Innovation, Sciences et Développement économique Canada
Office de la Propriété Intellectuelle du Canada

Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

CA 2809756 C 2018/04/24

(11)(21) 2 809 756

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(86) Date de dépôt PCT/PCT Filing Date: 2011/09/27
(87) Date publication PCT/PCT Publication Date: 2012/04/05
(45) Date de délivrance/Issue Date: 2018/04/24
(85) Entrée phase nationale/National Entry: 2013/02/27
(86) N° demande PCT/PCT Application No.: JP 2011/005433
(87) N° publication PCT/PCT Publication No.: 2012/042854
(30) Priorité/Priority: 2010/09/28 (JP2010-217370)

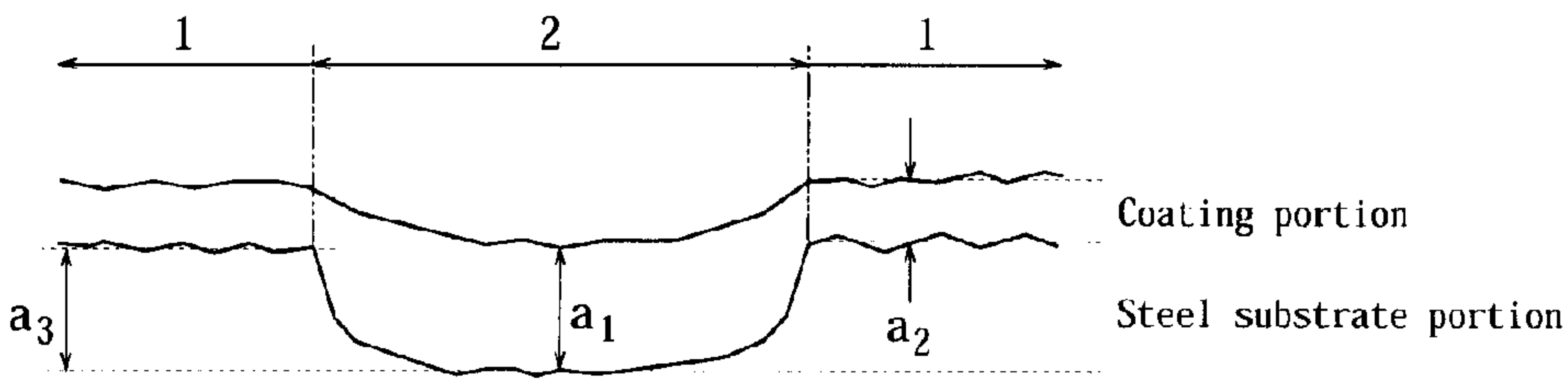
(51) Cl.Int./Int.Cl. *C23C 22/00* (2006.01), *B32B 15/04* (2006.01), *C21D 8/12* (2006.01), *C22C 38/00* (2006.01), *C22C 38/04* (2006.01), *C22C 38/60* (2006.01), *H01F 1/16* (2006.01), *H01F 1/18* (2006.01)

(72) Inventeurs/Inventors:
WATANABE, MAKOTO, JP;
OKABE, SEIJI, JP;
TAKAMIYA, TOSHITO, JP

(73) Propriétaire/Owner:
JFE STEEL CORPORATION, JP

(74) Agent: SMART & BIGGAR

(54) Titre : TOLE D'ACIER ELECTROMAGNETIQUE ORIENTEE
(54) Title: GRAIN ORIENTED ELECTRICAL STEEL SHEET



(57) Abrégé/Abstract:
The present invention provides a grain oriented electrical steel sheet that may keep iron loss at low level when assembled as an actual transformer and has excellent iron loss properties as an actual transformer, in which a film thickness al (μm) of insulating coating at the floors of linear grooves, a film thickness a2 (μm) of the insulating coating on a surface of the steel sheet at portions other than the linear grooves, and a depth a3 (μm) of the linear grooves are controlled to satisfy formulas (1) and (2):
$0.3\ \mu m \le a_2 \le 3.5\ \mu m$ ····· (1), and
$a_2 + a_3 - a_1 \le 15 \mu m$ ····· (2).

ABSTRACT

The present invention provides a grain oriented electrical steel sheet that may keep iron loss at low level when assembled as an actual transformer and has excellent iron loss properties as an actual transformer, in which a film thickness a_1 (μm) of insulating coating at the floors of linear grooves, a film thickness a_2 (μm) of the insulating coating on a surface of the steel sheet at portions other than the linear grooves, and a depth a_3 (μm) of the linear grooves are controlled to satisfy formulas (1) and (2):

$0.3\ \mu m \leq a_2 \leq 3.5\ \mu m \cdots\cdots (1)$, and

$a_2 + a_3 - a_1 \leq 15\ \mu m \cdots\cdots (2)$.

DESCRIPTION

GRAIN ORIENTED ELECTRICAL STEEL SHEET

TECHNICAL FIELD

[0001] The present invention relates to grain oriented electrical steel sheets for use in iron core materials of transformers or the like.

BACKGROUND ART

[0002] Grain oriented electrical steel sheets, which are mainly used as iron cores of transformers, are required to have excellent magnetic properties, in particular, less iron loss.

