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(54) **IRON-SILICON MATERIAL SUITABLE FOR MEDIUM FREQUENCY APPLICATIONS**

(57) The present invention relates to a grain-oriented electrical steel sheet and to its use in electric transformers, in electric motors or in electric devices, preferably where magnetic flux has to be channeled or contained at medium frequency.

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Description

[0001] The present invention relates to a grain-oriented steel strip and to the use in electric transformers, in electric motors or in electric device, preferably where magnetic flux has to be channeled or contained.

[0002] Grain Oriented Electrical Steel (GOES) is a soft magnetic material preferably containing high silicon content providing high permeability to the magnetic field, easily magnetizing and demagnetizing. For example, GOES is the steel sheet used for manufacturing electric transformer cores with a minimum specific loss and a high achievable working induction, for example up to 1.85 T for a wide range of thicknesses like 0.23 to 0.35 mm.

[0003] According to Wuppermann et al., Electrical Steel, Stahl-Informationen-Zentrum, Düsseldorf, Ed. 2005, pages 5 and 6, the iron crystal axis is an axis of easy magnetization of the body-centred cubic iron crystal. This axis, oriented closely to the rolling direction, gives excellent magnetic properties to the GOES in this direction of the steel strip. These are the orientation grains called "Goss grains" which provide a strongly anisotropic behavior and reduce the power loss. The Goss texture makes it very difficult to orient the magnetic moments out of the plane of the sheet and in the direction perpendicular to the direction of rolling.

[0004] According to N. Chen et al., Acta Materialia 51 (2003), pages 1755 to 1765 and K. Günther et al., Journal of Magnetism and Magnetic Materials 320 (2008), 2411 to 2422 the manufacturing of GOES is in general performed according to different technologies across the world. To achieve the highly oriented Goss texture, the metallurgical process is highly complex and may consist in the following manufacturing steps: steel melting via a blast furnace and basic oxygen converter or an electric arc furnace, steel metallurgy refining via a vacuum degassing vessel, casting to slab via continuous casting or thin slab or thin strip, slab reheating or direct slab rolling on a hot rolling mill to get a hot rolled coil, coil surface preparation, hot strip annealing and pickling, cold rolling in one or two stages down to a final thickness, decarburization annealing and optionally a surface nitridation, providing a MgO coating of the strip surface, high temperature box annealing where the cold rolled decarburized coils are stacked, heat flattening and insulation coating and optionally a magnetic domain refinement.

[0005] According to the so called "High Heating" technology, the casting and the high temperature slab reheating conditions to about 1400 °C make it possible to have a well-developed inhibition system comprising particles of AlN, MnS and other compounds in the iron matrix, even before the cold process, which promotes abnormal grain growth. However, in low heating technology, with the low temperature in the slab heating process, the inhibition system is absent or weak, therefore low heating technology requires a nitridation treatment of the strip surface after the decarburization annealing stage to build a required inhibition system.

[0006] Therefore, the primary recrystallization (PRX), occurring during this decarburization anneal will control and prepare the secondary grain growth. However, due to the large number of metallurgical phenomena competing during this stage like carbon removal, formation of the oxide layer, primary grain growth, this process is unstable but fundamental for obtaining an efficient nitridation, a high-quality glass film, and many Goss germs in the matrix. Indeed it is known that a dense oxide layer, produced during the beginning of annealing, can be favorable to a good surface aspect, but may become a barrier to decarburization and nitration.

[0007] According to the prior art, the next metallurgical step is to hold the steel strip in a high temperature annealing cycle either in a batch annealing furnace or a rotary batch annealing furnace, where secondary recrystallization (SRX) occurs and where the main objectives are to develop abnormal grain growth to obtain a Goss texture with the inhibitors previously formed, to eliminate all elements as sulphur or nitrogen when SRX is finished and to form a coating layer named glass film containing Mg_2SiO_4 to ensure electric insulation and surface tension.

