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- **SHEN, Kanyi**
Shanghai 201900 (CN)
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- **MA, Changsong**
Shanghai 201900 (CN)
- **HU, Zhining**
Shanghai 201900 (CN)
- **XIAO, Wen**
Shanghai 201900 (CN)

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(71) Applicant: **BAOSHAN IRON & STEEL CO., LTD.**
Shanghai 201900 (CN)

(72) Inventors:

- **ZHANG, Huabing**
Shanghai 201900 (CN)
- **LI, Guobao**
Shanghai 201900 (CN)

(74) Representative: **Maiwald GmbH**
Elisenhof
Elisenstraße 3
80335 München (DE)

(54) **HIGH-MAGNETIC-INDUCTION ORIENTED SILICON STEEL AND MANUFACTURING METHOD THEREFOR**

(57) The present disclosure relates to an oriented silicon steel having high magnetic induction, in addition to Fe and inevitable impurities, comprising the following chemical elements in mass percentage: C $\leq$ 0.005%; Si: 3.0-3.8%; Als: 0.010-0.035%; Mn: 0.05-0.20%; wherein in the inevitable impurities, N $\leq$ 0.005%, S $\leq$ 0.005%, V $\leq$ 0.005%, and Ti $\leq$ 0.005%. The average secondary grain

size of the oriented silicon steel having high magnetic induction is 6-16 mm; and the area percentage of secondary grains with an average deviation angle in the range of 0° to 3° accounts for > 50% of all secondary grains. Correspondingly, the present disclosure also provides a method for manufacturing the oriented silicon steel having high magnetic induction.

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Description

TECHNICAL FIELD

5 [0001] The present disclosure relates to a steel and a manufacturing method therefor, in particular to an oriented silicon steel and a manufacturing method therefor.

BACKGROUND ART

10 [0002] Oriented silicon steel is a soft magnetic material having excellent magnetic properties, consisting of crystal grains known as Goss texture. The Goss texture is expressed by Miller indices such as $\{110\}\langle 001 \rangle$, where the $\{110\}$ crystal plane of the grains is parallel to the rolling plane, and the $\langle 001 \rangle$ crystal direction of the grains is parallel to the rolling direction. The $\langle 001 \rangle$ crystal direction of iron has the best easy magnetization performance under a directional magnetic field. By fully utilizing the anisotropy of magnetocrystalline, the optimal magnetic performance of polycrystalline materials can be achieved. For transformer cores made of oriented silicon steel, under the working conditions of a directional magnetic field, materials and electrical energy can be saved significantly due to their extremely high magnetic induction and extremely low iron loss.

15 [0003] Generally, the magnetic performance level of oriented silicon steel is characterized by iron loss $P_{17/50}$ and magnetic induction B_8 , where $P_{17/50}$ represents the iron loss per kg of the sample at a magnetic induction of 1.7 T and a frequency of 50 Hz; B_8 represents the magnetic induction corresponding to a magnetic field intensity of 800 A/m. These two parameters can effectively reflect the superiority or inferiority of the magnetic performance of oriented silicon steel under different magnetic field and frequency conditions.

20 [0004] In order to obtain a finished plate with abnormal growth of Goss grains, the conventional manufacturing processes all require complex procedures to achieve the control of the evolution of microstructure, texture, and inhibitors throughout the entire process. The manufacturing processes of oriented silicon steel can be divided according to the rolling process into a single cold rolling method and a double cold rolling method. The single cold rolling method is used to manufacture oriented silicon steel having high magnetic induction with AlN and MnS as the main inhibitors, while the double cold rolling method is used to manufacture regular oriented silicon steel with MnS and Cu_2S as the main inhibitors. The manufacturing processes can also be divided according to the slab heating temperature into a low-temperature slab heating process and a high-temperature slab heating process, wherein the low-temperature slab heating process has a slab heating temperature below 1250°C.

25 [0005] Since the low-temperature slab heating process can produce oriented silicon steel having high magnetic induction at a lower cost, such process has developed rapidly and gradually become the mainstream. In the low-temperature slab heating process, the inhibitors originate from the pre-existing inclusions in the slab, which are called primary inhibitors and have an important influence on primary recrystallization, thereby also affecting the magnetic performance of the final product; and from inclusions formed by nitriding treatment after decarburization annealing, which are called secondary inhibitors and promote secondary recrystallization together with the primary inhibitors. Although the low-temperature slab heating process makes inhibitor control difficult and the annealing process window narrow, with the application of some improved processes, such as adding auxiliary inhibitors, controlling inclusion morphology, and adopting rapid induction heating, the product grade of such process continues to improve.

30 [0006] To improve transformer efficiency, the fundamental measure is to improve the magnetic performance of the core material, which requires the core material to have properties of low iron loss and high magnetic induction. In particular, iron loss is determined not only by the material itself but also the operating frequency and magnetic induction of the material in an alternating magnetic field. As for magnetic induction, its value is mainly affected by the degree of Goss grain orientation of the material. The degree of grain orientation refers to the alignment direction and extent of the grains in the material. Generally, the higher the degree of Goss grain orientation, the higher the magnetic induction of the oriented silicon steel.

35 [0007] The iron loss of oriented silicon steel mainly consists of hysteresis loss and eddy current loss, of which eddy current loss accounts for the major part. Commonly used technologies to reduce the iron loss of oriented silicon steel include: improving the degree of grain orientation, reducing the strip steel thickness, and refining magnetic domains by scribing. However, as the manufacturing technology of oriented silicon steel continues to develop, improving the degree of grain orientation and refining magnetic domains by scribing have entered a relatively mature stage, offering limited potential on magnetic performance improvement. Therefore, reducing the strip steel thickness has become the main route of reducing the iron loss of oriented silicon steel at present.

40 [0008] The strip steel thickness has significant influence on the total loss of the iron core. By reducing the strip steel thickness, eddy current loss can be effectively suppressed, thereby significantly reducing the total loss of the iron core. As the number of stacked sheets increases, the total loss of a core of equal volume decreases at an accelerated rate. It should be noted that if the strip steel thickness is too thin, it may lead to sharply increased manufacturing costs, and due to the increase in hysteresis loss, the magnetic performance will also significantly deteriorate. Therefore, when choosing to

reduce the strip steel thickness, it is necessary to comprehensively consider the balance between manufacturing cost and magnetic performance.

[0009] Although reducing the strip steel thickness can lower iron loss, there are also some challenges and limitations. First, the reduction in the number of effective Goss nuclei: the specific surface area increases significantly with the decrease of strip steel thickness, which correspondingly reduce the number of effective Goss nuclei, and at the same time, the coarsening and decomposition of inhibitors during annealing intensify, weakening the inhibition effect. This will adversely affect the secondary recrystallization process, thereby affecting the magnetic performance of the product. Second, control of cold rolling reduction rate: in order to obtain the desired primary recrystallization texture, an appropriate cold rolling reduction rate needs to be ensured. However, if the strip steel thickness is too thin, the hot-rolled coil thickness must also be reduced, which increases the difficulty of controlling the shape of the hot-rolled plate and worsens the stability of hot rolling process. Third, the reduction in production efficiency of the hot-rolled plate annealing line: reducing the hot-rolled plate thickness leads to a significant decrease in the production efficiency of the annealing line. When the hot-rolled plate thickness is reduced from 2.6 mm to 1.8 mm, the line efficiency decreases by about 30%. It is precisely because of the above problems that, under the premise of ensuring product quality and production stability, the finished product thickness obtained by the existing oriented silicon steel manufacturing process is mostly between 0.23 and 0.30 mm, making further thickness reduction difficult.

[0010] In addition, to achieve the desired inhibitor distribution, hot-rolled plate annealing has become an indispensable process step for producing oriented silicon steel having high magnetic induction. During the hot-rolled plate annealing, the hot-rolled pickled plate is rapidly heated to about 1120°C, held for 2-4 minutes, air-cooled to about 900°C, and then water-quenched, or a two-stage treatment is applied where it is air-cooled, held for another 2 minutes, and then water-quenched. The surface recrystallized grains of the annealed hot-rolled plate grow, the rapid cooling process generates a certain amount of martensitic structure; and the rapid cooling and phase transformation stresses also produce mechanical twins. These factors all increase the difficulty of cold rolling. Due to reasons such as hot-rolled plate annealing and a large primary reduction rate, the conventional oriented silicon steel having high magnetic induction needs to be cold rolled using a twenty-high reversing rolling mill with high rolling stress, making it difficult to improve rolling efficiency.

[0011] In order to efficiently manufacture thin-gauge oriented silicon steel having high magnetic induction, several new manufacturing technologies for oriented silicon steel have been developed in recent years.

[0012] For example, a Chinese patent application with publication No. CN116460139A, publication date July 21, 2023, titled "An ultra-thin oriented silicon steel having high magnetic induction and rolling method thereof" discloses an ultra-thin oriented silicon steel having high magnetic induction and a rolling method thereof. In the technical solution, the final finished product thickness obtained is 0.12-0.20 mm. The main difference between the method and conventional manufacturing process of the oriented silicon steel having high magnetic induction lies in the rolling process, wherein the reversing rolling adopted by the conventional single cold rolling process is changed to a combined rolling of tandem cold rolling plus reversing rolling, wherein the diameter of the working roll in the tandem cold rolling is 300-500 mm, and the total reduction rate is 60-91%, while the diameter of the working roll in the reversing rolling is 70-150 mm, and the total reduction rate is 10-50%. Compared with conventional preparation processes, this technical solution only adjusts the cold rolling method, which has a limited effect on reducing the manufacturing cost of thin-gauge oriented silicon steel and improving product's magnetic performance. It also fails to solve the problem of difficult cold rolling after hot-rolled plate annealing of the conventional oriented silicon steel.

