



US 20130174940A1

(19) **United States**(12) **Patent Application Publication**
Cicale et al.(10) **Pub. No.: US 2013/0174940 A1**(43) **Pub. Date: Jul. 11, 2013**(54) **GRAIN ORIENTED STEEL STRIP WITH
HIGH MAGNETIC CHARACTERISTICS, AND
MANUFACTURING PROCESS OF THE SAME**(76) Inventors: **Stefano Cicale**, San Gemini (IT);
Giuseppe Abbruzzese, Montecastrilli
(IT); **Marco Antonio Da Cunha**,
Timoteo MG (BR); **Helcio De Araujo**
Quintao, Timoteo (BR); **Ronaldo**
Claret Ribeiro Silva, Timoteo (BR);
Angelo Jose De Faria Fonseca, Recanto
(BR)(21) Appl. No.: **13/635,743**(22) PCT Filed: **Mar. 18, 2011**(86) PCT No.: **PCT/IB2011/000582**

§ 371 (c)(1),

(2), (4) Date: **Mar. 8, 2013**(30) **Foreign Application Priority Data**

Mar. 19, 2010 (IB) PCT/IB2010/000591

Publication Classification(51) **Int. Cl.**

C21D 8/02	(2006.01)
C22C 38/02	(2006.01)
C22C 38/04	(2006.01)
C22C 38/00	(2006.01)
C22C 38/16	(2006.01)
C22C 38/06	(2006.01)

(52) **U.S. Cl.**

CPC **C21D 8/0284** (2013.01); **C21D 8/0226**
(2013.01); **C22C 38/16** (2013.01); **C22C 38/06**
(2013.01); **C22C 38/04** (2013.01); **C22C**
38/008 (2013.01); **C22C 38/002** (2013.01);
C22C 38/001 (2013.01); **C22C 38/02** (2013.01)
USPC **148/504**; 148/320; 148/332; 148/516

(57)

ABSTRACT

A method for the production of hot-rolled steel strip comprising the following steps: providing a steel slab comprising, in weight percentages: Si: 2.5 to 3.5%, C: 0.05 to 0.1%, Mn: 0.05 to 0.1%, Als: 0.015 to 0.026%, N: 0.0050 to 0.0100%, and further comprising S and/or Se so that S+ (32/79) Se is in an amount of 0.018 to 0.030%, and optionally comprising one or more elements chosen among Sb in an amount of 0.015 to 0.035%, Cu in an amount of 0.08% to 0.25%, Sn in an amount of 0.06% to 0.15%, P in an amount of 0.005% to 0.015%, the balance being iron and unavoidable impurities, reheating said slab to a temperature between 1300° C. and 1430° C., roughing hot-rolling said slab to produce a blank having a thickness below 50 mm, finishing hot-rolling of said blank to produce a hot rolled strip in three rolling passes or more, the temperature of said blank during the first pass being above 1150° C. and at least one rolling pass being performed with a reduction of 40% or more and being immediately followed by a holding of more than 20 sec, the average interpass holding temperature T_{av} being settled between 1000 and 1200° C., the total finishing hot rolling time t being controlled so that the value of T_{av} for any portion of said strip further respects the under mentioned equation: $T_{av} > T_1 + \alpha_1(t-78)$ [eq. 1] with $T_1 = 992.2 + 1493(Als)$ and $\alpha_1 = 1.204 + 24.9(Als)$, T_{av} and being expressed in ° C., t in seconds and Als in weight %, cooling of said hot-rolled strip from the finish rolling temperature to a temperature below 600° C. in less than 10 sec and coiling of said hot-rolled strip.

