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PROCESS FOR PRODUCING SILICON STEEL SHEET HAVING SOFT MAGNETIC CHARACTERISTICS.

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References cited:
DE-B- 2 024 525
JP-A- 6 115 919
US-A- 3 413 165

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Description

The present invention relates to an improvement of a method of producing high silicon iron sheet of more than 4wt% Si having excellent soft magnetic properties by hot rolling and cold rolling processes.

Silicon iron alloys have excellent soft magnetic properties and are used as magnetic cores of electric transformers or material for other electric devices. It is known that the more is the Si content, the more improved are the soft magnetic properties, and these properties show peaks at around 6.5wt%. However, in the event of Si contents of more than 4.0wt% the elongation properties would be rapidly decreased, and ordinary cold rolling could not be practised. Therefore it has been regarded as extremely difficult to industrially produce sheet containing Si of more than 4wt%.

A method of producing relatively ductile silicon iron sheets containing 4.5 to 7.5wt% Si is known from the DE-B-2 024 525. It comprises the step of rolling cast ingots at temperatures between 650 and 350 °C and a subsequent cold rolling step without re-heating the sheets to more than 350 °C. However, the rolling of high Si steel at temperatures of less than 650 °C require undesirable special rolling mills, and the known method is not particularly suited for mass production due to the necessary temperature control.

The invention deals with the problem of providing an effective method of mass producing the desired silicon iron sheets in a systematic manner and thereby avoiding, as far as possible, difficulties in connection with the hot rolling step.

This problem is solved by the method as defined in claim 1.

According to the invention, a molten Fe alloy is produced, which comprises Si: 4.0 to 7.0wt%, Mn: not more than 0.5wt%, P: not more than 0.1wt%, S: not more than 0.02wt% and Al: not more than 2wt%. The produced alloy is made as ingot or slab by continuous casting, subjected to a slabbing-roughing, or a roughing at temperature of more than 1000 °C and at total reduction of more than 50%, subjected to hot finish rolling under conditions specified as follows, and coiled at a temperature of not more than 750 °C.

The oxide scale of the hot rolled strip or plate is removed by pickling or grinding, and after trimming if required, it is entered to cold rolling. The cold rolled strip or sheet is subjected to an annealing for improving the magnetic properties. The annealing is done at a temperature of the cold rolled strip or sheet being more than 800 °C.

The most noted steps in the invention are said hot finish rolling at temperature of not more than 1100 °C and at a specific total reduction R(%), and the coiling at not more than 750 °C.

The total reduction R(%) is defined as follows.

Assuming that d(mm) is an average grain diameter before the hot finish rolling, and a critical grain boundery spacing value λ₀(mm) is given by

\[ \lambda_0 = 1.90 - 0.26 \times \text{Si(wt%)} \]

the total reduction R should depend from d and \( \lambda_0 \) as follows:

- if \( d > \lambda_0 \), \( R(\%) \geq (1 - \lambda / d) \times 100 \), and
- if \( d \leq \lambda_0 \), \( R(\%) \geq 0 \).

Herein, if \( R(\%) = 0 \), the hot finish rolling is not of course carried out, and this invention also includes such a case.

If the hot finish rolling conditions are selected in response to the microstructure of the alloy before hot finish rolling, a hot rolled plate having excellent cold workability may be produced, and it has been found that the cold workability of silicon iron alloys is regulated by a microstructural parameter of the hot rolled plate.

When the average grain diameter before the hot finish rolling is large, large hot rolling reduction is necessary to permit cold rolling. On the other hand, if the average grain diameter is small, cold rolling is possible even if the reduction at the hot finish rolling is small, and if the average grain diameter before the hot finish rolling is less than a certain determined value, the cold rolling is even possible without hot finish rolling.

An additional advantage results from the fact that in contrast to the prior art explained above it is not necessary to perform warm rolling at less than 650 °C in specific rolling machines. The invention permits the hot finish rolling temperature to be more than about 775 °C (according to the examples following below).