[0013] For another example, a Chinese patent application with publication No. CN114134423A, publication date March 4, 2022, titled "An ultra-short process rare earth oriented silicon steel and preparation method thereof" discloses a solution for preparing oriented silicon steel by a thin strip continuous casting process. The production process of the technical solution includes steps of molten steel smelting, thin strip continuous casting, cold rolling, primary recrystallization annealing, applying separator, secondary recrystallization annealing, etc., which directly obtains a cast strip with a thickness of 2-2.5 mm, and finished product thickness of the prepared oriented silicon steel is 0.20-0.35 mm, with an iron loss $P_{17/50}$ of 0.9-1.1 W/kg, and a magnetic induction B_8 of 1.87-1.95 T. Compared with the conventional process, this technical solution eliminates important procedures such as continuous casting, rough rolling, hot continuous rolling, and normalization-related heating in the conventional process, having obvious cost advantages. However, the production stability and product magnetic performance of the thin strip continuous casting technology need improvement.

SUMMARY OF THE DISCLOSURE

[0014] One objective of the present disclosure is to provide an oriented silicon steel, wherein the magnetic induction of the oriented silicon steel is improved by precisely controlling the steel composition, microstructure, and especially the size and proportion of grains in the oriented silicon steel. The present disclosure also provides a method for manufacturing the oriented silicon steel having high magnetic induction. Through the design of a reasonable process route, under the premise of eliminating the hot-rolled plate annealing step, a thin-gauge oriented silicon steel having high magnetic induction can be obtained, thereby reducing manufacturing costs while improving product magnetic performance.

[0015] To achieve the above objective, the present disclosure provides an oriented silicon steel having high magnetic induction, in addition to Fe and inevitable impurities, comprising the following chemical elements in mass percentage:

C $\leq$ 0.005%;
 Si: 3.0-3.8%;
 Als: 0.010-0.035%;
 Mn: 0.05-0.20%;
 wherein in the inevitable impurities, N $\leq$ 0.005%, S $\leq$ 0.005%, V $\leq$ 0.005%, Ti $\leq$ 0.005%.

[0016] The average secondary grain size of the above oriented silicon steel having high magnetic induction is 6-16 μ m; wherein the area percentage of secondary grains with an average deviation angle $(\alpha+\beta)/2$ in the range of 0° to 3° accounts for >50% of all secondary grains.

[0017] In the present disclosure, the average deviation angle is $(\alpha+\beta)/2$, wherein α is the rolling direction deviation angle, which is the deviation angle of the [001] crystal direction of the grain within the rolling plane (RD-TD plane) relative to the rolling direction (RD). In oriented silicon steel having high magnetic performance, it is generally desired that the [001] direction of the crystal is consistent with, or very close to, the rolling direction. The smaller the α angle, the better the magnetic performance. β is the rolling plane tilt angle, which is the tilt angle of the [001] crystal direction of the grain relative to the rolling plane. β has an optimal value of about 2°, at which point the total loss reaches a minimum. The higher the area percentage of secondary grains with an average deviation angle in the range of 0° to 3° relative to all secondary grains, the better the magnetic performance of the oriented silicon steel. In the present disclosure, the area percentage of secondary grains with an average deviation angle in the range of 0° to 3° accounts for >50% of all secondary grains, indicating that the oriented silicon steel of the present disclosure has excellent magnetic performance.

[0018] Preferably, in the oriented silicon steel having high magnetic induction of the present disclosure, the oriented silicon steel has the following chemical elements in mass percentage:

C $\leq$ 0.005%;
 Si: 3.0-3.8%;
 Als: 0.010-0.035%;
 Mn: 0.05-0.20%; and
 the balance is Fe and inevitable impurities; wherein in the inevitable impurities, N $\leq$ 0.005%, S $\leq$ 0.005%, V $\leq$ 0.005%, Ti $\leq$ 0.005%.

[0019] In the oriented silicon steel having high magnetic induction of the present disclosure, the design principles of each chemical element are as follows:

C: In the oriented silicon steel having high magnetic induction of the present disclosure, excessive C will precipitate fine and dispersed ϵ -carbide precipitates in the material, causing a magnetic aging phenomenon, i.e., the magnetic performance of the material changes with service time. Therefore, C is a residual element in the present disclosure, and during the production process of oriented silicon steel, C needs to be purified and removed in steps such as decarburization annealing and high-temperature annealing. On this basis, in the oriented silicon steel having high magnetic induction of the present disclosure, the mass percentage of C element is limited to C $\leq$ 0.005%.

[0020] **Si:** In the oriented silicon steel having high magnetic induction of the present disclosure, Si is a basic element in oriented silicon steel, which can increase electrical resistivity and reduce iron loss. It should be noted that when the mass percentage of Si in the steel is below 3.0%, the electrical resistivity of the material will decrease, and the eddy current loss of the oriented silicon steel cannot be effectively reduced. Meanwhile, the Si content in the steel should not be too high. When the mass percentage of Si in the steel is above 3.8%, due to the tendency of Si to segregate at grain boundaries, it will increase the brittleness of the steel plate, deteriorate rollability, and also make the recrystallization structure and inhibitors unstable, resulting in incomplete secondary recrystallization. On this basis, in the oriented silicon steel having high magnetic induction of the present disclosure, the mass percentage of Si element is controlled between 3.0 and 3.8%.

[0021] **Acid-soluble aluminum (Als):** In the oriented silicon steel having high magnetic induction of the present disclosure, Als can form secondary inhibitors during the subsequent nitriding treatment of the material, which can interact with primary inhibitors to form sufficient pinning strength to promote secondary recrystallization. However, it should be noted that when the mass percentage of Als in the steel is below 0.010%, the pinning strength of the inhibitors will be insufficient, the directional inhibition effect will be weakened, and secondary recrystallization will be incomplete, or even fail to occur; if the mass percentage of Als in the steel is above 0.035%, the nitrides of Als will coarsen, the inhibitor effect will decrease, and the magnetic performance of the material will deteriorate. On this basis, in the oriented silicon steel having high magnetic induction of the present disclosure, the mass percentage of Als is controlled between 0.010 and 0.035%.

[0022] **Mn:** In the oriented silicon steel having high magnetic induction of the present disclosure, the Mn element, similar to the Si element, can increase electrical resistivity and reduce eddy current loss. In addition, the Mn element can also

expand the γ phase region, which provides the effect of improving hot-rolling plasticity and microstructure, thereby effectively improving the hot-roll rollability of the material. However, it should be noted that when the mass percentage of Mn in the steel is below 0.05%, the above effects cannot be effectively exhibited; if the mass percentage of Mn incorporated to the steel is above 0.20%, α and γ mixed dual-phase structures are prone to appear, causing phase transformation stress and generating γ phase during annealing, resulting in unstable secondary recrystallization. On this basis, in the oriented silicon steel having high magnetic induction of the present disclosure, the mass percentage of Mn element is controlled between 0.05 and 0.20%.

[0023] S and N: In the oriented silicon steel having high magnetic induction of the present disclosure, excessive S or N will precipitate fine and dispersed precipitates such as MnS and Fe_{16}N_4 in the material, causing magnetic aging phenomenon, i.e., the magnetic performance of the material changes with service time. Therefore, S and N are impurity elements in the present disclosure. During the manufacturing process of oriented silicon steel, S and N need to be purified and removed in steps such as decarburization annealing and high-temperature annealing. On this basis, in the oriented silicon steel having high magnetic induction of the present disclosure, the mass percentage of S element is limited to $S \leq 0.005\%$, and the mass percentage of N element is limited to $N \leq 0.005\%$.

[0024] V and Ti: In the oriented silicon steel having high magnetic induction of the present disclosure, V and Ti are impurity elements. V element will form VN after the material undergoes nitriding treatment, affecting secondary recrystallization, which is not conducive to the magnetic performance of the material. As for the Ti element, because it can preferentially precipitate TiN, MnS then precipitates on TiN, and subsequently AlN precipitates on MnS, thus coarse MnS+AlN composite inclusions are easily formed, which is also detrimental to the magnetic performance of the material. In addition, reducing the contents of Ti and V can also reduce the harmful inclusions of TiN and VN in the finished product. On this basis, in the oriented silicon steel having high magnetic induction of the present disclosure, the mass percentage of Ti element is limited to $\text{Ti} \leq 0.005\%$, and the mass percentage of V element is limited to $V \leq 0.005\%$.

[0025] Preferably, the oriented silicon steel having high magnetic induction of the present disclosure further comprises at least one of the following chemical elements:

P: 0.01-0.08%; Cr: 0.01-0.40%; Sn: 0.03-0.30%; Cu: 0.01-0.40%; $0 < \text{Sb} \leq 0.1\%$; $0 < \text{Bi} \leq 0.1\%$; $0 < \text{Nb} \leq 0.1\%$; $0 < \text{Mo} \leq 0.1\%$.