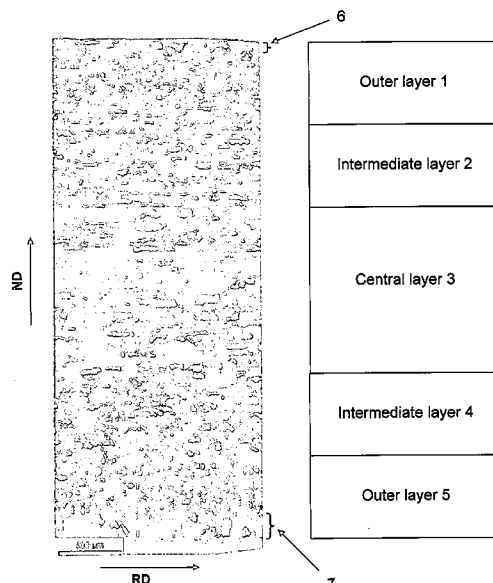


Figure 1

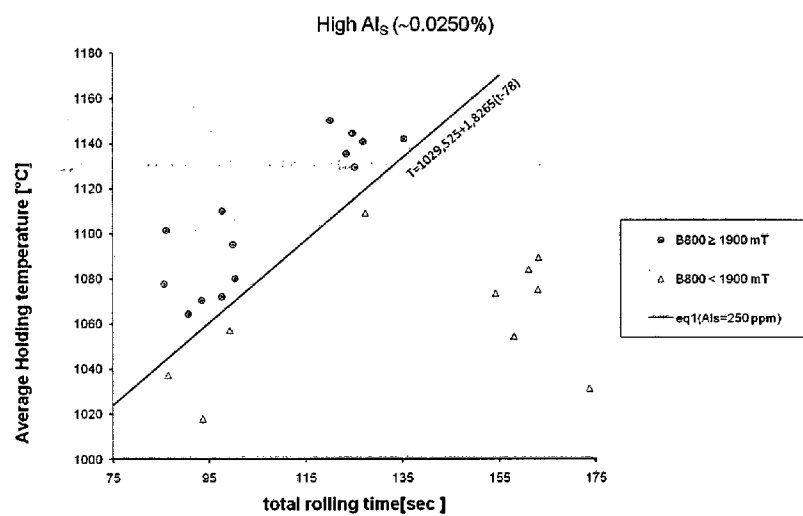
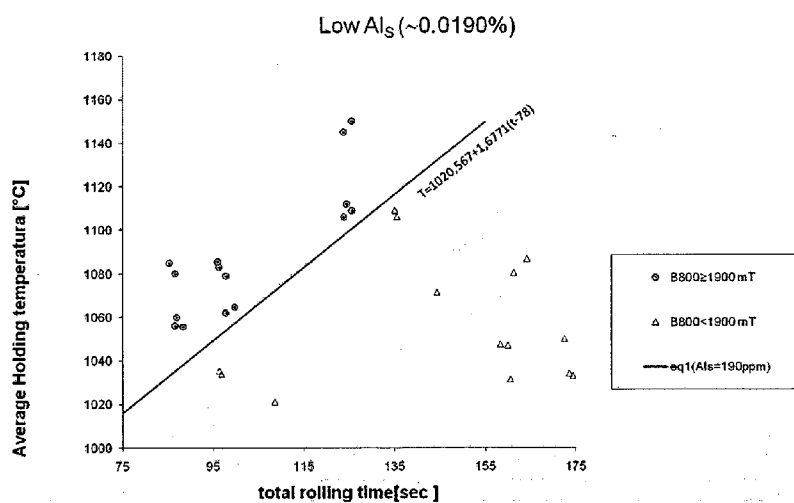
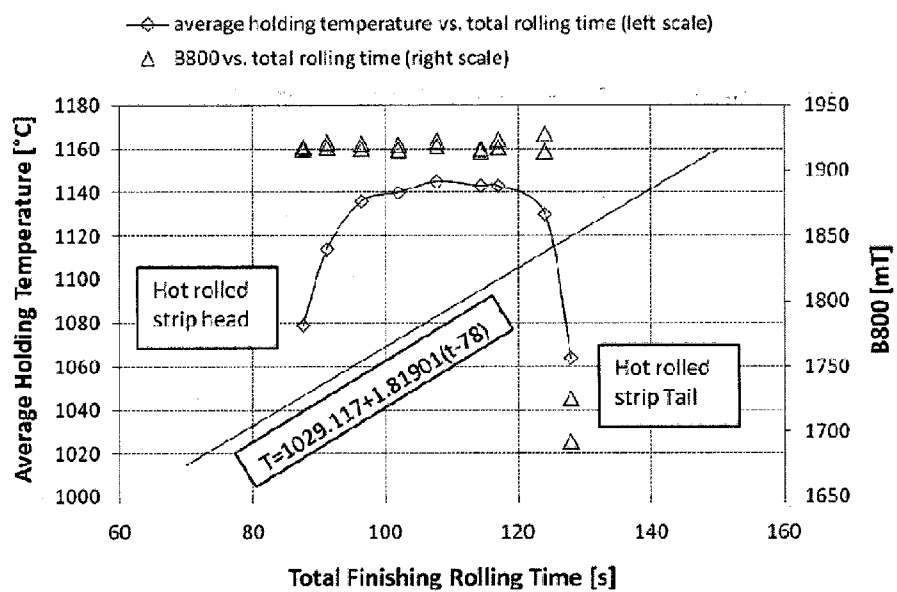


