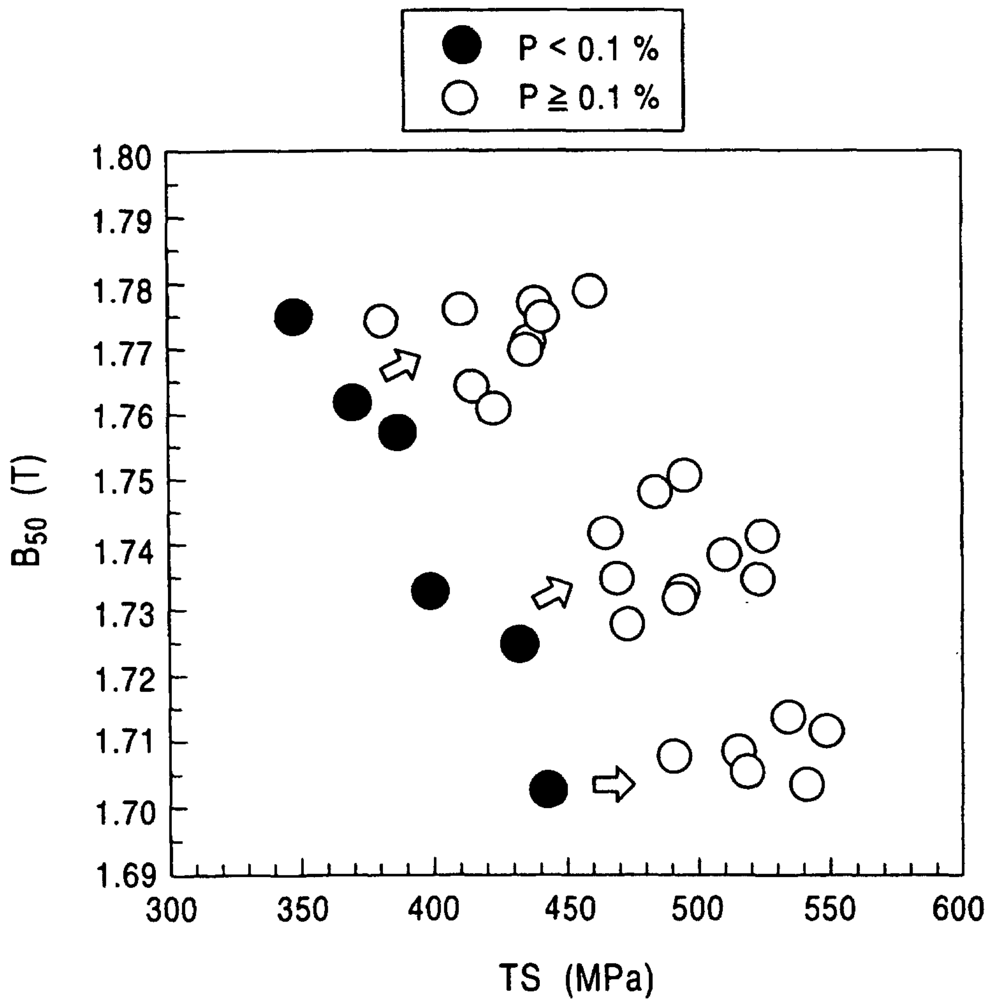
# FIG. 10


0.6 Si
1 Si
2 Si
1 Si-Ni
2 Si-Ni
1.5 Si
1.5 Si-Ni
21.01
21.00
20.99
20.98
20.97
20.96
20.95
20.94
0.00
0.05
0.10
0.15
0.20
0.25
0.30
PUNCHED HOLE DIAMETER (mm)
P CONTENT (mass%)