[0026] In the oriented silicon steel having high magnetic induction of the present disclosure, each of the above chemical elements can further improve the performance of the oriented silicon steel having high magnetic induction of the present disclosure, and their design principles are as follows:

P: In the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, P is a grain boundary segregation element, which can play a role as an auxiliary inhibitor. During the secondary recrystallization process, even at high temperatures around 1000°C, the P element still has a grain boundary segregation effect, which can delay the premature oxidative decomposition of AlN, benefiting secondary recrystallization. At the same time, the P element can also increase the electrical resistivity of the material and reduce eddy current loss. However, it should be noted that when the mass percentage of P in the steel is below 0.01%, the above effects cannot be effectively exhibited; but when the mass percentage of P in the steel is above 0.08%, it will not only reduce the nitriding efficiency but also worsen the cold rollability. Therefore, in the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the added mass percentage of P can preferably be controlled between 0.01-0.08%.

[0027] Cr: In the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, incorporating Cr element can not only increase electrical resistivity but also improve the mechanical properties of the material, and by promoting the oxidation of the steel plate, surface quality can be improved significantly. To fully exhibit the effect of the Cr element, the mass percentage of Cr in the steel is usually higher than 0.01%. However, when the Cr content in the steel is higher than 0.40%, it will form a dense oxide layer during decarburization, thereby affecting the decarburization and nitriding efficiency. Therefore, in the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the mass percentage of added Cr can preferably be configured to 0.01-0.40%.

[0028] Sn: In the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, Sn is a grain boundary segregation element, which has the effect of an auxiliary inhibitor. It can effectively compensate for the decline in inhibition force caused by the coarsening of AlN inclusions when the Si content in the steel is increased or the strip steel thickness is reduced. It can expand the process window and is conducive to the stability of product's magnetic performance. However, considering that when the mass percentage of Sn is below 0.03%, the above effects cannot be effectively obtained; while when the mass percentage of Sn is above 0.30%, it will not only affect the decarburization efficiency but also cause poor surface quality, and the magnetic performance will not be improved, raising manufacturing costs. Therefore, in the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the added mass percentage of Sn can preferably be set to 0.03-0.30%.

[0029] Cu: In the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the incorporation of Cu is because the Cu element can expand the γ phase region, which helps to obtain fine

AlN inclusions, similar to Mn element. In addition to expanding the γ phase region, the Cu element can also preferentially combine with the S element prior to Mn to form Cu_2S , thereby helping to suppress the variation of primary grain size. When the mass percentage of incorporated Cu in the steel is below 0.01%, the above effects cannot be exhibited; but if the mass percentage of incorporated Cu in the steel is above 0.40%, it will increase manufacturing costs and the magnetic performance will not be improved. Therefore, in the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the added mass percentage of Cu can preferably be set to 0.01-0.40%.

[0030] Sb and Bi: In the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the incorporation of Sb and Bi is because Sb and Bi are also grain boundary segregation elements and both act as auxiliary inhibitors, which can improve the grain boundary migration conditions of Goss nuclei and widen the process window, improving the magnetic induction of the finished product. However, when the mass percentage of Sb and Bi in the steel is higher than 0.1%, it will not only affect the decarburization efficiency but also cause poor surface quality, and the magnetic performance will not be significantly improved, increasing manufacturing costs. Therefore, in the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the mass percentage of Sb can preferably be set to 0.1% or less, and the mass percentage of Bi can also preferably be set to 0.1% or less.

[0031] Nb and Mo: In the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the incorporation of Nb and Mo is because Nb and Mo are both effective grain-refining microalloying elements, which can promote the formation of a fine and uniform primary grain size, while the carbonitrides formed can also serve as auxiliary inhibitors, reducing the difficulty of adjusting the morphology of primary inhibitors. However, if the mass percentage of Nb and Mo exceeds 0.1%, it will have a strong inhibiting effect on recrystallization, and secondary recrystallization will be incomplete. Therefore, in the oriented silicon steel having high magnetic induction of the present disclosure, in some preferred embodiments, the mass percentage of Nb can preferably be set to 0.1% or less, and the mass percentage of Mo can preferably be set to 0.1% or less.

[0032] Preferably, the thickness of the oriented silicon steel having high magnetic induction of the present disclosure is 0.13-0.20 mm. Unless otherwise specified, in the present disclosure, the "oriented silicon steel having high magnetic induction" refers to the finished oriented silicon steel product.

[0033] Preferably, in the oriented silicon steel having high magnetic induction of the present disclosure, the area percentage of secondary grains with a size of < 6 mm or > 16 mm relative to all secondary grains is less than 15%. In the present disclosure, the secondary grain size of the oriented silicon steel is preferably between 6-16 mm, which helps to increase magnetic induction, reduce iron loss, and improve the stability of product performance.

[0034] Preferably, the oriented silicon steel having high magnetic induction of the present disclosure has an iron loss $P_{17/50}$, wherein $P_{17/50} \leq 0.86 + 2 \times \text{finished plate thickness} - 16 \times \text{Si}$, and a magnetic induction B_8 , wherein $B_8 \geq 2.14 - 6.5 \times \text{Si}$, wherein the finished plate thickness is in mm, the element symbol Si in the formula is substituted with the mass percentage of the Si element in the finished plate, wherein $P_{17/50}$ is in W/kg, and B_8 is in T.

[0035] The above formulas are empirical formulas obtained through optimization in the actual production. The present disclosure can better balance the iron loss and the magnetic induction by reasonably controlling the Si content in the oriented silicon steel. The oriented silicon steel that satisfies the above limitations for iron loss and magnetic induction has better comprehensive performance.

[0036] Another objective of the present disclosure is to provide a method for manufacturing the above oriented silicon steel having high magnetic induction. By adopting the method in conjunction with the above composition design, a thin-gauge oriented silicon steel having high magnetic induction can be obtained under the premise of eliminating the hot-rolled plate annealing step, thereby reducing manufacturing costs while improving product magnetic performance.

[0037] To achieve the above objective, the present disclosure provides a manufacturing method for an oriented silicon steel having high magnetic induction, comprising the following steps:

- (1) Smelting and casting to obtain a slab;
- (2) Heating the slab;
- (3) Hot rolling;
- (4) Primary cold rolling;
- (5) Intermediate annealing;
- (6) Secondary cold rolling;
- (7) Decarburization annealing, nitriding treatment, and applying a separator coating; an obtained decarburized and annealed plate has an average primary grain size of 6-18 μm , and a proportion of the number of Goss grains with an average deviation angle $(\alpha+\beta)/2$ of less than 15° is more than 1.5%;
- (8) High-temperature annealing;
- (9) Applying an insulation coating and flattening annealing.

[0038] In the manufacturing method of the present disclosure, the morphology of the inhibitors can be adjusted in step (5) intermediate annealing, rather than in the conventional hot-rolled plate annealing process. This modification can

eliminate the hot-rolled plate annealing process, such that the difficulty of cold rolling can be greatly reduced.

[0039] In the conventional decarburized plates of oriented silicon steel having high magnetic induction, the proportion of the number of Goss grains with an average deviation angle $(\alpha+\beta)/2$ of less than 15° is usually less than 1.5%. The reduction in strip thickness leads to the problem of an insufficient number of effective Goss nuclei, which adversely affects the magnetic performance of the product.

[0040] The present disclosure adopts a two-step cold rolling process including a primary cold rolling and a secondary cold rolling, which can better regulate the primary recrystallization structure, texture, and primary inhibitors, so that the decarburized plate in step (7) obtains a high proportion of Goss grains more easily. This means that the present disclosure can increase the number of effective Goss nuclei to solve the problems caused by reduced strip thickness, thereby improving the magnetic performance of the product.

[0041] Preferably, in step (2) of the manufacturing method of the present disclosure, the slab heating temperature is in the range of 1140°C to 1250°C .

[0042] Preferably, in step (4) of the manufacturing method of the present disclosure, the primary cold rolling adopts tandem cold rolling with a reduction rate of 50-75%.

[0043] Preferably, in step (6) of the manufacturing method of the present disclosure, the secondary cold rolling adopts tandem cold rolling with a reduction rate of 60-85%.

[0044] Although in the present disclosure, cold rolling steps (4) and/or (6) can also adopt conventional reversing rolling, tandem cold rolling is preferred from the perspective of improving rolling efficiency and yield.

[0045] In addition, in the manufacturing method of the present disclosure, by adopting the cold rolling reduction rates of step (4) and step (6) in the two-step cold rolling, it is beneficial for the decarburized plate to form fine and uniform recrystallized grains, and also beneficial for increasing the proportion of the number of Goss grains. Moreover, since the rolling efficiency and yield of tandem cold rolling are significantly superior to those of reversing rolling, the overall cold rolling efficiency in the present disclosure is also significantly improved.

[0046] Preferably, in step (5) of the manufacturing method of the present disclosure, the intermediate annealing has a maximum temperature of $900\text{-}1050^\circ\text{C}$.