The invention will now be explained in more detail. Fig. 1 is a graph showing a range where no cracks are generated in a relation between the average grain diameter before the hot finish rolling and the total reduction during the hot finish rolling; Fig. 2 is a graph showing a relation between Si content and \( \lambda_0 \); and
Fig. 3 is a graph showing the scope realized in the embodiment where the cold rolling is possible.

Fig. 1 shows the cold workability of 6.5% silicon iron alloy, in which lateral and vertical axes indicate the average grain diameter d(mm) before hot finish rolling and the total reduction R(%) of the hot finish rolling, respectively.

The figure was obtained by investigating samples with various average grain diameters, which were prepared from the 50 kg ingots. The samples were soaked at 1000 °C and hot-rolled by six passes to each amount of the total reduction. The finish temperature was 850 ± 10 °C.

In the figure, O indicates that no edge cracks were generated when the hot-rolled plates were cold-rolled at a total reduction of 85%; in other words, the cold workability was preferable. X indicates that cracks were generated at the beginning of said cold rolling and further rolling was impossible.

From this figure, it is obvious that when the average grain diameter d(mm) before the hot finish rolling is large, large hot rolling reduction is necessary to undertake the cold rolling (for example, when the average grain diameter is 3mm, the total hot rolling reduction of more than 95% is necessary), and on the other hand, if the average grain diameter were small, the cold rolling would be possible even if the reduction at the hot finish rolling were small (for example, when the average grain diameter is 0.32mm, the cold rolling is possible even if the total reduction is 40%).

In addition, if said average grain diameter were less than a certain determined value, the cold rolling would be possible without the hot finish rolling.

The microstructure obtained by said hot finish rolling is fibrous or lamellar where the grains are elongated in the rolling direction, while polygonal is the microstructure when the total reduction at the hot finish rolling is zero. From this result, it is seen that if a microstructural parameter, that is, average spacings λ(mm) between grain boundaries in the direction of plate thickness were introduced, irrespectively of differences in the morphology of microstructure, general cold workability could be explained by λ. λ corresponds to the average grain diameter in thickness direction when the structure is fibrous or lamellar, and when it is polygonal, λ becomes the same as the average grain diameter which is usually defined. The recrystallization temperature of this kind of alloys is 1000 to 1100 °C. Therefore, λ of the fibrous structure obtained by the hot finish rolling at the starting temperature of not more than 1100 °C, quite agrees to a value calculated by the average grain diameter before the hot finish rolling and the total hot rolling reduction, since the recrystallization scarcely takes place in said temperature range and the grains are only cracked evenly in the thickness. The curve of Fig.1 shows calculated total reduction of the hot finish rolling, as λ becomes 0.2mm. This curve shows a very good agreement to boundaries between the cold rolling possible range and impossible range. From this fact it is seen that the cold rolling is possible by lowering λ below 0.2mm in the 6.5wt% silicon iron alloy, irrespectively of shapes of crystal grains. If λ = 0.2mm is assumed as a critical value and expressed with λc, λc is varied by Si content. That is, when λc was gained by the same experiment as Fig.1 with respect to the alloys of 1 to 6wt% Si, a result was shown in Fig.2. If λc is expressed as a function of Si content from said result,

\[ \lambda_c = 1.90 \times 0.26 \times \text{Si( wt\%)} \]

From the above mentioned result, it was possible to clarify the hot finish rolling conditions for producing the hot rolled plate suitable to the cold rolling. However the average grain diameters of the ingots or the continuously cast slabs ordinarily produced are large, and in order to refine the average spacings between the grain boundaries in the thickness direction less than λc, the total reduction thereof must be extremely large, and in such a condition the ingot or slab is frequently cracked. Therefore, it is necessary to refine the microstructure of the ingot or the continuously cast slab prior to the hot finish rolling. By forming the fibrous (lamellar) structure, the refinement to a certain extent could be accomplished, but if utilizing the recrystallization, the refinement could be more effectively carried out. In the inventors’ studies, if the hot rolling of more than 50% was done at the temperature of more than 1000 °C, the microstructure of the high silicon iron alloy could be refined without generating crackings. If the alloy is subjected to the slabbing or the roughing prior to the hot finish rolling under the above mentioned conditions, it is possible to produce an intermediate material (for example, roughed bar material) to be entered to the hot finish rolling by using the ingot or the continuously cast slab.