[0008] As iron-silicon alloy is an electrical conductive media, induced currents develop over the sheet thickness under the effect of a magnetic flux variation over time; they are called the Eddy currents. The reduction of the thickness as well as the increase of the electrical resistivity by addition of alloy elements as for example silicon, are the main two factors able to reduce significantly the losses induced by the eddy currents. Indeed a 10% thickness decrease results in a reduction by ca. 20% in Eddy current losses at the same 50 Hz induction level. Whereas a 0.5% increase Silicon content results in a reduction by ca. 12% in Eddy current losses at the same 50 Hz induction level.

[0009] Eddy current losses represent ca 10% to 25% of the total specific losses at 50Hz, whereas they may represent far more than 30% at medium frequency (e.g. @ 1.5T 1kHz 50%) depending on the material thickness, the frequency and induction levels. Furthermore the motions of magnetic domains along the hysteresis loop are hindered by resistance to change in magnetization-demagnetization. It is due to pinning sites like any non-metallic inclusions or interface roughness between glass film and iron-silicon steel matrix. Such interface reduces the part of magnetic core material which is magnetically active under the effect of a magnetizing field. As a consequence this increases the magnetic polarisation in the magnetically active cross section of the material with regards to the aimed level and thus the specific total losses. When medium frequency magnetization is involved, and if the skin depth is reduced due to strong contribution of the eddy currents, this non magnetically active part reduces even further the ability to magnetise the material. Therefore a thin iron-silicon alloy gauge having no interface roughness or a smooth interface would be a great step ahead in lowering specific total losses.

[0010] However, the issues in the conventional GOES manufacturing are that thinner thickness and more silicon content make the material more brittle, more difficult to cold roll and more difficult to reach a stable secondary recrystallization SRX particularly for material having a final thickness gauge lower than 0.22 mm.

[0011] The object of the present invention is therefore to provide grain-oriented electrical steel sheets having a particular low thickness and high silicon content. At the same time, the grain-oriented electrical steel shall have a less rough interface between core layer and one outer layer and the largest part of really active magnetic core material under magnetization field at 50 Hz and more preferably at medium frequency of at least 400 Hz. A grain-oriented electrical steel sheet shall be provided having lower specific total losses GOES compared to the known products.

[0012] These objects can be solved by grain-oriented electrical steel comprising a core layer containing at least Fe and Si having two outer surfaces, at least one interface layer present on each outer surface of the core and at least one outer layer present above each interface layer, wherein the thickness of the core layer is at least 25 times higher than the sum of the thicknesses of the outer layers.

[0013] The grain-oriented electrical steel according to the present invention has preferably the following composition, remainder being Fe and unavoidable impurities, all numbers are in % by weight. Unless explicitly stated otherwise, in the present text and the claims, the contents of particular alloy elements are each reported in % by weight.

[0014] According to the present invention, the amount of Mn present in the grain-oriented electrical steel is preferably 0.001 to 3.0% Mn, particularly preferably 0.01 to 0.3% Mn.

[0015] According to the present invention, the amount of Cu present in the grain-oriented electrical steel is preferably 0.001 to 3.0% Cu, particularly preferably 0.01 to 0.3% Cu.

[0016] According to the present invention, the amount of Al present in the grain-oriented electrical steel is preferably 0.001 to 2.0% Al, particularly preferably 0.01 to 1.0% Al.

[0017] According to the present invention, the amount of Cr and Sn and Ti and B in sum present the grain-oriented electrical steel is less than 3, particularly preferably less than 1.

[0018] Particularly preferably, the grain-oriented electrical steel comprises, beside Fe and unavoidable impurities (all amounts are % by weight) 2 to 5% Si, 0.01 to 0.3% Mn, 0.01 to 0.3% Cu, 0.01 to 1.0% Al.

[0019] Preferably, the core layer of the grain oriented electrical steel according to the present invention comprises Si, preferably in an amount of 1 to 5% by weight, more preferably 2 to 4% by weight, particularly preferably 2.5 to 3.5% by weight.