[0047] In the manufacturing method of the present disclosure, it is possible to control the total oxygen content of the annealed sample plate to ≤ 600 ppm and the C element content to ≥ 300 ppm. This is beneficial for the stable production of the secondary tandem cold rolling in step (6) and promotes the formation of a strong γ texture, which further promotes the formation of a complete secondary recrystallization.

[0048] In one embodiment of the present disclosure, the manufacturing method further comprises a hot-rolled plate annealing step after step (3) and before step (4), wherein a temperature of the hot-rolled plate annealing is $\leq 1000^\circ\text{C}$.

[0049] As mentioned above, in the manufacturing method of the present disclosure, cold rolling can be performed directly after hot rolling without hot-rolled plate annealing, thereby reducing the process steps, improving production efficiency, and lowering production costs. However, in some embodiments, hot-rolled plate annealing can also be performed after the hot rolling step, but the annealing temperature of the hot-rolled plate needs to be $\leq 1000^\circ\text{C}$, because when the maximum annealing temperature is higher than 1000°C , it will cause coarsening of the surface layer grains of the hot-rolled plate, which is not conducive to the stable production of the subsequent primary tandem cold rolling in step (4).

[0050] Preferably, in step (7) of the manufacturing method of the present disclosure, a temperature of the decarburization annealing is $800\text{-}900^\circ\text{C}$, a time of the decarburization annealing is 80-170 seconds, and a heating rate is $30\text{-}150^\circ\text{C/s}$.

[0051] Preferably, in step (7) of the manufacturing method of the present disclosure, the decarburized and annealed plate after the nitriding treatment has a nitrogen content of 160-260 ppm.

[0052] In the manufacturing method of the present disclosure, through nitriding treatment, nitrogen combines with the pre-existing aluminum in the steel to form fine and dispersed secondary inhibitors such as AlN , $(\text{Al}, \text{Si})\text{N}$, and $(\text{Al}, \text{Si}, \text{Mn})\text{N}$ precipitates. During the subsequent high-temperature annealing process, the secondary inhibitors together with the primary inhibitors promote the secondary recrystallization process.

[0053] Compared with the prior art, the oriented silicon steel having high magnetic induction of the present disclosure has the following advantages and beneficial effects: the solution of the present disclosure obtains an oriented silicon steel with good comprehensive performance by reasonably controlling the steel composition, the secondary grain size and proportion of the steel plate, etc.

[0054] The manufacturing method of the oriented silicon steel having high magnetic induction in the present disclosure has the following beneficial effects:

By adopting a two-step cold rolling method to adjust the primary recrystallization structure, texture, and primary inhibitor precipitation, as well as appropriate composition and process design, the oriented silicon steel having high magnetic induction of the present disclosure can significantly reduce the temperature of the hot-rolled plate annealing or even eliminate hot-rolled plate annealing, achieving the efficient production of thin-gauge oriented silicon steel having high magnetic induction by tandem cold rolling.

[0055] Compared with the prior art, the present disclosure can solve the problem of insufficient number of effective Goss nuclei after strip thickness reduction, which is beneficial to improving the magnetic performance of the final product.

Therefore, thin-gauge oriented silicon steel having high magnetic induction can be produced without further reducing the hot-rolled plate thickness, thereby avoiding a series of problems caused by producing thin-gauge hot-rolled coils on conventional hot rolling production lines.

[0056] At the same time, eliminating hot-rolled plate annealing and achieving efficient production of thin-gauge oriented silicon steel having high magnetic induction by tandem cold rolling can significantly reduce manufacturing costs.

DETAILED DESCRIPTION

[0057] The oriented silicon steel having high magnetic induction and the manufacturing method thereof of the present disclosure will be further explained and illustrated below in conjunction with specific examples. However, such explanation and illustration do not constitute improper limitations on the technical solution of the present disclosure.

[0058] First, the various testing methods for the examples and comparative examples of the present disclosure are described as follows:

- (1) Average primary grain size is determined by the grain size of the decarburized plate after treatment measured according to the equivalent circle diameter method specified in GB/T 36165-2018.
- (2) Finished product secondary grain size is determined by the grain size of the finished plate after pickling measured according to the intercept point method specified in GB/T 6394-2017.
- (3) Goss orientation deviation angle is measured by EBSD (Electron Backscatter Diffraction), including the rolling direction deviation angle α and the rolling plane tilt angle β .
- (4) $P_{17/50}$ and B_8 of the non-scribed product steel is measured according to the method for measuring the magnetic properties of electrical steel sheets (strips) with an Epstein frame as specified in GB/T 3655-2022.
- (5) $P_{17/50}$ and B_8 of the scribed product steel are measured according to the method for measuring magnetic properties of electrical steel sheets (strips) with a single sheet tester as specified in GB/T 13789-2022.

Examples 1-6 and Comparative Examples 1-5

[0059] The oriented silicon steels having high magnetic induction of Examples 1-6 and the comparative steels of Comparative Examples 1-5 were manufactured according to the following steps carried out in sequence:

- (1) Smelting and casting: smelting using a converter or an electric furnace, then continuous casting into a slab with a thickness of 230 mm.
- (2) Slab heating: controlling the slab heating temperature to 1140°C and the heating time to 200 min.
- (3) Hot rolling: rolling into a hot-rolled plate with a thickness of 1.8 mm, 2.4 mm, or 2.6 mm, as shown in Table 1-1.
- (4) Preparing cold-rolled plates with a finished product thickness of 0.18 mm according to the process shown in Table 1-1, wherein Examples 1-6 and Comparative Examples 3-5 adopted the two-step cold rolling method of the present disclosure, while hot-rolled plate annealing was not performed. Intermediate annealing was performed between the primary cold rolling and the secondary cold rolling. The intermediate annealing adopted a manner of uncoiling continuous annealing, and the intermediate annealing and its maximum temperature were controlled according to the process shown in Table 1-1, with an annealing time of 220 seconds. Comparative Examples 1-2 adopted a conventional single-step cold rolling method, wherein the maximum temperature of the hot-rolled plate annealing was controlled at 1150°C and the annealing time was controlled at 250 seconds.
- (5) Decarburization annealing: the decarburization annealing temperature was 835°C, the decarburization annealing time was 125 seconds, and the heating rate in the heating section was 115°C/s. The [C] content in the steel plate was reduced to 30 ppm or less. After testing, the primary grain size and the proportion of the number of Goss grains were obtained, as shown in Table 1-2.
- (6) Nitriding treatment: controlling the nitrogen content of the decarburized and annealed plate to 180-250 ppm.
- (7) Applying a MgO coating: applying the steel plate with a MgO coating.
- (8) High-temperature annealing: performing purification annealing at a high-temperature annealing temperature of 1200°C in a conventional reducing atmosphere for 20 hours, reducing the [S] and [N] contents in the steel to 40 ppm or less.
- (9) Applying an insulation coating and flattening annealing: after applying an insulation coating and performing hot stretch flattening annealing, a finished product was obtained. The obtained finished product comprises the following chemical elements in mass percentage: Si 3.22%, C 0.0016%, Als 0.0334%, N 0.0012%, Mn 0.088%, S 0.0013%, V 0.0025%, Ti 0.0015%. The elements P, Cr, Sn, Cu, Sb, Bi, Nb, and Mo in the finished steel plate were not intentionally added, and their contents were below the detection limit. The measured features of the secondary grains of the finished product are listed in Table 1-2.

Table 1-1

No.	Process category	Hot-rolled plate thickness (mm)	Hot-rolled plate annealing	Primary cold-rolled plate thickness (mm)	Primary cold rolling reduction rate (%)	Intermediate annealing	Maximum intermediate annealing temperature (°C)	Secondary cold-rolled plate thickness (mm)	Secondary cold rolling reduction rate (%)
Example 1	Two-step cold rolling method	2.4	No	0.6	75.0%	Yes	940	0.18	70.0%
Example 2	Two-step cold rolling method	2.4	No	0.8	66.7%	Yes	940	0.18	77.5%
Example 3	Two-step cold rolling method	1.8	No	0.9	50.0%	Yes	940	0.18	80.0%
Example 4	Two-step cold rolling method	1.8	No	0.45	75.0%	Yes	940	0.18	60.0%
Example 5	Two-step cold rolling method	2.6	No	0.9	65.4%	Yes	940	0.18	80.0%
Example 6	Two-step cold rolling method	2.6	No	1.2	53.8%	Yes	940	0.18	85.0%
Comparative Example 1	<u>Single-step cold rolling method</u>	2.4	Yes	0.18	92.5%	No	-	-	-
Comparative Example 2	<u>Single-step cold rolling method</u>	2.6	Yes	0.18	93.1%	No	-	-	-
Comparative Example 3	Two-step cold rolling method	2.4	No	1.1	54.2%	Yes	<u>850</u>	0.18	83.6%

(continued)

No.	Process category	Hot-rolled plate thickness (mm)	Hot-rolled plate annealing	Primary cold-rolled plate thickness (mm)	Primary cold rolling reduction rate (%)	Intermediate annealing	Maximum intermediate annealing temperature (°C)	Secondary cold-rolled plate thickness (mm)	Secondary cold rolling reduction rate (%)
Comparative Example 4	Two-step cold rolling method	2.4	No	0.9	62.5%	Yes	<u>850</u>	0.18	80.0%
Comparative Example 5	Two-step cold rolling method	2.4	No	1.1	54.2%	Yes	<u>850</u>	0.18	83.6%

[0060] Table 1-2 lists the average primary grain size of the decarburized plates, the proportion of the number of Goss grains in the decarburized plates, the average secondary grain size, the proportion of average deviation angle in the range of 0° - 3° , the proportion of secondary grain size <6 mm or >16 mm, the finished product $P_{17/50}$, and the finished product B_8 of Examples 1-6 and Comparative Examples 1-5.