In this regard, it is important to highly accord secondary recrystallized grains of a steel sheet with (110)[001] orientation, i.e., what is called "Goss orientation," and reduce impurities in a product steel sheet. However, there are limits on controlling crystal grain orientations and reducing impurities in view of production cost, and so on. Accordingly, there have been developed techniques for iron loss reduction, which is to apply non-uniform strain to a surface of a steel sheet physically to subdivide magnetic domain width, i.e., magnetic domain refining techniques.

[0003] For example, JP 57-002252 B proposes a technique of irradiating a steel sheet after final annealing with a laser to introduce high-dislocation density regions into a surface layer of the steel sheet, thereby narrowing magnetic domain widths and reducing iron loss of the steel sheet.

In addition, JP 62-053579 B proposes a technique of refining magnetic domains by forming linear grooves having a depth of more than 5 μm on the steel substrate portion of a steel sheet after being subjected to final annealing at a load of 882 MPa to 2156 MPa (90 kgf/mm^2 to 220 kgf/mm^2), and then subjecting the steel sheet to heat treatment at a temperature of 750 °C or higher.

Moreover, JP 3-069968 B proposes a technique of introducing linear notches (grooves) of 30 μm to 300 μm wide and 10 μm to 70 μm deep, in a direction substantially perpendicular to the rolling direction of a steel sheet, at intervals of 1 mm or more in the rolling direction.

With the development of the magnetic domain refining techniques as above, it is now becoming possible to obtain grain oriented electrical steel sheets having good iron loss properties.

CITATION LIST

Patent Literature

[0004] JP 57-002252 B
JP 62-053579 B
JP 3-069968 B.

PROBLEM STATEMENT

[0005] Usually, however, when a steel sheet having grooves formed on a surface thereof is sheared into iron core materials to be assembled into a transformer or the like, each successive iron core material is stacked with a sliding motion on top of the previously stacked iron core material. Accordingly, a problem that could arise is that the sliding motion of an iron core material is interrupted by groove portions, which results in lower working efficiency.

Moreover, in addition to the problem of working efficiency, another problem that could arise is that the interruption by groove portions causes local stress to be placed on the steel sheet, introduces strain into the steel sheet, and thereby deteriorates the magnetic properties thereof.

SUMMARY OF INVENTION

[0005a] According to an aspect, there is provided a grain oriented electrical steel sheet comprising: linear grooves provided on a surface of the steel sheet; and insulating coating applied to the surface, the insulating coating containing silica and phosphate as its principal components or using borate and alumina sol, wherein a film thickness a_1 (μm) of the insulating coating at floors of the linear grooves, a film thickness a_2 (μm) of the insulating coating on the surface of the steel sheet at portions other than the linear grooves, and a depth

a_3 (μm) of the linear grooves being within a range of 20 μm to 50 μm satisfy formulas (1) and (2):

$$0.3\ \mu m \leq a_2 \leq 3.5\ \mu m \ ..... (1), \text{ and}$$

$$a_2 + a_3 - a_1 \leq 15\ \mu m \ ..... (2).$$

[0006] Embodiments of the present invention may provide such a grain oriented electrical steel sheet having grooves for magnetic domain refinement formed thereon that is capable of keeping iron loss at low level when assembled as an actual transformer and has excellent iron loss properties as an actual transformer.

[0007] That is, the arrangement of an embodiment of the present invention is summarized as follows:

[1] A grain oriented electrical steel sheet comprising: linear grooves provided on a surface of the steel sheet; and insulating coating applied to the

surface, wherein a film thickness a_1 (μm) of the insulating coating at the floors of the linear grooves, a film thickness a_2 (μm) of the insulating coating on the surface of the steel sheet at portions other than the linear grooves, and a depth a_3 (μm) of the linear grooves satisfy formulas (1) and (2):

$0.3\ \mu m \leq a_2 \leq 3.5\ \mu m$ ····· (1), and

$a_2 + a_3 - a_1 \leq 15\ \mu m$ ····· (2).

[0008] [2] The grain oriented electrical steel sheet according to [1] above, wherein tension applied to the steel sheet by the insulating coating is 8 MPa or less.

[0009] [3] The grain oriented electrical steel sheet according [1] or [2] above, wherein the insulating coating is formed by using a phosphate-silica-based coating treatment liquid.

[0010] Embodiments of the present invention may provide a grain oriented electrical steel sheet that is capable of effectively reducing iron loss when assembled as an actual transformer and that has excellent iron loss properties as an actual transformer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The present invention will be further described below with reference to the accompanying drawings, wherein:

FIG. 1 is a schematic diagram illustrating parameters of the present invention, including a coating film thickness a_1 (μm) at the floor of a linear groove, a coating film thickness a_2 (μm) at portions other than the linear groove, and a linear groove depth a_3 (μm); and

FIG. 2 illustrates how to measure and calculate the tension applied by insulating coating to the steel sheet.

DESCRIPTION OF EMBODIMENTS

[0012] The present invention will be specifically described below.
Usually, when linear grooves (hereinafter, referred to simply as "grooves") are formed on a surface of a steel sheet, the following processes are carried out in order to ensure the insulation property of a steel sheet: grooves are first formed on the surface of the steel sheet, then a forsterite film is formed on the

surface, and thereafter a film for insulation (hereinafter, referred to "insulating coating" or simply as "coating") is applied to the surface.