The above mentioned findings may be summarized as under

1. The cold workability of the high silicon iron alloy depends upon the average spacings λ(mm) between the grain boundaries in the thickness direction prior to the cold rolling

2. If said spacings are made less than a certain critical value λc (mm) which is determined by the Si content, an excellent cold workability could be provided.

3. The hot finish rolling conditions are specified so as to realize the above mentioned λc, and they must
be decided in response to the average grain diameter \( d \) (mm) prior to the hot finish rolling. That is, in the hot finish rolling at the temperature of below 1100 °C where the recrystallization does not take place, the reduction should be made by a value \( \{(1 - \lambda_0/d) \times 100(\%)\} \) which is decided geometrically from the values of \( \lambda_0 \) and \( d \).

(4) For realizing said hot finish rolling, the refinement through the roughing or slabbing is required, and it is accomplished by the rolling at the temperature of above 1000 °C and at the total reduction of more than 50%.

(5) If the average spacings between the grain boundaries in the thickness direction of less than said \( \lambda_0 \) (mm) were obtained by the roughing or slabbing conditions, the material per se displays the excellent cold workability (not undertaking the hot finish hot rolling).

This invention is based on the above mentioned concept, and references will be made in detail to the specifying conditions and others.

(Composition of steel)

Si is an element which improves the soft magnetic properties, and it displays the most excellent effect at around 0.5wt%. The invention specifies Si content at 4.0 to 7.0wt%. If Si were less than 4.0wt%, no problem would occur about the cold workability, and if it were more than 7.0wt%, soft magnetic properties would be deteriorated through increment of magnetostriiction and decrement of saturation induction and maximum permeability and in addition, cold workability would be extremely bad. Thus, the range of Si is 4.0 to 7.0wt%.

Mn is added to fix S as an impurity. But if Mn content were increased, the workability would be worsened and if MnS were increased, bad influences would be given to the soft magnetic properties, hence Mn ≤ 0.5wt%.

P lowers iron loss. However, if P content were increased, the workability would be worsened and it is specified as P ≤ 0.1wt%.

S is required to be lessened as far as possible as mentioned above, and the invention specifies S ≤ 0.02wt%.

Al is added for deoxidation at preparing the molten steel. Further, it is known that Al fixes solute N which deteriorates the soft magnetic properties, and electric resistance is increased. By adding enough Al it is possible to coarsen the size of precipitated AlN until it has scarcely resistance against moving of magnetic domain wall. However, if Al were added too much, the cold workability would be made bad, and a cost-up would be invited, and therefore it is Al ≤ 2wt%.

C is a harmful element which increases the electric iron loss and is a main factor of a magnetic aging, and therefore the C content is desirous to be small. But since C enlarges the \( \gamma \rightarrow \alpha \) loop of the Fe-Si equilibrium diagram, and \( \gamma \rightarrow \alpha \) transformation point appears during cooling if an apt amount of C to be determined by the Si content is added, a heating treatment utilizing said transformation would be possible. It is preferable that C is not more than 1wt%.

(Slabbing-roughing conditions)

The cast alloy is undertaken with the slabbing and roughing if it is an ingot, and it is done with the roughing if it is a continuously cast slab. These rolling conditions are decided for performing the refinement by recrystallization. In a slab of silicon iron alloy, the recrystallization does not take place at the temperatures of less than 1000 °C, and if the rolling were forcibly carried out at ranges of said temperatures, cracks would be created, and therefore the rolling temperature is more than 1000 °C. Further, for accomplishing satisfied refinement, strain of more than 50% is required, and the total reduction be specified more than 50%.