Table 1-2

No.	Average primary grain size of decarburized plate (μm)	Proportion of the number of Goss grains with average deviation angle $(\alpha+\beta)/2 < 15^{\circ}$ in decarburized plate (%)	Average secondary grain size (mm)	Proportion of average deviation angle between 0° - 3° (%)	Proportion of secondary grain size of $<6\text{mm}$ or $>16\text{mm}$ (%)	Finished product $P_{17/50}$ (W/kg)	Finished product B_8 (T)
Example 1	12.0	2.4%	15.5	50.9%	9.7%	0.638	1.945
Example 2	11.7	1.6%	7.2	62.4%	7.3%	0.673	1.958
Example 3	10.0	3.7%	14.1	56.3%	10.4%	0.683	1.968
Example 4	17.7	6.3%	15.9	53.5%	14.7%	0.578	1.945
Example 5	6.9	2.3%	6.0	67.4%	11.3%	0.650	1.961
Example 6	12.3	2.6%	14.1	62.8%	13.9%	0.702	1.936
Comparative Example 1	9.4	<u>0.6%</u>	10.3	<u>41.3%</u>	<u>15.7%</u>	<u>0.875</u>	<u>1.784</u>
Comparative Example 2	16.8	<u>0.4%</u>	<u>5.5</u>	<u>21.9%</u>	<u>31.1%</u>	<u>1.343</u>	<u>1.568</u>
Comparative Example 3	<u>18.2</u>	2.7%	<u>16.2</u>	52.4%	8.5%	<u>0.863</u>	<u>1.906</u>
Comparative Example 4	<u>5.7</u>	3.1%	9.8	<u>26.1%</u>	<u>24.1%</u>	<u>1.215</u>	<u>1.613</u>
Comparative Example 5	10	<u>1.4%</u>	13.5	53.1%	10.2%	0.703	<u>1.922</u>

[0061] It can be seen from Tables 1-1 and 1-2 that Examples 1-6, using the two-step cold rolling method of the present disclosure to prepare oriented silicon steel of 0.18 mm, a suitable primary grain size was obtained and the proportion of the number of Goss grains with an average deviation angle $(\alpha+\beta)/2$ less than 15° in the decarburized plate was higher. At the same time, the features of the secondary grains also met the requirements, and the obtained products had a better magnetic performance. Their iron loss $P_{17/50}$ was all lower than the reference iron loss of 0.705 W/kg calculated based on the formula $0.86 + 2 \times \text{finished plate thickness} - 16 \times \text{Si}$, and their magnetic induction B_8 was all higher than the reference magnetic induction of 1.931 T calculated based on the formula $2.14 - 6.5 \times \text{Si}$. Comparative Examples 1-2 using the conventional single-step cold rolling method to prepare oriented silicon steel of 0.18 mm, and Comparative Examples 3-5 using the two-step cold rolling method but with intermediate annealing temperatures not meeting the requirements of the present disclosure. The average primary grain sizes of the decarburized plate or proportions of the number of Goss grains in the decarburized plate of Comparative Examples 1-5 did not meet the requirements of the present disclosure, resulting in iron loss and/or magnetic induction inferior to the reference values calculated above.

Examples 7-10 and Comparative Examples 6-13

[0062] The oriented silicon steels having high magnetic induction of Examples 7-10 and the comparative steels of Comparative Examples 6-13 were manufactured according to the following steps carried out in sequence:

- (1) Smelting and casting: smelting using a converter or an electric furnace, then continuous casting into a slab with a thickness of 230 mm.

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(2) Slab heating: controlling the slab heating temperature to 1190°C and the heating time to 160 min.

(3) Hot rolling: rolling into a hot-rolled plate with a thickness of 2.6 mm.

(4) Primary tandem cold rolling: primary cold rolling to the thickness shown in Table 2-1.

(5) Intermediate annealing: annealing for 180 seconds in a manner of uncoiling continuous annealing, controlling the maximum intermediate annealing temperature as shown in Table 2-1, and obtaining the total oxygen content and C element content of the intermediate annealed plate as shown in Table 2-1.

(6) Secondary tandem cold rolling: secondary cold rolling to a steel plate thickness of 0.15 mm.

(7) Decarburization annealing: controlling the decarburization annealing temperature as shown in Table 2-1 with a decarburization annealing time of 100 seconds, heating rate in the heating section of 80°C/s, reducing the [C] content in the steel plate to 30 ppm or less. After testing, the primary grain size and the proportion of the number of Goss grains were obtained, as shown in Table 2-2.

(8) Nitriding treatment: controlling the nitrogen content of the decarburized and annealed plate, as shown in Table 2-1.

(9) Applying a MgO coating: Applying the steel plate with a MgO coating.

(10) High-temperature annealing: performing purification annealing at a high-temperature annealing temperature of 1170°C in a conventional reducing atmosphere for 18 hours, reducing the [S] and [N] contents in the steel to 50 ppm or less.

(11) Applying an insulation coating and flattening annealing: after applying the insulation coating and performing hot stretch flattening annealing, a finished product was obtained. The obtained finished product comprises the following chemical elements in mass percentage: Si 3.39%, C 0.0007%, Als 0.0275%, N 0.0017%, Mn 0.183%, S 0.0008%, V 0.0031%, Ti 0.0010%. The elements P, Cr, Sn, Cu, Sb, Bi, Nb, and Mo in the finished steel plate were not intentionally added, and their contents were below the detection limit. The features of the secondary grains of the finished product are listed in Table 2-2.

Table 2-1

No.	Primary cold-rolled plate thickness (mm)	Primary cold rolling reduction rate (%)	Secondary cold rolling reduction rate (%)	Maximum intermediate annealing temperature (°C)	Total oxygen content of intermediate annealed plate (ppm)	C element content of intermediate annealed plate (ppm)	Decarburization annealing temperature (°C)	Nitriding amount of decarburized plate (ppm)
Example 7	0.7	73.1%	78.6%	900	598	321	800	209
Example 8	0.8	69.2%	81.3%	950	484	503	840	243
Example 9	0.9	65.4%	83.3%	1000	402	756	900	258
Example 10	1.0	61.5%	85.0%	1050	161	939	820	162
Comparative Example 6	0.6	<u>76.9%</u>	75.0%	900	<u>605</u>	612	<u>795</u>	<u>158</u>
Comparative Example 7	0.35	<u>86.5%</u>	<u>57.1%</u>	950	546	<u>297</u>	820	253
Comparative Example 8	0.85	67.3%	82.4%	950	<u>787</u>	<u>137</u>	830	176
Comparative Example 9	0.85	67.3%	82.4%	950	414	<u>191</u>	860	172
Comparative Example 10	0.85	67.3%	82.4%	<u>890</u>	304	330	<u>905</u>	216
Comparative Example 11	0.85	67.3%	82.4%	<u>1060</u>	397	375	800	236
Comparative Example 12	0.85	67.3%	82.4%	950	<u>603</u>	716	840	218
Comparative Example 13	1.4	<u>46.2%</u>	<u>89.3%</u>	950	502	516	900	<u>261</u>

Table 2-2

No.	Average primary grain size of decarburized plate (μm)	Proportion of the number of Goss grains with average deviation angle $(\alpha+\beta)/2 < 15^\circ$ in decarburized plate (%)	Average secondary grain size (mm)	Proportion of average deviation angle between 0° - 3° (%)	Proportion of secondary grain size of $< 6\text{mm}$ or $> 16\text{mm}$ (%)	Finished product $P_{17/50}$ (W/kg)	Finished product B_8 (T)
Example 7	6.1	3.3%	7.6	50.5%	12.8%	0.607	1.935
Example 8	17.8	5.4%	6.7	55.0%	9.3%	0.573	1.938
Example 9	15	3.1%	6.5	58.2%	14.6%	0.531	1.948
Example 10	12.3	2.1%	11.8	54.3%	8.6%	0.588	1.925
Comparative Example 6	15.6	1.7%	7.0	<u>31.4%</u>	<u>20.2%</u>	<u>1.048</u>	<u>1.633</u>
Comparative Example 7	10.3	3.5%	10.6	<u>43.7%</u>	7.3%	<u>0.833</u>	<u>1.913</u>
Comparative Example 8	11.9	3.9%	8.9	50.7%	<u>19.5%</u>	<u>0.636</u>	1.936
Comparative Example 9	8.7	<u>0.7%</u>	13.6	<u>46.5%</u>	9.0%	<u>0.734</u>	<u>1.901</u>
Comparative Example 10	<u>5.8</u>	4.4%	6.9	<u>36.3%</u>	<u>19.1%</u>	<u>0.956</u>	<u>1.879</u>
Comparative Example 11	<u>21.8</u>	1.9%	<u>16.6</u>	<u>29.5%</u>	8.3%	<u>0.922</u>	<u>1.828</u>
Comparative Example 12	9.4	<u>1.1%</u>	7.3	<u>47.4%</u>	<u>26.0%</u>	<u>1.054</u>	<u>1.638</u>
Comparative Example 13	10.9	2.8%	<u>5.4</u>	<u>33.3%</u>	<u>22.8%</u>	<u>1.024</u>	<u>1.628</u>