During decarburization in manufacturing a grain oriented electrical steel sheet, an internal oxidation layer, which is mainly composed of SiO_2, is formed on a surface of the steel sheet, and then an annealing separator containing MgO is applied on the surface. Subsequently, the forsterite film is formed during final annealing at a high temperature for a long period of time such that the internal oxidation layer is allowed to react with MgO.

[0013] On the other hand, the insulating coating to be applied by top coating on the forsterite film may be obtained by application of a coating liquid and subsequent baking.

When these films are quenched to normal temperature after being formed at high temperature for application, those films having a small contraction rate serve to apply tensile stress to the steel sheet as a function of their differences in thermal expansion coefficient from the steel sheet.

[0014] An increase in the film thickness of the insulating coating leads to an increase in the tension applied to the steel sheet, which is more effective in improving iron loss properties. On the other hand, there has been a tendency that the stacking factor (the proportion of the steel substrate) decreases at the time of assembling an actual transformer and that the transformer iron loss (building factor) decreases relative to the material iron loss. Accordingly, conventional methods only control the film thickness (coating weight per unit area) of the steel sheet as a whole.

[0015] FIG. 1 is a schematic diagram illustrating a coating film thickness a_1 at the floor of a linear groove, a coating film thickness a_2 at portions other than the linear groove, and a linear groove depth a_3. In FIG. 1, reference numeral 1 is the portions other than the linear groove and reference numeral 2 is the linear groove. In addition, the lower ends of a_1 and a_2 as well as the upper and lower ends of a_3 represent the respective interfaces between the insulating coating and the forsterite film.

As a result of investigations to solve the above-described problems, the inventors of the present invention have found that these problems may be addressed by controlling the coating film thickness a_1, coating film thickness a_2 and linear groove depth a_3 illustrated in FIG. 1 in an appropriate manner.

[0016] That is, the coating film thickness a_2 needs to satisfy formula (1) shown below according to the present invention. This is because if the coating film thickness a_2 is below 0.3 μm, the insulating coating becomes so thin that the interlaminar resistance and corrosion resistance deteriorate. Alternatively, if a_2 is above 3.5 μm, the assembled actual transformer has a larger stacking factor.

$$0.3\ \mu m \leq a_2 \leq 3.5\ \mu m \cdots\cdots (1)$$

[0017] Then, as an important point of the present invention, the coating film thicknesses a_1 and a_2 as well as the linear groove depth a_3 need to satisfy formula (2):

$$a_2 + a_3 - a_1 \leq 15\ (\mu m) \cdots\cdots (2)$$

This is because as the value of the left-hand side of the formula (2) becomes smaller, the entire steel sheet involves less surface asperities and assumes a flatter shape, which avoids interruption of handling of the steel sheet and thus improves working efficiency without a problem that the magnetic properties of the steel sheet under strain deteriorate due to local stress. The linear groove depth a_3 represents a depth from the surface of the steel sheet, including the thickness of the forsterite film as mentioned above. It is also preferred that the lower limit of the formula (2) is 3 (μm) and the linear groove depth a_3 is within a range of about 10 μm to 50 μm.

[0018] To reduce surface asperities, i.e., to lower the value of the left-hand side of the formula (2), it is necessary to increase the film thickness a_1 at the floors of the grooves. To this end, for example, it is preferable to reduce the viscosity of the coating liquid and use hard rolls as coater rolls.

[0019] It is also preferred in the present invention that tension generated by the coating film of the insulating coating is 8 MPa or less.

This is because the present invention involves locally increased tension because the groove portions have an increased film thickness of coating. This results in a non-uniform stress distribution in the surface of the steel sheet, and hence the insulating coating film becomes susceptible to exfoliation. To avoid this situation, it is preferable to reduce the coating tension.

Additionally, without any particular limitation, the lower limit of the tension generated by the coating film is to be about 4 MPa in view of improving iron loss properties by means of the tension effect.

[0020] Preferably, the above-described coating film is formed by using, for example, a phosphate-silica-based coating treatment liquid. At this moment, tension may be controlled by increasing the proportion of phosphate, using such phosphate that contributes to a higher thermal expansion coefficient (such as calcium phosphate or strontium phosphate), and so on. Application of this low-tension coating reduces the degree of variation in tension due to a difference in film thickness between the linear groove and the portions other than the linear groove, which makes the coating less prone to exfoliation.

As used herein, the portions other than the linear groove 1 represents a portion excluding the portion of the linear groove 2 as illustrated in FIG. 1.

[0021] Additionally, in the present invention, the tension of the steel sheet generated by the insulating coating is measured and calculated as follows. Firstly, each steel sheet was immersed in an alkaline aqueous solution with tape applied to the measurement surface so as to exfoliate the insulating coating on the non-measurement surface. Then, as illustrated in FIG. 2, L and X are measured as warpage conditions of the steel sheet to determine L_M and X_M.