# FIG. 11

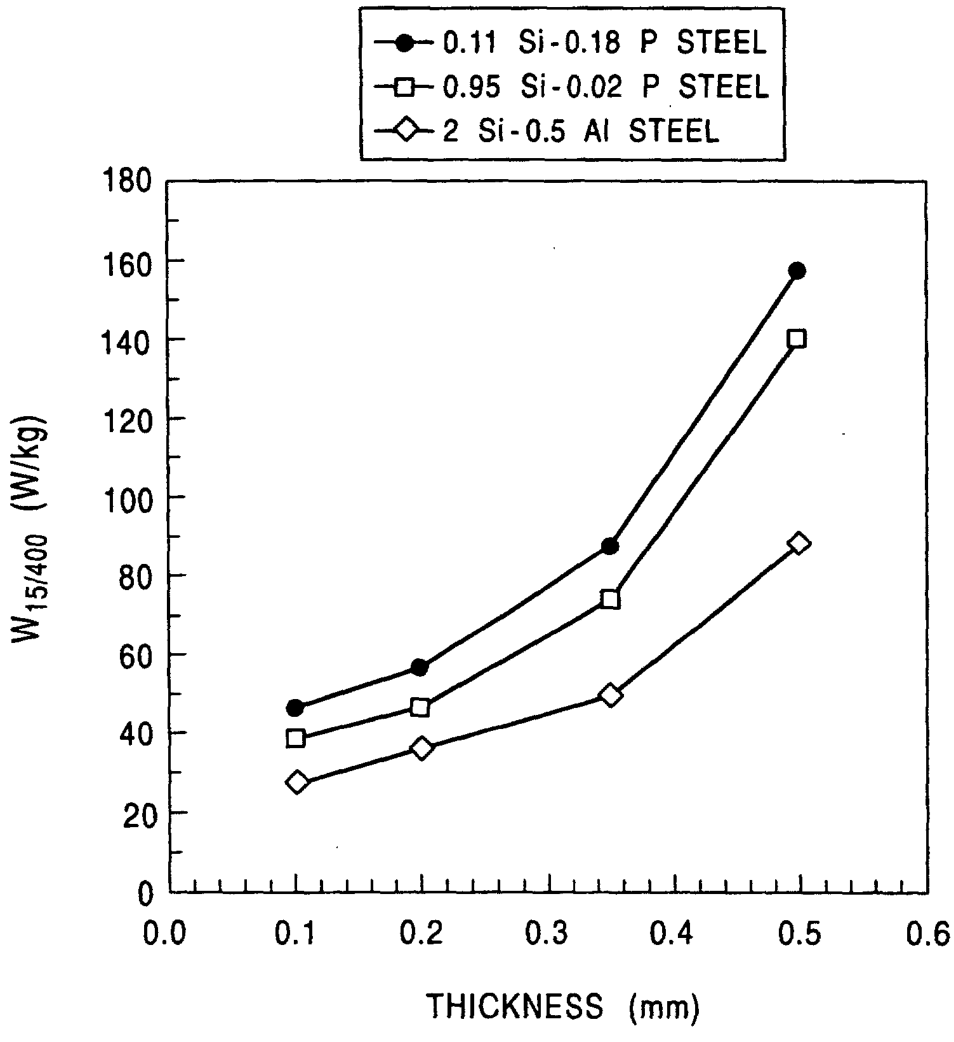

0.6 Si
1 Si
2 Si
1 Si-Ni
2 Si-Ni
1.5 Si
1.5 Si-Ni
PUNCHED HOLE DIAMETER (μm)
0
5
10
15
20
0.00
0.05
0.10
0.15
0.20
0.25
0.30
P CONTENT (mass%)