[0063] It can be seen from Tables 2-1 and 2-2 that although both Examples 7-10 and Comparative Examples 6-13 adopted the two-step cold rolling method of the present disclosure to prepare oriented silicon steel of 0.15 mm, the primary cold rolling reduction rate, secondary cold rolling reduction rate, maximum intermediate annealing temperature, total oxygen content of the intermediate annealed plate, C element content of the intermediate annealed plate, nitriding amount of the decarburized plate, average primary grain size of the decarburized plate, proportion of the number of Goss grains in the decarburized plate, and various features of the secondary grains in Examples 7-10 all met the requirements of the present disclosure. Therefore, their iron loss $P_{17/50}$ was all lower than the reference iron loss of 0.618 W/kg calculated based on the formula $0.86 + 2 \times \text{finished plate thickness} - 16 \times \text{Si}$, and their magnetic induction B_8 was all higher than the reference magnetic induction of 1.920 T calculated based on the formula $2.14 - 6.5 \times \text{Si}$. In contrast, the iron loss and/or magnetic induction of Comparative Examples 6-13 were inferior to the reference values calculated above.

Examples 11-22 and Comparative Examples 14-21

[0064] The oriented silicon steel having high magnetic inductions of Examples 11-22 and the comparative steel of Comparative Examples 14-21 were manufactured according to the following steps carried out in sequence:

- (1) Smelting and casting: smelting using a converter or an electric furnace, continuous casting into a slab with a thickness of 230 mm.
- (2) Slab heating: controlling the slab heating temperature to 1200°C and the heating time to 250 min.
- (3) Hot rolling: rolling into a hot-rolled plate with a thickness of 2.3 mm.
- (4) Primary tandem cold rolling: primary cold rolling to obtain a steel plate with a thickness of 0.75 mm, controlling the

primary tandem cold rolling reduction rate to 67.4%.

(5) Intermediate annealing: adopting a manner of uncoiling continuous annealing, controlling the maximum intermediate annealing temperature to 975°C and the intermediate annealing time to 120 seconds, obtaining the total oxygen content of the intermediate annealed sample plate in the range of 261-594 ppm and the C element content in the range of 308-939 ppm.

(6) Secondary tandem cold rolling: secondary cold rolling to obtain a steel plate with a thickness of 0.19 mm, controlling the secondary tandem cold rolling reduction rate to 74.7%.

(7) Decarburization annealing: controlling a decarburization annealing temperature of 835°C, a decarburization annealing time of 125 seconds, a heating rate in the heating section of 115°C/s, reducing the [C] content in the steel plate to 50 ppm or less, obtaining the primary grain size and the proportion of the number of Goss grains, as shown in Table 4.

(8) Nitriding treatment: controlling the nitrogen content of the decarburized and annealed plate to 190-250 ppm.

(9) Applying a MgO coating: Applying the steel plate with a MgO coating.

(10) High-temperature annealing: performing purification annealing at a high-temperature annealing temperature of 1180°C in a conventional reducing atmosphere for 25 hours, reducing the [S] and [N] contents in the steel to 50 ppm or less.

(11) Applying an insulation coating and flattening annealing: after applying an insulation coating and performing hot stretch flattening annealing, finished products with chemical compositions as shown in Tables 3-1 and 3-2 were obtained. The features of the secondary grains of the finished products are listed in Table 4.

Table 3-1 (wt%, balance of Fe and inevitable impurities except N, S, V, and Ti)

No.	C	Si	Als	Mn	S	N	V	Ti
Example 11	0.0012	3.12	0.0330	0.083	0.0035	0.0014	0.0035	0.0035
Example 12	0.0021	3.39	0.0289	0.052	0.0018	0.0022	0.0023	0.0049
Example 13	0.0003	3.79	0.0303	0.199	0.0015	0.0031	0.0050	0.0045
Example 14	0.0010	3.58	0.0177	0.183	0.0023	0.0015	0.0035	0.0025
Example 15	0.0048	3.24	0.0195	0.164	0.0008	0.0012	0.0049	0.0005
Example 16	0.0018	3.29	0.0313	0.069	0.0004	0.0023	0.0028	0.0037
Example 17	0.0022	3.52	0.0101	0.150	0.0030	0.0016	0.0015	0.0050
Example 18	0.0023	3.69	0.0205	0.075	0.0050	0.0013	0.0041	0.0034
Example 19	0.0016	3.50	0.0347	0.111	0.0013	0.0020	0.0025	0.0025
Example 20	0.0020	3.48	0.0274	0.099	0.0013	0.0023	0.0035	0.0013
Example 21	0.0050	3.59	0.0213	0.144	0.0035	0.0030	0.0011	0.0023
Example 22	0.0010	3.02	0.0244	0.123	0.0008	0.0025	0.0005	0.0015
Comparative Example 14	0.0009	3.09	0.0341	0.149	0.0045	<u>0.0052</u>	<u>0.0051</u>	0.0045
Comparative Example 15	0.0015	3.41	<u>0.0358</u>	0.173	<u>0.0056</u>	0.0037	0.0015	<u>0.0052</u>
Comparative Example 16	<u>0.0051</u>	3.80	0.0159	0.053	0.0020	0.0050	0.0035	0.0035
Comparative Example 17	0.0010	3.29	0.0198	<u>0.048</u>	0.0033	0.0012	0.0035	0.0024
Comparative Example 18	0.0012	3.34	0.0272	0.076	<u>0.0051</u>	0.0011	<u>0.0055</u>	0.0025
Comparative Example 19	0.0011	3.48	0.0304	<u>0.205</u>	0.0018	0.0028	0.0015	0.0016
Comparative Example 20	<u>0.0053</u>	3.12	<u>0.0099</u>	0.112	0.0013	0.0024	0.0035	<u>0.0058</u>
Comparative Example 21	0.0017	3.25	0.0226	0.198	0.0048	<u>0.0051</u>	0.0005	0.0043

Table 3-2 (Content of incorporated optional element, wt%)

No.	P	Cr	Sn	Cu	Sb	Bi	Nb	Mo
Example 11	0.079	0	0.298	0	0.099	0	0	0.097

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(continued)

No.	P	Cr	Sn	Cu	Sb	Bi	Nb	Mo
Example 12	0	0	0.049	0	0.001	0	0.045	0.003
Example 13	0	0.08	0.083	0	0.084	0	0	0
Example 14	0.021	0	0.032	0.29	0	0.003	0	0.076
Example 15	0.075	0.24	0	0	0.066	0.036	0.029	0.022
Example 16	0	0	0.253	0.21	0.012	0.079	0.069	0
Example 17	0.044	0.14	0.065	0.12	0.024	0.098	0.099	0
Example 18	0.067	0.01	0	0.39	0	0	0	0.018
Example 19	0.037	0.35	0.165	0.02	0	0.019	0	0.034
Example 20	0.012	0.40	0.101	0	0.031	0	0	0.045
Example 21	0	0	0	0	0	0	0	0
Example 22	0.029	0	0	0	0.050	0.063	0.002	0.059
Comparative Example 14	0.031	0.20	0.22	0.23	<u>0.109</u>	0.077	0.097	0
Comparative Example 15	0	0.06	0	0.08	0.027	0.053	0	0.096
Comparative Example 16	<u>0.009</u>	<u>0.42</u>	0.124	0	0.0008	0	0.005	0.043
Comparative Example 17	0	0.37	<u>0.029</u>	<u>0.009</u>	0	0.067	0.0008	0.053
Comparative Example 18	0.013	0	0.038	0.17	0.064	<u>0.101</u>	0.016	<u>0.102</u>
Comparative Example 19	0.056	0.14	<u>0.308</u>	0.34	0	0.0007	0.074	0.007
Comparative Example 20	0	0.24	0.064	<u>0.41</u>	0.003	0.098	0	0.087
Comparative Example 21	<u>0.082</u>	0	0	0	0.081	0.033	<u>0.104</u>	0.016