[0020] Preferably, according to a preferred embodiment of the present invention the core layer comprises sulfur, preferably in an amount of less than 7 ppm.

[0021] The present invention preferably relates to the grain-oriented electrical steel sheet according to the present invention, wherein the content of magnesium in the interface layers is lower than 1 % by weight.

[0022] According to a preferred embodiment of the present invention, the grain-oriented electrical steel sheet according to the present invention comprises a soft magnetic material.

[0023] According to the present invention the grain-oriented electrical steel comprising a core layer containing at least Fe and Si having two outer surfaces, at least one interface layer present on each outer surface of the core and at least one outer layer present above each interface layer. According to a preferred embodiment of the present invention, further layers may be present, for example coating layers as described in DE102008008781A, US3948786A and JPS5328375B2.

[0024] According to the present invention, the thickness of the core layer is at least 25 times higher than the sum of the thicknesses of the outer layers. Therefore, formula (2) applies to the grain-oriented electrical steel according to the present invention:

$$t_{\text{core}} / \sum t_{\text{ol}} \geq 25 \quad (2),$$

wherein t_{core} and t_{ol} have the following meanings:

t_{core} thickness of the core layer in μm , and

t_{ol} thickness of one outer layer in μm .

[0025] The core layer of the grain-oriented steel according to the present invention containing at least Fe and Si has a thickness of 50 to 220 μm , preferably 100 to 220 μm .

[0026] The grain-oriented electrical steel sheet according to the present invention comprises two outer surfaces. Preferably these outer surfaces are present on the top of respectively each interface layers up and bottom side of the core.

[0027] The grain-oriented steel according to the present invention comprises at least one interface layer present above each outer surface of the core. According to a preferred embodiment of the present invention, the grain-oriented steel

according to the present invention comprises a first interface layer present beneath the top outer surface and a second interface layer beneath the bottom outer surface.

[0028] The thickness of the at least one interface layer is preferably 1 to 500 nm, more preferably 10 to 100 nm.

[0029] The interface layer according to the present embodiment mainly differentiates from the core layer by its magnetic characteristics like magnetic permeability.

[0030] The grain-oriented electrical steel according to the present invention further comprises at least one, preferably one, outer layer present on each interface layer. The sum of the thicknesses of the outer layers is preferably less than 5 μm , more preferably 0.1 to 2 μm .

[0031] According to a preferred embodiment of the present invention, no further coating or layer is present on one or both outer layers of the grain-oriented steel. According to another preferred embodiment of the present invention a coating or layer is present on one or both outer layers of the grain-oriented steel. This coating may be selected from DE102008008781A, US3948786A and JPS5328375B2 or combinations thereof. The present invention therefore preferably relates to the grain-oriented electrical steel sheet according to the present invention, wherein at least one further coating is present on at least one outer layer.

[0032] According to a preferred embodiment, the present invention relates to the grain-oriented electrical steel sheet according to the present invention, wherein formula (1) applies:

$$t_{il} < (t_{ol} / t_{core}) * (\rho / (\mu_0 * \mu_{dif} * \pi * f))^{1/2} * 10^{-9} \quad (1),$$

wherein t_{il} , t_{ol} , t_{core} , ρ , μ_0 , μ_{dif} and f have the following meanings:

t_{il} thickness of the interface layer in nm,
 t_{ol} thickness of the outer layer in μm ,
 t_{core} thickness of the core layer in μm ,
 ρ electrical resistivity of the core layer in $\Omega \cdot \text{m}$,
 μ_0 magnetic constant $4 * \pi * 10^{-7}$,
 μ_{dif} differential permeability of the core layer,
 f measurement frequency of 1000 Hz

[0033] If the inequation according to formula (1) is fulfilled, the grain-oriented electrical steel according to the present invention shows particularly improved magnetic loss behaviour at medium frequencies.