(Hot finish rolling conditions)

As mentioned, under the premise of a fibrous (or lamellar) microstructure, the rolling should be begun at a temperature of not more than 1100 °C. If the total reduction is assumed as \( R(\%) \), \( \lambda \) is geometrically decided by \( d \) and \( R \), and so \( R \geq \{(1 - \lambda_0/d) \times 100(\%)\} \) is required for satisfying \( \lambda \leq \lambda_0 \). If \( d \leq \lambda_0 \) is obtained by the roughing or other means, the hot finish rolling is not necessary in view of the cold workability, but the rolling may be necessary in the practise for other reasons. In the case of polygonal microstructure, the cold rolling is also possible if \( \lambda \leq \lambda_0 \) is realized.

A reason for specifying the coiling temperature of not more than 750 °C is that otherwise recrystal-
lization and grain growth may happen during cooling the coil.

(Cold (or warm) rolling and annealing conditions)

Warm rolling in which the temperature of the rolled sheet is less than 400 °C, is also possible instead of the cold rolling on the hot rolled plates, and such a warm rolling is effective to improve the workability.

The annealing after the cold or warm rolling is carried out for imparting magnetic properties to the silicon iron sheet, and the annealing is done at the temperature of the sheet being more than 800 °C. If the annealing temperature were less than 800 °C, the excellent magnetic properties would not be provided since the crystal grains are too fine.

Apart from the above mentioned annealing, it is possible to carry out the annealing on the hot rolled plate at a temperature of not more than 750 °C before the cold rolling, and/or otherwise carry out an intermediate annealing at the temperature of not more than 750 °C in the course of the cold rolling. These annealings are for improving the cold workability and accomplishing decarburization, and the both are done if required.

EMBODIMENTS FOR PRACTISING THE INVENTION

(Example 1)

The continuously cast slabs (thickness: 200mm) having the chemical composition shown in Table 1 were heated at temperatures of 1200 °C and 1300 °C for 3 hours respectively, immediately followed by the roughing. The roughings were performed by 5 passes, and the slabs were practised with pass scheduls of each 3 levels for changing the grain size. Subsequently, these materials were heated at the temperature of 900 °C and, after 30 minutes, entered into the hot finish rolling. The objective finish thicknesses were selected by each several standards in response to the average grain sizes of the roughed bar materials with reference to the result of Fig.1. The finishing temperatures were 775 to 880 °C and the cooling temperatures were 855 to 610 °C. The hot finish rolled strips were subjected to the cold rolling after the pickling, and the cold workability was tested as in Fig.1. The roughing and the hot rolling conditions and the measured values of the average grain size are shown in Table 2, and the tested results of the cold workability are shown in Fig.3. ○ marks in Fig.3 show that the cold rollings were done without causing cracks, while X marks show that heavy defects occurred or the strips were broken. Further, the curve in Fig. 3 shows conditions that the spacings between the grain boundaries are λ₀ = 0.2mm as in Fig.1. It was confirmed therefrom that the tendency obtained in Fig.1 will be obtained in the actually practising operations.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>(wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>0.007</td>
</tr>
</tbody>
</table>
High silicon iron alloys having the chemical composition shown in Table 3 were melted in the vacuum melting furnace and cast into ingots. These ingots were sectioned into 25mm thicknesses and further sectioned at the temperature of 1150°C and 1180°C.

The average grain diameters of the cast samples were 420 & 580 μm. The grain diameters of the finished castings were 800 μm, the average thicknesses of the cast samples being 0.22 mm. The average thickness of the finished castings was 0.23 mm.

### Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Reduction</th>
<th>Grain Diameter</th>
<th>Thickness</th>
<th>Heating Temp.</th>
<th>Roughing Temp.</th>
<th>Total Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- A: Heat treatment
- C: Total Reduction
- M: Melting Temperature
- R: Roughing Temperature
- G: Grain Diameter

Table 3 shows the chemical composition of the cast samples.