Table 4

No.	Average primary grain size of decarburized plate (μm)	Proportion of the number of Goss grains with average deviation angle ($\alpha+\beta$)/2 <15° in decarburized plate (%)	Average secondary grain size (mm)	Proportion of average deviation angle between 0°-3° (%)	Proportion of secondary grain size <6mm or >16mm (%)	Finished product P _{17/50} (W/kg)	Finished product B ₈ (T)	Reference iron loss based on formula (W/kg)	Reference magnetic induction based on formula (T)
Example 11	13.9	3.3%	12.5	64.5%	8.6%	0.718	1.945	0.741	1.937
Example 12	14.9	5.4%	8.8	56.8%	9.1%	0.663	1.958	0.698	1.920
Example 13	15	3.1%	10.2	59.5%	13.9%	0.626	1.919	0.634	1.894
Example 14	12.8	2.1%	10.0	61.0%	12.3%	0.658	1.935	0.667	1.907
Example 15	16.1	1.7%	14.2	56.2%	9.6%	0.653	1.941	0.722	1.929
Example 16	6.3	3.5%	11.0	63.7%	5.8%	0.668	1.952	0.714	1.926
Example 17	17.7	3.9%	6.2	52.9%	6.4%	0.626	1.921	0.677	1.911
Example 18	12.7	1.7%	14.4	51.7%	13.9%	0.649	1.931	0.650	1.900
Example 19	9.2	4.4%	14.5	63.7%	14.5%	0.601	1.944	0.680	1.913
Example 20	13.1	1.9%	9.5	52.7%	12.8%	0.589	1.940	0.683	1.914
Example 21	15.6	4.1%	14.9	63.9%	6.8%	0.595	1.919	0.666	1.907
Example 22	17.1	2.8%	10.4	59.6%	11.1%	0.678	1.963	0.757	1.944
Comparative Example 14	<u>19.6</u>	2.5%	<u>28.5</u>	54.2%	13.7%	<u>0.752</u>	<u>1.923</u>	0.746	1.939
Comparative Example 15	10.8	2.2%	8.7	<u>40.6%</u>	10.7%	<u>0.821</u>	<u>1.872</u>	0.694	1.918
Comparative Example 16	8.6	<u>0.9%</u>	15.5	<u>47.1%</u>	9.5%	<u>0.663</u>	1.920	0.632	1.893
Comparative Example 17	9.6	2.6%	<u>5.7</u>	<u>40.3%</u>	13.9%	<u>0.879</u>	<u>1.811</u>	0.714	1.926
Comparative Example 18	8.6	1.8%	15.0	51.5%	<u>19.9%</u>	<u>0.720</u>	1.924	0.706	1.923
Comparative Example 19	<u>5.8</u>	3.7%	9.3	<u>45.8%</u>	11.9%	<u>0.922</u>	<u>1.901</u>	0.683	1.914
Comparative Example 20	11.8	<u>0.6%</u>	11.5	<u>33.3%</u>	<u>23.1%</u>	<u>0.945</u>	<u>1.769</u>	0.741	1.937
Comparative Example 21	10.9	1.9%	12.6	50.3%	<u>15.3%</u>	0.690	<u>1.916</u>	0.720	1.929

[0065] In view of Tables 3-1, 3-2, and 4, it can be seen that for the oriented silicon steel having high magnetic inductions of Examples 11-22 of the present disclosure, the slab composition, the average primary grain size of the decarburized plate, the proportion of the number of Goss grains in the decarburized plate, and various features of the secondary grains all met the ranges defined in the claimed range of the present disclosure. Therefore, their iron loss $P_{17/50}$ was all lower than the reference iron loss calculated based on the formula $0.86 + 2 \times \text{finished plate thickness} - 16 \times \text{Si}$, and their magnetic induction B_8 was all higher than the reference magnetic induction calculated based on the formula $2.14 - 6.5 \times \text{Si}$. In contrast, the iron loss and/or magnetic induction of Comparative Examples 14-21 were inferior to the reference values calculated above.

Examples 23-29 and Comparative Examples 22-28

[0066] The oriented silicon steel having high magnetic inductions of Examples 23-29 and the comparative steel of Comparative Examples 22-28 were manufactured according to the following steps carried out in sequence:

- (1) Smelting and casting: smelting using a converter or an electric furnace, continuous casting into a slab with a thickness of 230 mm.
- (2) Slab heating: controlling the slab heating temperature to 1250°C and the heating time to 120 min.
- (3) Hot rolling: rolling into a hot-rolled plate with a thickness of 2.5 mm, and performing hot-rolled plate annealing on some of the hot-rolled plates according to Table 5-1.
- (4) Primary tandem cold rolling: primary cold rolling to obtain a steel plate with a thickness of 0.75 mm, controlling the primary tandem cold rolling reduction rate to 70.0%.
- (5) Intermediate annealing: performing intermediate annealing according to the manner of intermediate annealing, maximum intermediate annealing temperature, and intermediate annealing time shown in Table 5-1, wherein the uncoiling continuous annealing time was 220 seconds, and the bell-type annealing time of the coil was 12 hours. The total oxygen content of the intermediate annealed sample plate was in the range of 350-450 ppm, and C element content was in the range of 450-550 ppm.
- (6) Secondary tandem cold rolling: secondary cold rolling to obtain a steel plate with a thickness of 0.13 mm, controlling the secondary tandem cold rolling reduction rate to 82.7%.
- (7) Decarburization annealing: controlling the heating rate in the heating section, decarburization annealing temperature, and decarburization annealing time according to Table 5-1, reducing the [C] content in the steel plate to 30 ppm or less, obtaining the primary grain size and the proportion of the number of Goss grains, as shown in Table 5-2.
- (8) Nitriding treatment: controlling the nitrogen content of the decarburized and annealed plate to 200-230 ppm.
- (9) Applying a MgO coating: applying the steel plate with a MgO coating.
- (10) High-temperature annealing: performing purification annealing at a high-temperature annealing temperature of 1200°C in a conventional reducing atmosphere for 20 hours, reducing the [S] and [N] contents in the steel to 30 ppm or less.
- (11) Applying an insulation coating and flattening annealing: after applying an insulation coating and performing hot stretch flattening annealing, a finished product was obtained. The obtained finished product comprises the following chemical elements in mass percentage: Si 3.17%, C 0.0009%, Als 0.0254%, N 0.0019%, Mn 0.144%, S 0.0027%, V 0.0025%, Ti 0.0015%, Sn 0.065%, Cu 0.12%. The elements P, Cr, Sb, Bi, Nb, and Mo in the finished steel plate were not intentionally added, and their contents were below the detection limit. The various features of the secondary grains of the finished product are listed in Table 5-2.

Table 5-1

No.	Hot-rolled plate annealing	Maximum hot-rolled plate annealing temperature (°C)	Intermediate annealing manner	Maximum intermediate annealing temperature (°C)	Heating rate in decarburization annealing section (°C/s)	Decarburization annealing temperature (°C)	Decarburization annealing time (s)
Example 23	No	-	Continuous	900	30	800	170
Example 24	No	-	Continuous	1000	60	830	120
Example 25	No	-	Bell-type	1050	60	830	120
Example 26	No	-	Bell-type	1000	60	840	120
Example 27	Yes	900	Bell-type	950	100	840	120
Example 28	Yes	950	Continuous	950	100	840	120
Example 29	Yes	1000	Continuous	950	150	900	80
Comparative Example 22	No	-	Continuous	<u>895</u>	100	860	<u>172</u>
Comparative Example 23	No	-	Continuous	1000	100	830	<u>78</u>
Comparative Example 24	No	-	Bell-type	<u>1060</u>	100	830	120
Comparative Example 25	No	-	Bell-type	950	<u>155</u>	840	120
Comparative Example 26	Yes	950	Bell-type	<u>895</u>	60	<u>905</u>	120
Comparative Example 27	Yes	950	Continuous	950	<u>25</u>	840	120
Comparative Example 28	Yes	<u>1010</u>	Continuous	950	60	<u>795</u>	120

Table 5-2

No.	Average primary grain size of decarburized plate (μm)	Proportion of the number of Goss grains with average deviation angle $(\alpha+\beta)/2 < 15^\circ$ in decarburized plate (%)	Average secondary grain size (mm)	Proportion of average deviation angle between 0° - 3° (%)	Proportion of secondary grain size of $< 6\text{mm}$ or $> 16\text{mm}$ (%)	Finished product $P_{17/50}$ (W/kg)	Finished product B_8 (T)
Example 23	11.7	3.5%	8.9	55.2%	12.5%	0.596	1.967
Example 24	14	3.6%	10.6	52.8%	11.4%	0.563	1.934
Example 25	10.2	2.9%	13.3	52.3%	10.0%	0.602	1.952
Example 26	13.3	3.6%	12.7	62.0%	12.4%	0.592	1.946
Example 27	17.6	3.5%	15.3	52.4%	5.4%	0.575	1.960
Example 28	10.2	2.9%	14.6	65.5%	8.4%	0.579	1.951
Example 29	9	3.7%	10.8	58.6%	11.0%	0.609	1.945
Comparative Example 22	<u>23.7</u>	4.0%	<u>46.2</u>	50.4%	<u>33.8%</u>	<u>0.794</u>	1.970
Comparative Example 23	5.7	2.6%	<u>23.2</u>	<u>40.4%</u>	10.8%	<u>1.033</u>	<u>1.767</u>
Comparative Example 24	Strip breakage during rolling						
Comparative Example 25	10.7	<u>1.4%</u>	<u>18.6</u>	52.8%	14.4%	<u>0.811</u>	1.934
Comparative Example 26	<u>21.7</u>	1.7%	8.3	50.9%	<u>19.4%</u>	<u>0.748</u>	<u>1.909</u>
Comparative Example 27	12.4	<u>1.1%</u>	12.7	<u>41.3%</u>	11.3%	<u>1.003</u>	<u>1.868</u>
Comparative Example 28	Strip breakage during rolling						

[0067] It can be seen from Tables 5-1 and 5-2 that although both Examples 23-29 and Comparative Examples 22-28 adopted the two-step cold rolling method of the present disclosure to prepare oriented silicon steel with a finished product thickness of 0.13 mm, the hot-rolled plate annealing and maximum annealing temperature, intermediate annealing and maximum annealing temperature, heating rate in the decarburization annealing heating section, decarburization annealing temperature, decarburization annealing time, as well as the average primary grain size of the decarburized plate, the proportion of the number of Goss grains in the decarburized plate, and various features of the secondary grains in Examples 23-29 all met the requirements of the present disclosure. Therefore, their iron loss $P_{17/50}$ was all lower than the reference iron loss of 0.613 W/kg calculated based on the formula $0.86 + 2 \times \text{finished plate thickness} - 16 \times \text{Si}$, and their magnetic induction B_8 was all higher than the reference magnetic induction of 1.934 T calculated based on the formula $2.14 - 6.5 \times \text{Si}$. In contrast, the iron loss and/or magnetic induction of Comparative Examples 22-28 were inferior to the reference values calculated above, and some even faced with strip breakage due to rolling difficulties.