[0034] The process of preparation of the grain-oriented electrical steel according to the present invention preferably comprises a step of pickling. This step has an effect onto the amount of sulphur present in the electrical steel.

[0035] Preferably, the present invention relates to the grain-oriented electrical steel sheet according to the present invention, wherein the amount of sulphur in the core after 5% to 11% of pickling by mass is less than 0.0007% related to the total amount of Fe and Si.

[0036] The grain-oriented electrical steel according to the present invention can be prepared by the following process at least comprising the following steps:

(A) providing a hot rolled steel strip based on a steel comprising, beside Fe and unavoidable impurities (all amounts are % by weight):

1 to 8 Si,
less than 0.010 S + Se, and
less than 3 C + Mn + Cu + Cr + Sn + Al + N + Ti + B,

(B) at least one cold rolling step of the hot strip of step (A) to obtain a cold strip,

(C) a primary recrystallization annealing of the cold strip obtained in step (B) optionally including a nitriding treatment,

(D) a secondary recrystallization annealing treatment by heating to a temperature OTAG2 with a heating rate of at least 40 K/s to obtain the grain-oriented electrical steel sheet,

wherein the temperature OTAG2 is set according to the following equation (I):

$$1420\text{K} - \text{DP} \times \text{PGS} \times \rho_{\text{HAGB}} / \log((\text{S} + \Delta\text{N}) \times \text{HSRX} / 20) < \text{OTAG2} < 1420\text{K} \quad (I),$$

wherein OTAG2, HRSRX, PGS, ΔN , DP, S and $\rho HAGB$ have the following meanings:

OTAG2	Optimum Temperature of Abnormal Grain Growth in K,
HRSRX	Heating Rate to Secondary Recrystallization Treatment in K/s,
PGS	Average Primary Grain Size in μm ,
ΔN	Nitriding Degree in ppm, calculated by Nitrogen Degree in ppm before SRX annealing (D) minus Nitrogen Degree in ppm before primary recrystallization annealing (C)
DP	Atmosphere Dew Point during heating rate in K,
S	sum of Sulphur content and Selenium content in ppm,
$\rho HAGB$	High Angle ($> 15^\circ$) primary Grain Boundary average density in μm^{-1} .

[0037] Step (A) of the process comprises providing a hot rolled steel strip based on a steel as mentioned above.

[0038] In general, the step of providing a hot rolled steel strip based on a steel as defined above is known to the skilled artisan and is, for example, described in DE 19745455 C1 and EP 1 752 549 B1.

[0039] In particular, step (A) of the process comprises a steelmaking to obtain a steel having the above mentioned composition. The step of steelmaking is also known to the skilled artisan and is described in the documents mentioned above. Afterwards the steel is preferably processed in a hot melt casting to obtain slabs of steel. More preferably, the slabs obtained accordingly are hot rolled into hot band strips which preferably undergo a hot strip annealing and pickling. The hot band strips that are obtained in step (A) of the process preferably have a thickness of 0.5 to 3.5 mm, more preferably 1.0 to 3.0 mm.

[0040] After step (A) hot band strips having the above mentioned composition and thickness are obtained. These hot band strips are preferably directly introduced into step (B) of the process.

[0041] Step (B) of the process comprises at least one cold rolling step of the hot strip of step (A) to obtain a cold strip. Cold rolling which is done in step (B) of the process is in general known to the skilled artisan and is, for example, described in WO 2007/014868 and WO 99/19521.

[0042] According to the present invention, in step (B) one, two or more cold rolling steps are conducted. Preferably, in step (B) of the process at least two cold rolling steps are conducted.

[0043] Further preferred, in step (B) of the process, a first cold rolling step is conducted, in which the hot band strip that is obtained from step (A) of the is cold rolled down to a thickness of for example 0.05 to 2.00 mm, preferably 0.10 to 0.55 mm. Apparatuses in which cold rolling is conducted are in general known to the skilled artisan, for example mentioned in WO 2007/014868 and WO 99/19521.