### Table 3

<table>
<thead>
<tr>
<th>Element</th>
<th>Cast Sample</th>
<th>Ingot Sample</th>
<th>Roughing Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- C: Cast Sample
- I: Ingot Sample
- R: Roughing Sample

**Example 2:**

- Cold workability: C: Comparative samples
- Machinability: C: Comparative samples
- Heat treatment: C: Comparative samples
- Properties: C: Comparative samples

**Note:**
- A: Heat treatment
- C: Total Reduction
- M: Melting Temperature
- R: Roughing Temperature

### Table 4

<table>
<thead>
<tr>
<th>Sample</th>
<th>Reduction</th>
<th>Grain Diameter</th>
<th>Thickness</th>
<th>Heating Temp.</th>
<th>Roughing Temp.</th>
<th>Total Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- A: Heat treatment
- C: Total Reduction
- M: Melting Temperature
- R: Roughing Temperature
- G: Grain Diameter

Table 4 shows the chemical composition of the cast samples.
and the tested results of the cold workability. With respect to the cold workability, the O marks show the rollings to 0.5mm thickness without causing cracks, while the X marks show the heavy defects or breakages of the strips.

Table 4 show the result that although the microstructures of the hot rolled plates satisfy the conditions of $\lambda \leq \lambda_0$, the cold rollings could not be carried out due to the chemical compositions.

<table>
<thead>
<tr>
<th>Samples</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>T.A.C</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0.003</td>
<td>6.52</td>
<td>0.15</td>
<td>0.49</td>
<td>0.009</td>
<td>0.006</td>
</tr>
<tr>
<td>2.</td>
<td>0.004</td>
<td>6.48</td>
<td>0.13</td>
<td>0.11</td>
<td>0.007</td>
<td>0.010</td>
</tr>
<tr>
<td>3.</td>
<td>0.004</td>
<td>6.48</td>
<td>0.14</td>
<td>0.002</td>
<td>0.0007</td>
<td>0.007</td>
</tr>
<tr>
<td>4.</td>
<td>0.004</td>
<td>6.49</td>
<td>0.14</td>
<td>0.11</td>
<td>0.0009</td>
<td>0.009</td>
</tr>
<tr>
<td>5.</td>
<td>0.002</td>
<td>6.51</td>
<td>0.15</td>
<td>0.45</td>
<td>0.009</td>
<td>0.010</td>
</tr>
<tr>
<td>6.</td>
<td>0.003</td>
<td>6.50</td>
<td>0.16</td>
<td>0.49</td>
<td>0.0007</td>
<td>0.007</td>
</tr>
<tr>
<td>7.</td>
<td>0.003</td>
<td>6.51</td>
<td>0.15</td>
<td>0.49</td>
<td>0.0009</td>
<td>0.009</td>
</tr>
<tr>
<td>8.</td>
<td>0.002</td>
<td>6.50</td>
<td>0.15</td>
<td>0.48</td>
<td>0.0009</td>
<td>0.007</td>
</tr>
<tr>
<td>9.</td>
<td>0.003</td>
<td>6.51</td>
<td>0.15</td>
<td>0.48</td>
<td>0.0007</td>
<td>0.009</td>
</tr>
<tr>
<td>10.</td>
<td>0.003</td>
<td>6.52</td>
<td>0.14</td>
<td>0.48</td>
<td>0.0009</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 3
The continuously cast slabs (thickness: 200mm) having the chemical composition shown in Table 1 were heated at the temperature of 1008°C at the exit side of the reheating furnace, and immediately the roughing temperature was 1120°C. The finishing temperature was 950°C. The finishing rolling was performed immediately after the roughing at the final pass of 40%. The average grain diameter of the roughed bar, the hot rolling, a sample was cut out from the hot rolled coil, and the measured average spacing of the grain was 1.9 μm. The table shows the grain size after the roughing at the final pass of 40%.