Then, the following formulas (3) and (4) are used:

$$L = 2R\sin(\theta/2) \cdots\cdots (3), \text{ and}$$

$$X = R\{1 - \cos(\theta/2)\} \cdots\cdots (4).$$

Then, the radius of curvature R is given by formula (5):

$$R = (L^2 + 4X^2)/8X \cdots\cdots (5).$$

In this formula (5), substituting $L = L_M$ and $X = X_M$ yields the radius of curvature R. Further, a tensile stress σ on the surface of the steel substrate may be calculated by substituting the radius of curvature R in formula (6):

$$\sigma = E\cdot\varepsilon = E\cdot(d/2R) \cdots\cdots (6)$$

where E: Young's modulus ($E100 = 1.4 \times 10^5$ MPa);

ε: interface strain of steel substrate (at sheet thickness center, $\varepsilon = 0$); and

d: sheet thickness.

[0022] In the present invention, a slab for a grain oriented electrical steel sheet may have any chemical composition that causes secondary recrystallization having a great magnetic domain refining effect. As secondary recrystallized grains have a smaller deviation angle from Goss orientation, a greater effect of reducing iron loss can be achieved by magnetic domain refinement. Therefore, the deviation angle from Goss orientation is preferably 5.5° or less.

As used herein, the deviation angle from Goss orientation is the square root of (α^2 + β^2), where α represents an α angle (a deviation angle from the (110)[001] ideal orientation around the axis in normal direction (ND) of the orientation of secondary recrystallized grains); and β represents a β angle (a deviation angle from the (110)[001] ideal orientation around the axis in transverse direction (TD) of the orientation of secondary recrystallized grains). The deviation angle from Goss orientation was measured by performing orientation measurement on a sample of 280 mm × 30 mm at pitches of 5 mm. In this case, averages of the absolute values of α angle and β angle were determined and considered as the values of the above-described α and β, while ignoring any abnormal values obtained at the time of measuring grain boundary and so on. Accordingly, the values of α and β each represent an average per area, not an average per crystal grain.

In addition, regarding the compositions and manufacturing methods described below, numerical range limitations and selective elements/steps are merely illustrative of representative methods of manufacturing a grain oriented electrical steel sheet, and hence the present invention is not limited to the disclosed arrangements.

[0023] In the present invention, if an inhibitor, e.g., an AlN-based inhibitor is used, Al and N may be contained in an appropriate amount, respectively, while if a MnS/MnSe-based inhibitor is used, Mn and Se and/or S may be contained in an appropriate amount, respectively. Of course, these inhibitors may also be used in combination. In this case, preferred contents of Al, N, S and Se are: Al: 0.01 mass% to 0.065 mass%; N: 0.005 mass% to 0.012 mass%; S: 0.005 mass% to 0.03 mass%; and Se: 0.005 mass% to 0.03 mass%, respectively.

[0024] Further, the present invention is also applicable to a grain oriented electrical steel sheet having limited contents of Al, N, S and Se without using an inhibitor.

In this case, the contents of Al, N, S and Se are preferably limited to Al: 100 mass ppm or less, N: 50 mass ppm or less, S: 50 mass ppm or less, and Se: 50 mass ppm or less, respectively.

[0025] The basic elements and other optionally added elements of the slab for a grain oriented electrical steel sheet of the present invention will be specifically described below.

C ≤ 0.15 mass%

Carbon (C) is added for improving the texture of a hot-rolled sheet. However, C content in steel exceeding 0.15 mass% makes it more difficult to reduce the C content to 50 mass ppm or less where magnetic aging will not occur during the manufacturing process. Thus, the C content is preferably 0.15 mass% or less. Besides, it is not necessary to set up a particular lower limit to the C content because secondary recrystallization is enabled by a material not containing C.

[0026] **2.0 mass% ≤ Si ≤ 8.0 mass%**

Silicon (Si) is an element that is effective in terms of enhancing electrical resistance of steel and improving iron loss properties thereof. However, Si content in steel below 2.0 mass% cannot provide a sufficient effect of improving iron loss. On the other hand, Si content in steel above 8.0 mass% significantly deteriorates formability and also decreases flux density of the steel. Accordingly, the Si content is preferably in the range of 2.0 mass% to 8.0 mass%.

[0027] **0.005 mass% ≤ Mn ≤ 1.0 mass%**

Manganese (Mn) is an element that is necessary in terms of achieving better hot workability of steel. However, Mn content in steel below 0.005 mass% cannot provide such a good effect of manganese. On the other hand, Mn content in steel above 1.0 mass% deteriorates magnetic flux of a product steel sheet. Accordingly, the Mn content is preferably in the range of 0.005 mass% to 1.0 mass%.

[0028] Further, in addition to the above elements, the slab may also contain the following elements as elements for improving magnetic properties as deemed appropriate:

at least one element selected from Ni: 0.03 mass% to 1.50 mass%, Sn: 0.01 mass% to 1.50 mass%, Sb: 0.005 mass% to 1.50 mass%, Cu: 0.03

mass% to 3.0 mass%, P: 0.03 mass% to 0.50 mass%, Mo: 0.005 mass% to 0.10 mass%, and Cr: 0.03 mass% to 1.50 mass%.

Nickel (Ni) is an element that is useful for improving the microstructure of a hot rolled steel sheet for better magnetic properties thereof. However, Ni content in steel below 0.03 mass% is less effective for improving magnetic properties, while Ni content in steel above 1.5 mass% makes secondary recrystallization of the steel unstable, thereby deteriorating magnetic properties thereof. Thus, Ni content is preferably in the range of 0.03 mass% to 1.5 mass%.