[0044] Further preferred, the cold rolled strip that is obtained in this first cold rolling step is decarburized after the first cold rolling step. This can be done according to methods known to the skilled artisan, for example in an Intermediate Annealing stage at a temperature of 700 to 950 °C, preferably 800 to 900 °C. The Dew Point of the atmosphere which is present in this annealing stage can be 10 to 80 °C. Apparatuses in which this annealing is conducted are in general known to the skilled artisan, for example described in WO 2007/014868 and WO 99/19521. Annealing is preferably conducted to obtain a steel sheet or strip having a low carbon content, for example less than 30 ppm.

[0045] Preferably a pickling step is conducted after the annealing stage and the optional nitriding stage, which can be made according to methods known to the skilled artisan. For example, pickling can be conducted by using aqueous solutions of acids like phosphoric acid, sulfuric acid and/or hydrochloric acid. The present invention therefore preferably relates to the process according to the present invention, wherein a pickling step is conducted after step (C) and before step (D).

[0046] According to a preferred embodiment of the process, the steel sheet that is obtained after the first cold rolling step in step (B) of the process has a carbon content of less than 30 ppm before the final, preferably the second, cold rolling step in step (B).

[0047] Further preferred, a second cold rolling step is conducted, in which the cold rolled strip obtained from the first cold rolling step, preferably after annealing and pickling, is further rolled down to a thickness of 0.05 to 0.35 mm, more preferably 0.10 to 0.22 mm.

[0048] Step (C) of the process comprises an annealing of the cold strip obtained in step (B) resulting in primary recrystallization and optionally a nitriding treatment.

[0049] This annealing is preferably conducted at a temperature of for example 400 to 950 °C, more preferably 600 to 900 °C. The optional nitriding treatment is further preferably conducted in an atmosphere comprising N_2 or N-comprising compounds, for example NH_3 . Annealing and nitriding can be conducted separately in two successive steps, wherein annealing is conducted first. According to a second embodiment, annealing and nitriding can be conducted in one single step.

[0050] The annealing step (C) is preferably conducted to obtain a cold rolled strip having a nitriding degree, calculated by Nitrogen Degree in ppm before SRX annealing (D) minus Nitrogen Degree in ppm before primary recrystallization annealing (C), of 0 to 300 ppm, more preferably 20 to 250 ppm. Furthermore, the strip that is obtained after step (C) of

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the process has an average grain size of preferably 5 to 25 μm , more preferably 5 to 20 μm . In addition, the strip that is obtained after step (C) of the process has preferably an average High Angle primary Grain Boundary density of 0.005 to 0.1 μm^{-1} , more preferably of 0.01 to 0.09 μm^{-1} .

[0051] Further details of step (C) of the process are known to the skilled artisan.

[0052] Step (D) of the process comprises a secondary recrystallization annealing treatment by heating to a temperature OTAG2 with a heating rate of at least 40 K/s, preferably at least 50 K/s, to obtain the grain-oriented electrical steel sheet. Temperature OTAG2 is set according to the following equation (I):

$$1420\text{K} - \text{DP} \times \text{PGS} \times \rho\text{HAGB} / \log((\text{S} + \Delta\text{N}) \times \text{HRSRX} / 20) < \text{OTAG2} < 1420\text{K} \quad (\text{I}),$$

wherein OTAG2, HRSRX, PGS, ΔN , DP, S and ρHAGB have the following meanings:

OTAG2	Optimum Temperature of Abnormal Grain Growth in K,
HRSRX	Heating Rate to Secondary Recrystallization Treatment in K/s,
PGS	Average Primary Grain Size in μm ,
ΔN	Nitriding Degree in ppm, calculated by Nitrogen Degree in ppm before SRX annealing (D) minus Nitrogen Degree in ppm before primary recrystallization annealing (C)
DP	Atmosphere Dew Point during heating rate in K,
S	sum of Sulphur content and Selenium content in ppm,
ρHAGB	High Angle ($> 15^\circ$) primary Grain Boundary average density in μm^{-1} .