[0068] In addition, the present disclosure also used a laser scribing method to refine the magnetic domains of the finished sample plates with a thickness of 0.13 mm in Examples 23-29 in Table 5-2, and the iron loss comparison results before and after scribing are listed in Table 6.

Table 6

No.	Iron loss $P_{17/50}$ before scribing (W/kg)	Iron loss $P_{17/50}$ after scribing (W/kg)
Example 23	0.596	0.543

(continued)

No.	Iron loss $P_{17/50}$ before scribing (W/kg)	Iron loss $P_{17/50}$ after scribing (W/kg)
Example 24	0.563	0.498
Example 25	0.602	0.536
Example 26	0.592	0.524
Example 27	0.575	0.505
Example 28	0.579	0.499
Example 29	0.609	0.533

[0069] It can be seen from Table 6 that the iron loss of each Example after scribing decreased compared to its original iron loss.

[0070] In summary, it can be seen that the oriented silicon steel having high magnetic induction and the manufacturing method thereof of the present disclosure have significant advantages and beneficial effects compared with the prior art, which can improve product quality, reduce manufacturing costs, and avoid common problems, having good application prospects.

[0071] It should be noted that the composition design and manufacturing process of the present disclosure are not only applicable to thin-gauge oriented silicon steel with a thickness of 0.13-0.20 mm, but are also equally applicable to oriented silicon steel of a conventional thickness, such as 0.23-0.30 mm. For oriented silicon steel having conventional thickness, the prominence of the problems addressed by the present disclosure can be relatively low. However, since the manufacturing principles of oriented silicon steels of different thicknesses are similar, it can be considered that the technical solution proposed by the present disclosure is also applicable to the manufacture of oriented silicon steel having conventional thickness.

[0072] It should be noted that the combination of various technical features in the present disclosure is not limited to the combinations described in the claims of the disclosure or the combinations described in the specific embodiments. All technical features described in the present disclosure may be combined or integrated in any manner, unless they contradict with each other.

[0073] It should also be noted that the examples listed above are only specific embodiments of the present disclosure. Obviously, the present disclosure is not limited to the above examples. Similar changes or modifications that can be directly derived or easily conceived by those skilled in the art from the present disclosure should all fall within the protection scope of the present disclosure.

Claims

1. An oriented silicon steel, in addition to Fe and inevitable impurities, the oriented silicon steel comprises the following chemical elements in mass percentage:

$C \leq 0.005\%$; $Si: 3.0-3.8\%$; $Als: 0.010-0.035\%$; $Mn: 0.05-0.20\%$;
 wherein in the inevitable impurities, $N \leq 0.005\%$, $S \leq 0.005\%$, $V \leq 0.005\%$, $Ti \leq 0.005\%$;
 wherein the oriented silicon steel has an average secondary grain size of 6-16 mm; an area percentage of secondary grains having an average deviation angle $(\alpha+\beta)/2$ in the range of 0° to 3° accounts for $> 50\%$ of all secondary grains, wherein α is rolling direction deviation angle, and β is rolling plane tilt angle.

2. The oriented silicon steel according to claim 1, wherein the oriented silicon steel has the following chemical elements in mass percentage:

$C \leq 0.005\%$; $Si: 3.0-3.8\%$; $Als: 0.010-0.035\%$; $Mn: 0.05-0.20\%$; and
 the balance is Fe and inevitable impurities; wherein in the inevitable impurities, $N \leq 0.005\%$, $S \leq 0.005\%$, $V \leq 0.005\%$, $Ti \leq 0.005\%$.

3. The oriented silicon steel according to claim 1 or 2, wherein the oriented silicon steel further comprises at least one of the following chemical elements:

$P: 0.01-0.08\%$; $Cr: 0.01-0.40\%$; $Sn: 0.03-0.30\%$; $Cu: 0.01-0.40\%$; $0 < Sb \leq 0.1\%$; $0 < Bi \leq 0.1\%$; $0 < Nb \leq 0.1\%$; $0 < Mo \leq 0.1\%$.

4. The oriented silicon steel according to claim 1 or 2, wherein the oriented silicon steel has a thickness of 0.13-0.20 mm.
5. The oriented silicon steel according to claim 1 or 2, wherein an area percentage of secondary grains having a size of <6 mm or >16 mm accounts for < 15% of all secondary grains.
6. The oriented silicon steel according to claim 1 or 2, wherein the oriented silicon steel has an iron loss $P_{17/50}$, wherein $P_{17/50} \leq 0.86 + 2 \times \text{finished plate thickness} - 16 \times \text{Si}$, and a magnetic induction B_8 , wherein $B_8 \geq 2.14 - 6.5 \times \text{Si}$, wherein the finished plate thickness is in mm; during calculation, element symbol Si in the formulas is substituted with the mass percentage of the Si element in the finished plate; $P_{17/50}$ is in W/kg, and B_8 is in T.
7. A manufacturing method for the oriented silicon steel according to any one of claims 1-6, comprising the following steps:
 - (1) Smelting and casting to obtain a slab;
 - (2) Heating the slab;
 - (3) Hot rolling;
 - (4) Primary cold rolling;
 - (5) Intermediate annealing;
 - (6) Secondary cold rolling;
 - (7) Decarburization annealing, nitriding treatment, and applying a separator coating, wherein an obtained decarburized and annealed plate has an average primary grain size of 6-18 μm , and a proportion of the number of Goss grains with an average deviation angle $(\alpha+\beta)/2$ of less than 15° is more than 1.5%;
 - (8) High-temperature annealing;
 - (9) Applying an insulation coating and flattening annealing.
8. The manufacturing method according to claim 7, wherein in step (2), a slab heating temperature is in the range of 1140°C to 1250°C .
9. The manufacturing method according to claim 7, wherein in step (4), the primary cold rolling adopts tandem cold rolling with a reduction rate of 50-75%.
10. The manufacturing method according to claim 7, wherein in step (5), the intermediate annealing has a maximum temperature of $900-1050^\circ\text{C}$.
11. The manufacturing method according to claim 7, wherein in step (6), the secondary cold rolling adopts tandem cold rolling with a reduction rate of 60-85%.
12. The manufacturing method according to claim 7, wherein the manufacturing method further comprises a hot-rolled plate annealing step after step (3) and before step (4), wherein a temperature of the hot-rolled plate annealing is $\leq 1000^\circ\text{C}$.
13. The manufacturing method according to claim 7, wherein in step (7), a temperature of the decarburization annealing is $800-900^\circ\text{C}$, a time of the decarburization annealing is 80-170 seconds, and a heating rate is $30-150^\circ\text{C/s}$.
14. The manufacturing method according to claim 7, wherein in step (7), the decarburized and annealed plate after the nitriding treatment has a nitrogen content of 160-260 ppm.

INTERNATIONAL SEARCH REPORT

International application No.

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A. CLASSIFICATION OF SUBJECT MATTER

C22C38/02(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: C22C

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

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

CNABS, CNTXT, ENTXTC, VEN, WPABSC, WPABS, DWPI, CJFD, 超星读秀, DUXIU, CNKI, Web of Science, ScienceDirect: 宝山钢铁, 章华兵, 李国保, 沈侃毅, 杨勇杰, 崔光华, 马长松, 胡治宁, 肖稳, 取向, 方向性, 单向, 硅钢, 硅, Si, 铁, Fe, 锰, Mn, 碳, C, 酸溶铝, Als, 冷轧, 中间退火, 高斯, 二次晶粒, 尺寸, 偏离角, aluminum, aluminium, silicon, iron, manganese, carbon, oriented, silicon steel, directional, cool rolling, intermediate annealing, secondary grain, grain size, deviation angle, goss

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	CN 109715840 A (JFE STEEL CORP.) 03 May 2019 (2019-05-03) description, paragraphs 0019-0078	1-14
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Y	CN 107109552 A (JFE STEEL CORP.) 29 August 2017 (2017-08-29) description, paragraphs 0014-0029	1-14

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

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

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CN)
China No. 6, Xitucheng Road, Jimenqiao, Haidian District,
Beijing 100088

Authorized officer

Telephone No.

INTERNATIONAL SEARCH REPORT
Information on patent family members

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