[0029] In addition, tin (Sn), antimony (Sb), copper (Cu), phosphorus (P), molybdenum (Mo) and chromium (Cr) are useful elements in terms of improving magnetic properties of steel. However, each of these elements becomes less effective for improving magnetic properties of the steel when contained in steel in an amount less than the aforementioned lower limit, or alternatively, when contained in steel in an amount exceeding the aforementioned upper limit, inhibits the growth of secondary recrystallized grains of the steel. Thus, each of these elements is preferably contained within the respective ranges thereof specified above.

The balance other than the above-described elements is Fe and incidental impurities that are incorporated during the manufacturing process.

[0030] Then, the slab having the above-described chemical composition is subjected to heating before hot rolling in a conventional manner. However, the slab may also be subjected to hot rolling directly after casting, without being subjected to heating. In the case of a thin slab or thinner cast steel, it may be subjected to hot rolling or directly proceed to the subsequent step, omitting hot rolling.

[0031] Further, the hot rolled sheet is optionally subjected to hot band annealing. At this moment, in order to obtain a highly-developed Goss texture in a product sheet, a hot band annealing temperature is preferably in the range of 800 °C to 1200 °C. If a hot band annealing temperature is lower than 800 °C, there remains a band texture resulting from hot rolling, which makes it difficult to obtain a primary recrystallization texture of uniformly-sized grains and impedes the growth of secondary recrystallization. On the other hand, if a hot band annealing temperature exceeds 1200 °C, the grain size after the hot band annealing coarsens too much, which makes it extremely difficult to obtain a primary recrystallization texture of uniformly-sized grains.

[0032] After the hot band annealing, the sheet is subjected to cold rolling once, or twice or more with intermediate annealing performed therebetween, followed by primary recrystallization annealing and application of an annealing separator to the sheet. The steel sheet may also be subjected to nitridation or the like for the purpose of strengthening any inhibitor, either during the primary recrystallization annealing, or after the primary recrystallization annealing and before the initiation of the secondary recrystallization. After the application of the annealing separator prior to secondary recrystallization annealing, the sheet is subjected to final annealing for purposes of secondary recrystallization and formation of a forsterite film.

[0033] As described below, according to the present invention, the formation of grooves may be performed at any time as long as it is after the final cold rolling, such as before or after the primary recrystallization annealing, before or after the secondary recrystallization annealing, before or after the flattening annealing, and so on. However, if grooves are formed after tension coating, it would require extra steps to remove some portions of the film to make room for grooves to be formed, form the grooves in the manner described below, and re-form those portions of the film. Accordingly, the formation of grooves is preferably performed after the final cold rolling and before forming tension coating.

[0034] After the final annealing, it is effective to subject the sheet to flattening annealing to correct the shape thereof. According to the present invention, tension coating is applied to a surface of the steel sheet before or after the flattening annealing. It is also possible to apply a tension coating treatment liquid prior to the flattening annealing for the purpose of combining flattening annealing with baking of the coating.

In the present invention, when applying tension coating to the steel sheet, it is important to appropriately control, as mentioned earlier, the coating film thickness a_1 (μm) at the floors of the linear grooves, the coating film thickness a_2 (μm) at the portions other than the linear grooves, and furthermore, the groove depth a_3 (μm).

[0035] As used herein, the term "tension coating" indicates insulating coating that applies tension to the steel sheet for the purpose of reducing iron loss. It should be noted that any tension coating is advantageously applicable that contains silica and phosphate as its principal components. In addition to this, other coating is also applicable, such as coating using borate and alumina sol or coating using composite hydroxides.

[0036] Grooves are formed by different methods including conventionally well-known methods of forming grooves, e.g., a local etching method, a scribing method using cutters or the like, a rolling method using rolls with projections, and so on. The most preferable method is a method that involves adhering, by printing or the like, etching resist to a steel sheet after being subjected to the final cold rolling, and then forming grooves on a non-adhesion region of the steel sheet through some process, such as electrolytic etching. This is because in a method where grooves are formed in a mechanical manner, the resulting grooves are blunt-edged due to extremely severe abrasion of the cutters and rolls. Further, there is another problem associated with replacement of the cutters and rolls that leads to lower productivity.

[0037] In the present invention, it is preferable that grooves are formed on a surface of the steel sheet at intervals of about 1.5 mm to 10.0 mm, and at an angle in the range of about ±30° relative to a direction perpendicular to the rolling direction, so that each groove has a width of about 50 μm to 300 μm and a depth of about 10 μm to 50 μm. As used herein, "linear" is intended to encompass solid line as well as dotted line, dashed line, and so on.

[0038] According to the present invention, except the above-mentioned steps and manufacturing conditions, it is possible to use, as appropriate, a conventionally well-known method of manufacturing a grain oriented electrical steel sheet where magnetic domain refining treatment is applied by forming grooves.

Example 1

[0039] Steel slabs were manufactured by continuous casting, each steel slab having a composition containing, in mass%: C: 0.05 %; Si: 3.2 %; Mn: 0.06 %; Se: 0.02 %; Sb: 0.02 %; and the balance being Fe and incidental impurities. Then, each of these steel slabs was heated to 1400 °C, subjected to subsequent hot rolling to be finished to a hot-rolled sheet having a sheet thickness of 2.6 mm, and then subjected to hot band annealing at 1000 °C. Then, each steel sheet was subjected to cold rolling twice, with intermediate annealing performed therebetween at 1000 °C, to be finished to a cold-rolled sheet having a final sheet thickness of 0.30 mm.