[0053] If the secondary recrystallization annealing treatment in step (D) of the process is conducted by heating to a temperature OTAG2 with a heating rate of at least 40 K/s a grain oriented steel sheet is obtained having a high peak magnetic polarization for the peak magnetic field strength of 800 A/m and a low specific total loss.

[0054] According to the present invention, the upper limit of OTAG2 is preferably 1420 K, particularly preferably 1415 K.

[0055] The Heating Rate to Secondary Recrystallization Treatment is preferably 20 to 800 K/s, more preferably 50 to 750 K/s. The Heating Rate to Secondary Recrystallization Treatment is acquired with methods known to the skilled artisan, for example as described in EP 2 486 157.

[0056] The Average Primary Grain Size is preferably 5 to 25 μm , more preferably 5 to 20 μm . The Average Primary Grain Size is acquired with methods known to the skilled artisan, for example Grain size measured by EBSD analysis (OIM Analysis software).

[0057] The Nitriding Degree, calculated by Nitrogen Degree in ppm before SRX annealing (D) minus Nitrogen Degree in ppm before primary recrystallization annealing (C), is preferably 0 to 300 ppm, more preferably 20 to 250 ppm. The Nitriding Degree is acquired with methods known to the skilled artisan, for example Nitrogen Elemental Analyzer of A36 LECO Corporation.

[0058] The Atmosphere Dew Point during heating rate is preferably 223 to 273 K, more preferably 243 to 270 K. The Atmosphere Dew Point is acquired with methods known to the skilled artisan, for example as described in WO 2007/014868 and WO 99/19521.

[0059] The sum of Sulphur content and Selenium content is preferably 1 to 100 ppm, more preferably 10 to 100 ppm. The sum of Sulphur content and Selenium is acquired with methods known to the skilled artisan, for example as described in WO 2007/014868 and WO 99/19521.

[0060] The High Angle ($> 15^\circ$) primary Grain Boundary average density is preferably 0.005 to 0.1 μm^{-1} , more preferably 0.01 to 0.09 μm^{-1} . The High Angle ($> 15^\circ$) primary Grain Boundary average density is acquired with methods known to the skilled artisan, for example the Grain Boundary density is measured as primary grain boundary length per unit area and is provided directly by EBSD analysis (OIM Analysis software). The ρHAGB is the average of the values corresponding to misorientations higher than 15° ($>15^\circ$).

[0061] One particularly essential feature of the present invention is that step (D) of the process is conducted at the above defined temperature OTAG2, wherein OTAG2 is calculated according formula (I).

[0062] The heating in step (D) of the process is conducted at a heating rate of at least 40 K/s. Preferably, the heating in step (D) of the process is conducted at a heating rate of at least 70 K/s, more preferably at least 100 K/s. This rapid heating can be conducted by any method known to the skilled artisan, for example by induction, by resistive heating, by conductive heating.

[0063] The heating in step (D) of the process is preferably conducted at a dew point of 223 to 273 K, particularly preferably 243 to 270 K.

[0064] In step (D) of the process the Secondary Recrystallization is performed so that a grain-oriented steel sheet according to the present invention is obtained.

[0065] In general, after step (D) of the process, a grain-oriented steel sheet having the advantageous properties as outlined above is obtained.

[0066] According to a preferred embodiment of the process, the cold strip that is introduced into step (D) does not comprise any annealing separators, preferably no MgO based coating.

[0067] Preferably, further process steps are conducted after step (D).

[0068] Preferably, the strip or sheet that is obtained after step (D) of the process is rapidly heated to a temperature of 1423 K or above. This heating step is preferably conducted under a protective gas atmosphere, for example comprising H₂. Particularly preferably, the soaking at a temperature of 1423 K or above is conducted in an atmosphere comprising 5 to 95 vol.-% H₂, balance nitrogen or any inert gas or mix gas with a DP of at least 10 °C. The soaking is preferably conducted to remove disturbing atoms, in particular to remove N and S. In a more preferable practice the soaking temperature above 1523K is chosen.