### Table 4

<table>
<thead>
<tr>
<th>X</th>
<th>0.20</th>
<th>0.16</th>
<th>0.17</th>
<th>0.17</th>
<th>1.0 Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>8.8</td>
<td>15</td>
<td>1.6</td>
<td>0</td>
<td>&quot;</td>
</tr>
<tr>
<td>O</td>
<td>5.1</td>
<td>6.8</td>
<td>1.5</td>
<td>6</td>
<td>&quot;</td>
</tr>
<tr>
<td>O</td>
<td>9.8</td>
<td>6.8</td>
<td>0.6</td>
<td>1.5</td>
<td>Compaction</td>
</tr>
<tr>
<td>O</td>
<td>6.8</td>
<td>2.1</td>
<td>1.4</td>
<td>2</td>
<td>&quot;</td>
</tr>
<tr>
<td>O</td>
<td>0.6</td>
<td>2.6</td>
<td>1.4</td>
<td>5</td>
<td>&quot;</td>
</tr>
<tr>
<td>X</td>
<td>18</td>
<td>12.0</td>
<td>18</td>
<td>1.6</td>
<td>&quot;</td>
</tr>
<tr>
<td>O</td>
<td>8.8</td>
<td>6.8</td>
<td>1.9</td>
<td>3</td>
<td>&quot;</td>
</tr>
<tr>
<td>O</td>
<td>6.8</td>
<td>18</td>
<td>2.0</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>O</td>
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<td>2.2</td>
<td>1.9</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>C</td>
<td>0.1</td>
<td>1.0</td>
<td>0</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Note: H: Average grain diameter of crop samples of roughed bar.
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boundaries were 0.12mm. The hot rolled coil was pickled and 83% cold-rolled to 0.5mm thickness, and undertaken with a box annealing at the temperature of 1000 °C (H₂ atmosphere) and measured with AC magnetic properties. Table 5 shows the measured results.

Table 5

<table>
<thead>
<tr>
<th>AC magnetic properties (Thickness: 0.5mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron loss (W / Kg)</td>
</tr>
<tr>
<td>W₁₀₅₀</td>
</tr>
<tr>
<td>0.55</td>
</tr>
</tbody>
</table>

If Si content were more than 4wt%, the effect of cooling in a magnetic field becomes remarkable. Therefore, a sample cut from the coil was annealed at 800 °C for 10min, and given the magnetizing field of 200 Oe during the subsequent cooling, and AC magnetic properties (after said heating treatment in the magnetizing field) were measured. The results are shown in Table 6.

Table 6

<table>
<thead>
<tr>
<th>AC magnetic properties (Thickness: 0.5mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron loss (W / Kg)</td>
</tr>
<tr>
<td>W₁₀₅₀</td>
</tr>
<tr>
<td>0.48</td>
</tr>
</tbody>
</table>

It was apparent that high silicon iron sheets manufactured by the present invention exhibited the excellent soft magnetic properties.

(Example 4)

Silicon iron alloys having the chemical composition of Table 7 were molten in the vacuum melting furnace, and cast into ingots and soaked at the temperature of 1180 °C for 3 hours, and slabbled (the total reduction: 60%) into 200mm thickness, and further soaked at the temperature of 1180 °C for 1 hour and roughed to 35nm thickness and finished to 2.4mm in thickness. Those coils were pickled with hydrochloric acid and cold-rolled, and the cold workability was measured with the same appreciations as Example 1. Fig.8 shows the hot rolling conditions, the average grain size of crop samples after roughing, the hot finish rolled plate and the appreciated results of the cold workability.

Table 7

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>T.A.F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.007</td>
<td>4.2</td>
<td>0.13</td>
<td>0.010</td>
<td>0.003</td>
<td>0.43</td>
</tr>
<tr>
<td>2</td>
<td>0.006</td>
<td>5.6</td>
<td>0.12</td>
<td>0.009</td>
<td>0.002</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td>0.007</td>
<td>6.6</td>
<td>0.12</td>
<td>0.009</td>
<td>0.002</td>
<td>0.45</td>
</tr>
<tr>
<td>4</td>
<td>0.007</td>
<td>6.8</td>
<td>0.14</td>
<td>0.009</td>
<td>0.003</td>
<td>0.44</td>
</tr>
</tbody>
</table>
As seen from the above, according to the present method, it is possible to cold-rolled high silicon iron strip containing 4.0 to 7.0% Si. 