[0040] Thereafter, each steel sheet was applied with etching resist by gravure offset printing, and subjected to electrolytic etching and resist stripping in an alkaline solution, whereby linear grooves, each having a width of 150 μm and a depth of 20 μm, were formed at intervals of 3 mm at an angle of 10° relative to a direction perpendicular to the rolling direction.

Then, each steel sheet was subjected to decarburizing annealing at 825 °C, then applied with an annealing separator composed mainly of MgO, and subjected to subsequent final annealing for the purposes of secondary recrystallization and purification under the conditions of 1200 °C and 10 hours.

Then, each steel sheet was applied with a tension coating treatment solution and subjected to flattening annealing at 830 °C during which the tension coating was also baked simultaneously, to thereby provide a product steel sheet. In this case, as shown in Table 1, coating was applied, dried and baked under different film thickness conditions while changing the coater roll hardness, coating liquid viscosity and coating liquid composition. These products were used to manufacture oil-immersed transformers at 1000 kVA, for which iron loss was measured. In addition, each product thus obtained was evaluated for magnetic property, coating t ension, stacking factor, rust ratio, and interlaminar resistance.

The magnetic property, stacking factor and interlaminar resistance of each product were measured according to the method specified in JIS C2550, while the rust ratio was measured by visually determining the rust ratio of the product after holding the product in the atmosphere with a temperature of 50 °C and a dew point of 50 °C for 50 hours. In addition, the coating tension was measured in accordance with the above-mentioned method.

The above-described measurement results are shown in Table 2.

[0041] [Table 1]

Condition No.	Coater Roll Hardness JIS-A*	Coating Liquid Viscosity (cP)	Coating Liquid Composition
1	70	1.2	A
2	70	1.2	A
3	70	1.2	B
4	70	1.2	B
5	70	1.2	B
6	70	1.2	B
7	70	1.2	B
8	70	1.4	B
9	70	1.3	B
10	70	1.2	B
11	70	1.1	B
12	50	1.2	B
13	50	1.1	B
14	70	1.2	C
15	70	1.2	C

*JIS K6301-1975

A: Sr Phosphate: 40 mass pts., Colloidal SiO_2: 30 mass pts., Anhydrous Chromate: 5 mass pts., Silica Flour: 0.5 mass pts.
B: Al Phosphate: 40 mass pts., Colloidal SiO_2: 20 mass pts., Anhydrous Chromate: 5 mass pts., Silica Flour: 0.5 mass pts.
C: Mg Phosphate: 20 mass pts., Colloidal SiO_2: 30 mass pts., Anhydrous Chromate: 5 mass pts., Silica Flour: 0.5 mass pts.

[0042] [Table 2]

Experiment No.	Film Thickness at Floors of Grooves a_1 (μm)	Film Thickness at Portions other than Grooves a_2 (μm)	Groove Depth a_3 (μm)	$a_2 + a_3 - a_1$	Coating Tension (MPa)	Stacking Factor (%)	Rust Ratio (%)	Interlaminar Resistance ($\Omega \cdot cm^2$)	Cut Sheet Iron Loss $W_{17/50}$ (W/kg)	Transformer Iron Loss $W_{17/50}$ (W/kg)	Remarks
1	10.2	0.2	20	10.0	6.4	97.9	20	20	0.97	1.27	Comparative Example
2	9.5	0.3	20	10.8	6.5	97.9	5	≧ 200	0.96	1.14	Inventive Example
3	10.5	1.1	20	10.6	7.6	97.5	≦ 5	≧ 200	0.95	1.12	Inventive Example
4	11.9	2.1	20	10.2	7.1	97.5	≦ 5	≧ 200	0.95	1.10	Inventive Example
5	12.4	2.8	20	10.4	7.2	97.4	≦ 5	≧ 200	0.95	1.11	Inventive Example
6	13.6	3.5	20	9.9	7.5	97.3	≦ 5	≧ 200	0.95	1.13	Inventive Example
7	14.5	4.1	20	9.6	7.4	96.9	15	50	0.95	1.28	Comparative Example
8	2.4	2.2	20	19.8	7.3	97.4	20	20	0.95	1.26	Comparative Example
9	4.2	2.1	20	17.9	7.2	97.5	20	20	0.95	1.25	Comparative Example
10	7.4	2.3	20	14.9	7.3	97.6	5	≧ 200	0.95	1.15	Inventive Example
11	8.6	1.9	20	13.3	7.4	97.6	≦ 5	≧ 200	0.95	1.14	Inventive Example
12	12.1	2.3	20	10.2	7.5	97.6	≦ 5	≧ 200	0.95	1.12	Inventive Example
13	20.0	2.1	20	2.1	7.1	97.5	≦ 5	≧ 200	0.95	1.11	Inventive Example
14	13.3	2.2	20	8.9	10.5	97.4	5	100	0.95	1.20	Inventive Example
15	13.3	3.2	20	9.9	12.6	97.5	10	80	0.95	1.21	Inventive Example

* - Magnetic Property, Stacking Factor, Interlaminar Resistance: measured under JIS C2550.
- Rust Ratio: visually determined by measuring the rust ratio of each product after being held in atmosphere with temperature of 50 °C, dew point of 50 °C for 50 hours.