# FIG. 12



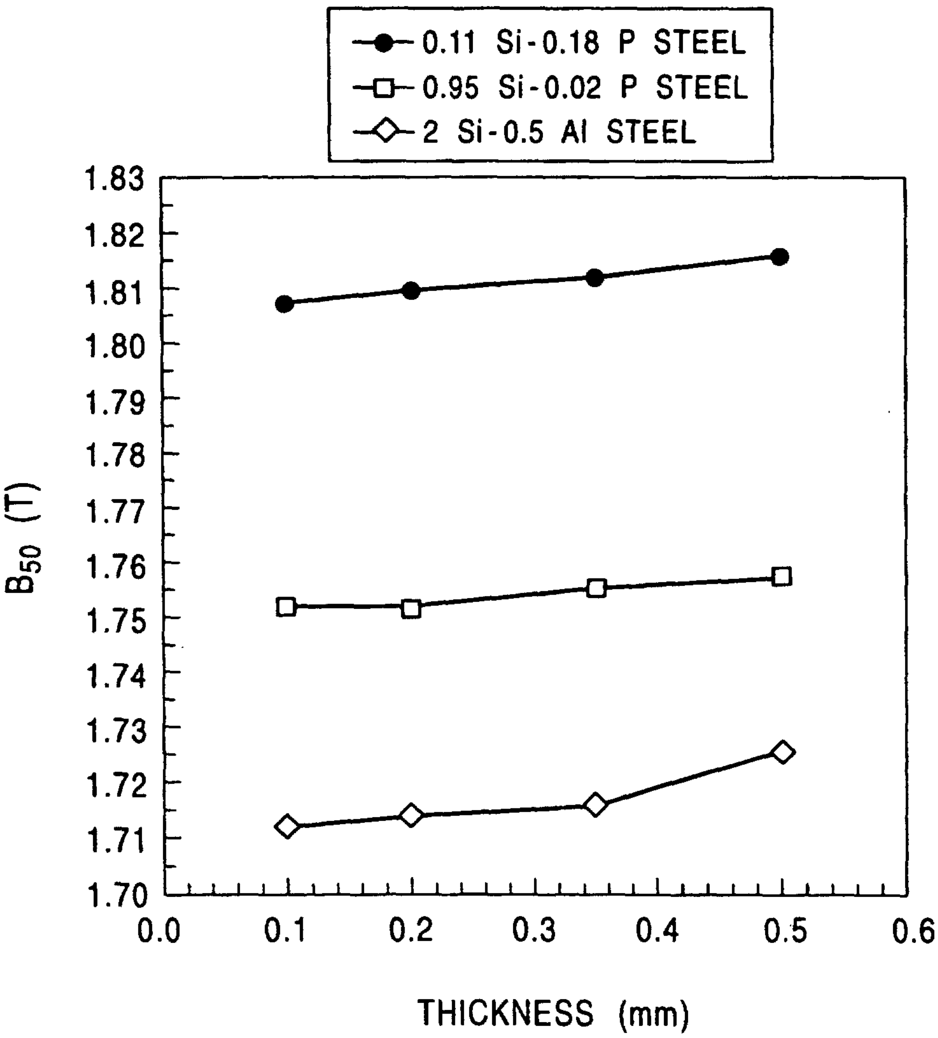
P < 0.1 %
P ≧ 0.1 %
1.80
1.79
1.78
1.77
1.76
1.75
1.74
1.73
1.72
1.71
1.70
1.69
B50 (T)
300
350
400
450
500
550
600
TS (MPa)

# FIG. 13



0.11 Si-0.18 P STEEL
0.95 Si-0.02 P STEEL
2 Si-0.5 Al STEEL
$W_{15/400}$ (W/kg)
180
160
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
THICKNESS (mm)

FIG. 14


0.11 Si-0.18 P STEEL
0.95 Si-0.02 P STEEL
2 Si-0.5 Al STEEL
1.83
1.82
1.81
1.80
1.79
1.78
1.77
1.76
1.75
1.74
1.73
1.72
1.71
1.70
B50 (T)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
THICKNESS (mm)

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP02/06458

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl[7] C22C38/00, 38/06, 38/60, C21D9/46, B21B3/02, H01F1/16

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)
Int.Cl[7] C22C38/00-60, C21D8/12, 9/46-48, B21B3/02, H01F1/16-18

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

| | | | |
|---|---|---|---|
| Jitsuyo Shinan Koho | 1926-1996 | Toroku Jitsuyo Shinan Koho | 1994-2002 |
| Kokai Jitsuyo Shinan Koho | 1971-2002 | Jitsuyo Shinan Toroku Koho | 1996-2002 |

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br>Y | JP 2599529 B2 (Nippon Steel Corp.),<br>09 January, 1997 (09.01.97),<br>Claims; table 1<br>(Family: none) | 2<br>1,3-5,7 |
| Y | US 6340399 B1 (Nippon Steel Corp.),<br>22 January, 2002 (22.01.02),<br>& JP 2001-59145 A & CN 1278016 A<br>& KR 2001007290 A | 1,4,5,8 |
| Y | JP 4-25346 B2 (Nippon Steel Corp.),<br>30 April, 1992 (30.04.92),<br>Claims<br>(Family: none) | 3,6 |

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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|---|---|---|
| X<br>Y | JP 11-12700 A (NKK Corp.),<br>19 January, 1999 (19.01.99),<br>Claims; table 1<br>(Family: none) | 6,11<br>7,8 |
| X | JP 9-263908 A (Sumitomo Metal Industries, Ltd.),<br>07 October, 1997 (07.10.97),<br>Claims<br>(Family: none) | 9,10 |
| X | JP 6-86648 B2 (Sumitomo Metal Industries, Ltd.),<br>02 November, 1994 (02.11.94),<br>Claims; columns 4 to 5<br>(Family: none) | 9,10 |

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