### Table 8

<table>
<thead>
<tr>
<th>C</th>
<th>Cold workability</th>
<th>I</th>
<th>Spacing between average grain boundaries in thickness direction of hot rolled plate</th>
<th>K</th>
<th>Starting temperature of hot finish rolling</th>
<th>R</th>
<th>Average grain diameters after roughing</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.13</td>
<td>0.009</td>
<td>1.17</td>
<td>9.3</td>
<td>10.58</td>
<td>2.3</td>
<td>3.57</td>
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<tr>
<td>6</td>
<td>0.15</td>
<td>0.015</td>
<td>0.94</td>
<td>9.5</td>
<td>10.55</td>
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<td>3.60</td>
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<tr>
<td>6</td>
<td>0.18</td>
<td>0.004</td>
<td>0.93</td>
<td>9.7</td>
<td>10.47</td>
<td>2.5</td>
<td>3.46</td>
</tr>
<tr>
<td>6</td>
<td>0.18</td>
<td>0.006</td>
<td>0.93</td>
<td>9.5</td>
<td>10.50</td>
<td>2.6</td>
<td>3.52</td>
</tr>
</tbody>
</table>

Note: C: Thickness of roughed bar, D: Average grain diameters after roughing.
electric transformers or materials for other electric devices.

Claims

1. Method of producing silicon iron sheets having excellent soft magnetic properties, comprising melting Fe alloy containing Si: 4.0 to 7.0 wt%, Mn: not more than 0.5 wt%, P: not more than 0.1 wt%, S: not more than 0.02 wt%, Al: not more than 2 wt,% making an ingot or a continuously cast slab, slabbing-roughing or otherwise roughing at temperature of more than 1000 °C and at total reduction of more than 50%, hot finish rolling at a temperature of not more than 1100 °C in response to average crystal grain size \( d \) before the hot finish rolling, coiling at temperature of not more than 750 °C, cold or warm rolling after a descaling treatment, and performing annealing, said hot finish rolling step being performed at a total reduction \( R \) depending on the average grain size \( d \) (mm) before the hot finish rolling and on a critical grain boundary spacing value \( \lambda_o \)

\[
\lambda_o (\text{mm}) = 1.90 - 0.26 \times \text{Si(wt%)}
\]

as follows:

\[
R(\%) \geq (1-\lambda_o/d) \times 100 \quad \text{if} \quad d > \lambda_o,
\]

and

\[
R(\%) \geq 0 \quad \text{if} \quad d \leq \lambda_o.
\]

2. Method as claimed in claim 1, characterized by annealing, after the hot finish rolling, the hot rolled strip or plate at a temperature of not more than 750 °C before or after said descaling treatment.

3. Method as claimed in claim 1 or 2, characterized by carrying out an intermediate annealing at a temperature of not more than 750 °C in the course of the cold or warm rolling.

Reivendications

1. Procédé de fabrication de tôles d'acier au silicium possédant d'excellentes propriétés magnétiques douces, comprenant :

la fusion d'un alliage de fer contenant Si: 4.0 à 7.0% en poids; Mn: pas plus de 0.5% en poids; P: pas plus de 0.1% en poids; S: pas plus de 0.02% en poids; Al: pas plus de 2% en poids,

l'obtention d'un lingot ou d'une braise de coulée continue, passage dans un laminoir à brame ou de dégrossissage à une température supérieure à 1100 °C, et avec un taux de réduction total supérieur à 50%,

un laminage à chaud de finition à une température ne dépassant pas 1100 °C en fonction de la dimension moyenne du grain cristallin \( d \) avant le laminage à chaud de finition,

le refroidissement à une température n'excédant pas 750 °C.