[0043] As shown in Table 2, all of the inventive grain oriented electrical steel sheets of Experiment Nos. 2 to 6 and 10 to 15 that satisfy the above formulas (1) and (2) exhibited extremely good iron loss properties when assembled as transformers.
However, the grain oriented electrical steel sheets of Experiment Nos. 1 and 7 that do not satisfy the formula (1), as well as the grain oriented electrical steel sheets of Experiment Nos. 8 and 9 that do not satisfy the formula (2) showed inferior iron loss properties when assembled as transformers.

REFERENCE SIGNS LIST

[0044] 1 Portions other than linear groove

2 Linear groove

CLAIMS:

1. A grain oriented electrical steel sheet comprising: linear grooves provided on a surface of the steel sheet; and insulating coating applied to the surface, the insulating coating containing silica and phosphate as its principal components or using borate and alumina sol, wherein a film thickness a_1 (μm) of the insulating coating at floors of the linear grooves, a film thickness a_2 (μm) of the insulating coating on the surface of the steel sheet at portions other than the linear grooves, and a depth a_3 (μm) of the linear grooves being within a range of 20 μm to 50 μm satisfy formulas (1) and (2):

$$0.3\ \mu m \leq a_2 \leq 3.5\ \mu m \ldots\ldots (1), \text{ and}$$

$$a_2 + a_3 - a_1 \leq 15\ \mu m \ldots\ldots (2).$$

2. The grain oriented electrical steel sheet according to claim 1, wherein tension applied to the steel sheet by the insulating coating is 8 MPa or less.

3. The grain oriented electrical steel sheet according to claim 1 or 2, wherein the insulating coating is formed by a coater roll having a coater roll hardness of 50 or more as determined according to JIS K6301-1975 to apply a phosphate-silica-based coating treatment liquid having a coating liquid viscosity of 1.2 cP or less, and wherein 20 mass pts. to 40 mass pts. of phosphate is contained in the phosphate-silica-based coating treatment liquid, the phosphate including at least one selected from calcium phosphate, strontium phosphate, aluminum phosphate and magnesium phosphate.

4. The grain oriented electrical steel sheet according to claim 3, wherein the coater roll hardness is 50 to 70 as determined according to JIS K6301-1975 and the coating liquid viscosity is 1.1 cP to 1.2 cP.