[0069] According to a preferred embodiment of the process, the strip or sheet is heated in step (D) to a temperature of 1423 K or above. More preferably, the strip or sheet is heated in step (D) to a temperature of 1523 K or above.

[0070] Further preferred, the steel strip is cooled down afterwards, in particular by methods known to the skilled artisan, for example by natural cooling down to room temperature.

[0071] In addition, according to a preferred embodiment of the process, the steel strip is cleaned, and optionally pickled. Methods with which the steel strip is pickled are known to the skilled artisan. Preferably, the steel strip is treated with an aqueous acidic solution. Suitable acids are for example phosphoric acid, sulfuric acid and/or hydrochloric acid. According to the present invention, the grain oriented electrical steel sheets can be prepared in any format, like steel strips that are provided as coils, or cut steel pieces that are provided by cutting these steel pieces from the steel strips. Methods to provide coils or cut steel pieces are known to the skilled artisan.

[0072] The grain-oriented electrical steel according to the present invention shows improved magnetic loss at medium frequencies compared to grain-oriented electrical steels according to the prior art. Therefore, the grain-oriented steel according to the present invention can advantageously be used in electric transformers, in electric motors or in electric devices, preferably where magnetic flux has to be channeled or contained.

[0073] The present invention therefore also relates to the use of the grain-oriented steel sheet according to the present invention in electric transformers, in electric motors or in electric devices, preferably where magnetic flux has to be channeled or contained at medium frequency.

Table 1:

No.	Silicon content in core layer [% by weight]	Sulfur content in core layer [ppm]	t _{core} [μm]	t _{il} [nm]	t _{ol} [μm]	t _{il} + t _{ol} [μm]	t _{core} / (Σ t _{ol})	t _{ol} /t _{core}	$(\rho/(\mu_0 \cdot \mu_{dif} \cdot \pi \cdot f))^{1/2} \cdot 10^{-9}$ [m]	$(t_{ol}/t_{core})^{(\rho/(\mu_0 \cdot \mu_{dif} \cdot \pi \cdot f))^{1/2} \cdot 10^{-9}}$ [m]	J800* [T]
1	2,90	5	50	50	0,3	0,3	83,3	0,005	11,0 *10 ⁻⁶	0,055*10 ⁻⁶	1,90
2	3,25	10	50	50	0,3	0,3	83,3	0,005	11,0*10 ⁻⁶	0,055*10 ⁻⁶	1,91
3	3,25	6	50	90	0,5	0,8	50,0	0,010	11,0 *10 ⁻⁶	0,110*10 ⁻⁶	1,87
4	2,90	5	100	12	0,3	0,3	166,7	0,003	10,5*10 ⁻⁶	0,026*10 ⁻⁶	1,92
5	3,25	5	100	20	0,3	0,3	166,7	0,003	10,5*10 ⁻⁶	0,026*10 ⁻⁶	1,91
6	2,90	5	150	15	0,3	0,3	250,0	0,002	12,8*10 ⁻⁶	0,021*10 ⁻⁶	1,90
V7	2,90	8	150	500	1,0	1,5	75,0	0,007	12,8*10 ⁻⁶	0,085*10 ⁻⁶	1,40
V8	3,10	7	150	250	0,5	0,8	150,0	0,003	12,8*10 ⁻⁶	0,043*10 ⁻⁶	1,56
9	3,25	4	150	12	0,3	0,3	250,0	0,002	12,8*10 ⁻⁶	0,021*10 ⁻⁶	1,90
V10	3,25	5	150	100	0,5	0,8	150,0	0,003	12,8*10 ⁻⁶	0,043*10 ⁻⁶	1,65
11	2,90	3	200	5	0,3	0,3	333,3	0,001	13,5*10 ⁻⁶	0,017*10 ⁻⁶	1,93
V12	2,90	11	200	500	1,0	1,5	100,0	0,005	13,5*10 ⁻⁶	0,068*10 ⁻⁶	1,42
V13	3,10	22	200	250	0,5	0,8	200,0	0,003	13,5 *10 ⁻⁶	0,034*10 ⁻⁶	1,50
V14	3,25	15	200	500	1,0	1,5	100,0	0,005	13,5*10 ⁻⁶	0,068*10 ⁻⁶	1,45
15	2,90	5	220	15	0,3	0,3	366,7	0,001	14,2*10 ⁻⁶	0,016*10 ⁻⁶	1,88
V16	2,90	9	220	500	1,0	1,5	110,0	0,005	14,2 *10 ⁻⁶	0,065*10 ⁻⁶	1,58
V17	2,90	5	220	250	0,5	0,8	220,0	0,002	14,2 *10 ⁻⁶	0,032*10 ⁻⁶	1,65
18	3,25	5	220	10	0,3	0,3	366,7	0,001	14,2*10 ⁻⁶	0,016*10 ⁻⁶	1,89
V19	3,25	11	220	500	1,0	1,5	110,0	0,005	14,2*10 ⁻⁶	0,065*10 ⁻⁶	1,50
* Peak magnetic polarization for the magnetic field strength of 800 A/m at 1 kHz											