le laminage à chaud ou à froid après un traitement de décalaminage, et

l'exécution d'un recuit,

l'adite étape de laminage à chaud de finition étant réalisée avec un taux de réduction total \( R \) dépendant de la grosseur moyenne de grain \( d \) (mm) avant le laminage à chaud de finition et d'une valeur critique de l'intervalle des joints de grains.
\( \lambda_0 \text{ (mm)} = 1.90 - 0.26 \times \text{Si} \% \text{ en poids} \)

comme suit:

\[ R(\%) \geq (1 - \frac{\lambda_0}{d}) \times 100, \text{ si } d > \lambda_0 \]

et

\[ R(\%) \geq 0, \text{ si } d \geq \lambda_0 \]

2. Procédé tel que revendiqué dans la revendication 1, caractérisé par un recuit après le laminage à chaud de finition, de la bande ou la plaque laminée à chaud à une température n'excédant pas 750 °C avant ou après ledit traitement de décalaminage.

3. Procédé tel que revendiqué dans la revendication 1 ou 2, caractérisée par la réalisation d'un recuit intermédiaire à une température n'excédant pas 750 °C au cours du laminage à chaud ou à froid.

**Patentansprüche**

1. Verfahren zum Herstellen von Silicium-Eisenblechen mit ausgezeichneten weichmagnetischen Eigenschaften,
   bei dem eine Fe-Legierung geschmolzen wird, die Si: 4.0 bis 7.0 Gewichts\%, Mn: nicht mehr als 0.5 Gewichts\%, P: nicht mehr als 0.1 Gewichts\%, S: nicht mehr als 0.02 Gewichts\%, Al: nicht mehr als 2 Gewichts\% enthält,
   ein Gußblock oder ein Gußstrang erzeugt wird,
   Brammen- oder sonstiges Vorwalzen bei einer Temperatur von mehr als 1000 °C und einer Gesamtreduzierung von mehr als 50% durchgeführt wird,
   Warmfertigwalzen bei einer Temperatur von nicht mehr als 1100 °C in Abhängigkeit von der mittleren Kristallkorngröße d vor dem Warmfertigwalzen durchgeführt wird,
   bei einer Temperatur von nicht mehr als 750 °C gewickelt wird, Kalt- und Warmwalzen nach einer Entzunderungsbehandlung durchgeführt wird,
   und ein Glühvorgang durchgeführt wird,
   wobei das Warmfertigwalzen mit einer Gesamtreduzierung R durchgeführt wird, die von der mittleren Korngröße d (mm) vor dem Warmfertigwalzen und von einem kritischen Korngrenzenabstandswert

\( \lambda_0 \text{ (mm)} = 1.90 - 0.26 \times \text{Si} \% \text{ (Gewichts\%)} \)

wie folgt abhängig ist:

\[ R(\%) \geq (1 - \frac{\lambda_0}{d}) \times 100, \text{ falls } d \geq \lambda_0, \]

und

\[ R(\%) \geq 0, \text{ falls } d \leq \lambda_0. \]

2. Verfahren nach Anspruch 1, dadurch gekennzeichnet, daß nach dem Warmfertigwalzen das warmgewalzte Band oder die warmgewalzte Platte vor oder nach der Entzunderungsbehandlung bei einer Temperatur von nicht mehr als 750 °C geglüht wird.

FIG. 1

TOTAL REDUCTION R(\%) OF HOT ROLLING

AVERAGE GRAIN DIAMETER \(d/\text{mm}\) BEFORE HOT ROLLING

FIG. 2

\[ \lambda_0 = 1.90 - 0.26 \times \text{Si (wt\%)} \]

\(\lambda_0\) (mm)

\(\text{Si (wt\%)}\)
FIG. 3

Conditions of hot finish rolling

- Reheating temperature: 900°C
- Finishing temperature: 775°C
- Coiling temperature: 655°C
  ~ 680°C
  ~ 610°C

Graph showing:
- Total reduction R(%) of hot rolling
- Average grain diameter d(mm) before hot rolling