FIG. 1

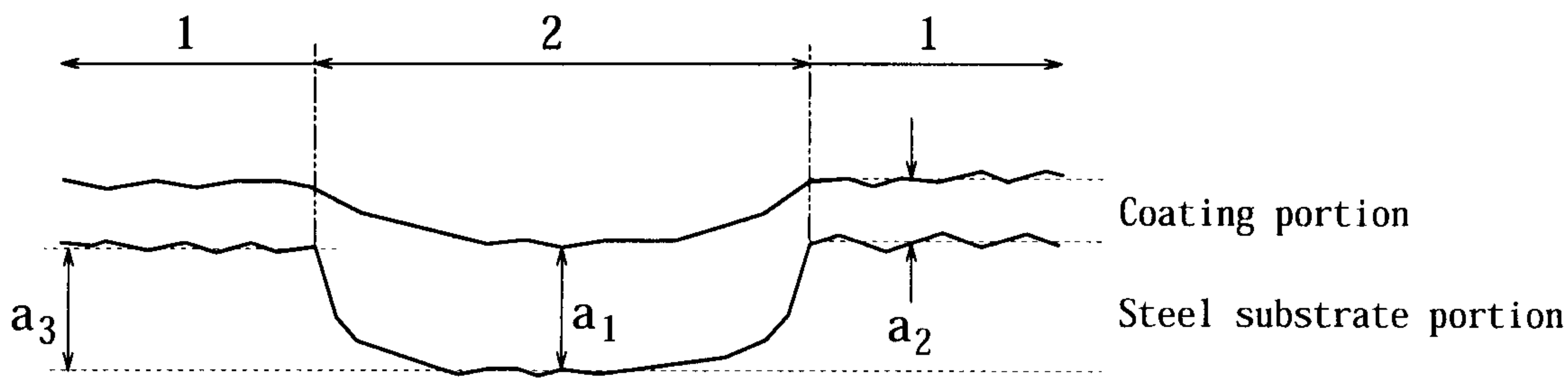
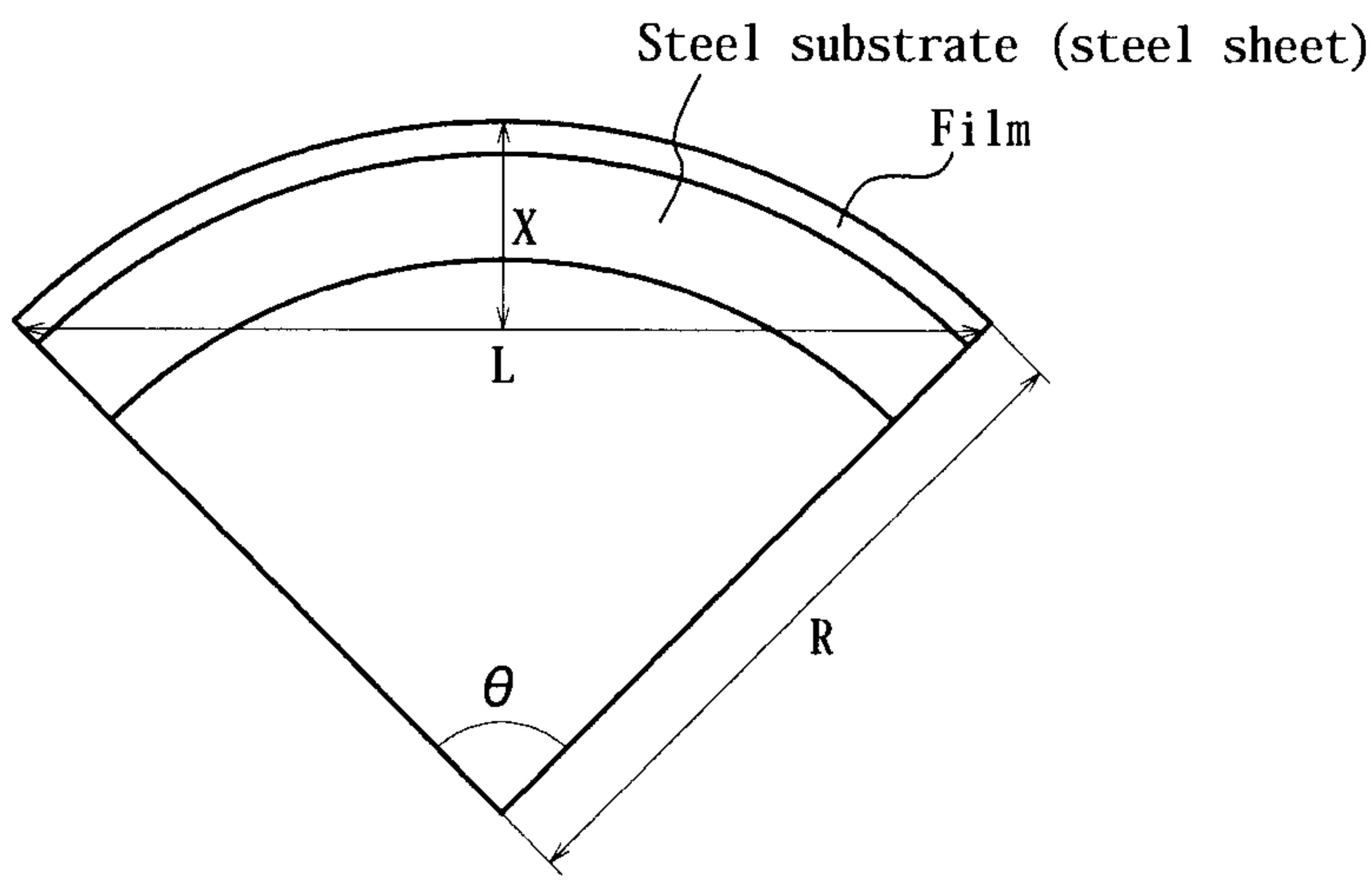
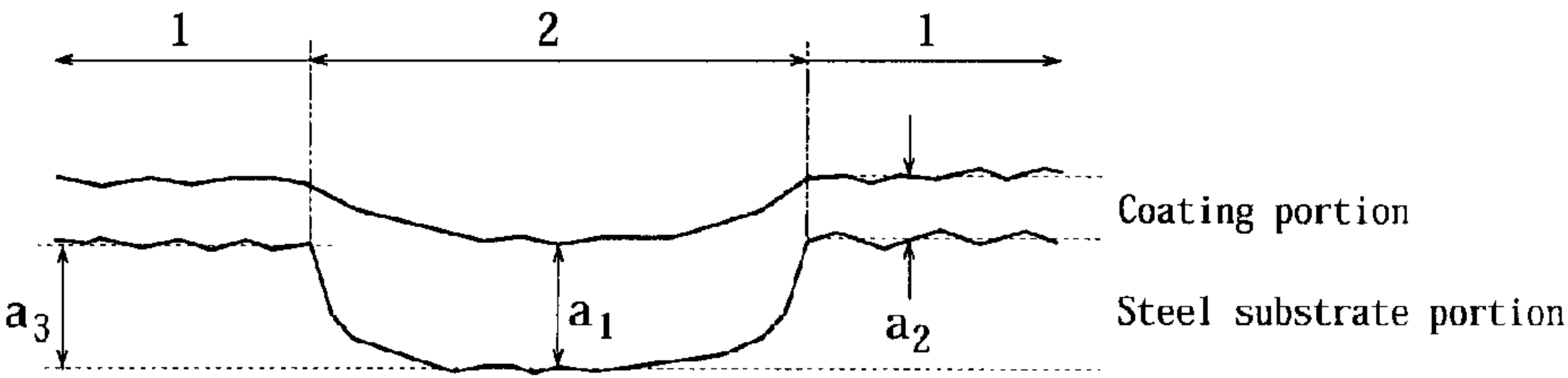

1
2
1
Coating portion
Steel substrate portion
a3
a1
a2

FIG. 2


Steel substrate (steel sheet)
Film
X
L
R
θ


1
2
1
Coating portion
Steel substrate portion
a3
a1
a2