[0074] The grain-oriented electrical steel sheet according to the present invention shows improved magnetic loss at medium frequencies and is therefore suitable for the use in electric transformers, in electric motors or in electric devices, preferably where magnetic flux has to be channeled or contained at medium frequency.

Claims

1. Grain-oriented electrical steel comprising a core layer containing at least Fe and Si having two outer surfaces, at least one interface layer present on each outer surface of the core and at least one outer layer present on each interface layer, wherein the thickness of the core layer is at least 25 times higher than the sum of the thicknesses of the outer layers.
2. Grain-oriented electrical steel sheet according to claim 1, wherein the content of magnesium in the interface layers is lower than 1 % by weight.
3. Grain-oriented electrical steel according to claim 1 or 2, wherein the sum of the thicknesses of the outer layers is less than 2 μm .
4. Grain oriented electrical steel sheet according to any one of claims 1 to 3, wherein the core layer contains 1 to 5% by weight Si.
5. Grain oriented electrical steel sheet according to any one of claims 1 to 4, wherein the core layer comprises a soft magnetic material.
6. Grain oriented electrical steel sheet according to any one of claims 1 to 5, wherein at least one further coating is present on at least one outer layer.
7. Grain oriented electrical steel sheet according to any one of claims 1 to 6, wherein formula (1) applies:

$$t_{il} < (t_{ol} / t_{core}) * (\rho / \mu_0 * \mu_{dif} * \pi * f)^{1/2} * 10^{-9} \quad (1),$$

wherein t_{il} , t_{ol} , t_{core} , ρ , μ_0 , μ_{dif} and f have the following meanings:

- t_{il} thickness of the interface layer in nm,
 - t_{ol} thickness of the outer layer in μm ,
 - t_{core} thickness of the core layer in μm ,
 - ρ electrical resistivity of the core layer in $\Omega * \text{m}$,
 - μ_0 magnetic constant $4 * \pi * 10^{-7}$,
 - μ_{dif} differential permeability of the core layer,
 - f frequency of the current in Hz.
8. Grain-oriented electrical steel sheet according to any one of claims 1 to 7, wherein the amount of sulphur in the core after 5% to 11% of pickling by mass is less than 0.0007% related to the total amount of Fe and Si.
 9. The use of the grain oriented steel sheet according to any one of claims 1 to 8 in electric transformers, in electric motors or in electric devices, preferably where magnetic flux has to be channeled or contained.



EUROPEAN SEARCH REPORT

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