Figure 2



**Figure 3**

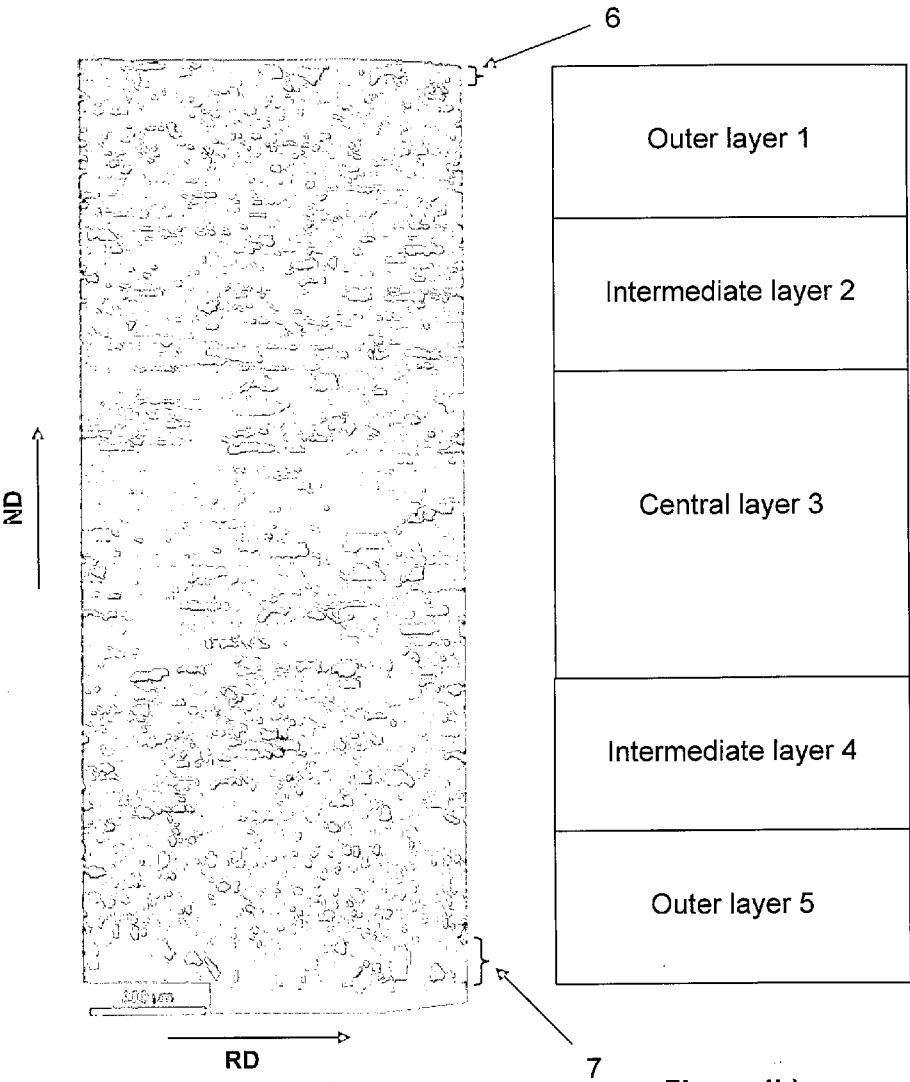


Figure 4a)

Figure 4b)

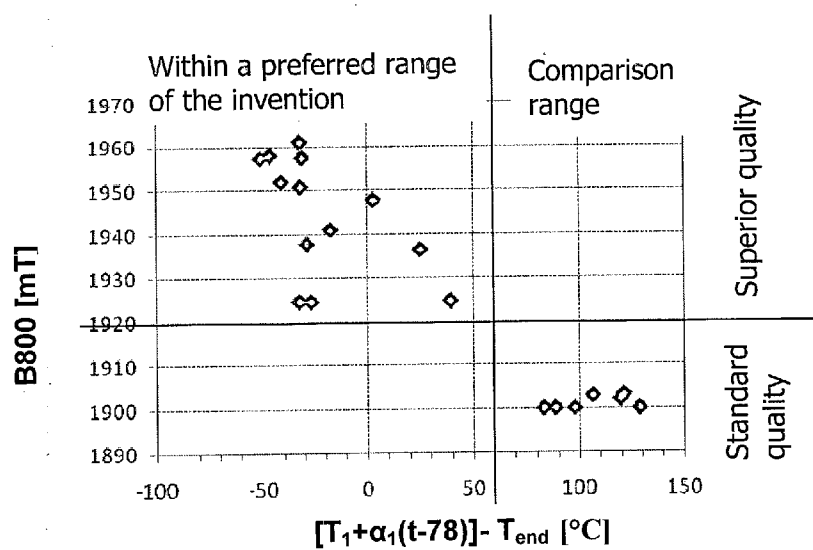


Figure 5

GRAIN ORIENTED STEEL STRIP WITH HIGH MAGNETIC CHARACTERISTICS, AND MANUFACTURING PROCESS OF THE SAME

[0001] The present invention deals with a process for the production of silicon-iron grain oriented electrical steel strips, generally used in the manufacturing of the cores of electric transformers.

[0002] From a metallurgical point of view, these products have ferritic (BCC) grains with a size ranging from some millimetres to some centimetres, with the $\langle 100 \rangle$ crystallographic direction aligned to the rolling direction and the $\{110\}$ crystallographic plane almost parallel to the rolling plane. The more the $\langle 100 \rangle$ direction is aligned to the rolling direction, the best the magnetic characteristics are (grains with orientation near to the ideal $\{110\}\langle 001 \rangle$ are called Goss grains).

[0003] Products classification is based on their magnetic characteristics (defined in Standard EN 10107 and IEC404-2):

[0004] "Magnetic induction at 800 A/m" B800 (expressed in Tesla), measured with an applied magnetic field equal to 800 A/m;

[0005] Power losses (expressed in W/kg) measured at fixed magnetic induction values (1.5 T for P15, 1.7 T for P17).

[0006] This high "orientation" of the grains is obtained by exploiting a metallurgical phenomenon called "secondary recrystallization": during batch annealing, performed at high temperature after primary recrystallization annealing, some of the grains of the microstructure, namely the ones with better orientation, abnormally grow consuming the other grains of the microstructure.

[0007] This phenomenon is influenced by the delicate balance among size and size distribution of primary recrystallized grains, their texture and fine dispersion of second phases (typically sulphides and/or selenides and/or nitrides), which inhibits grain growth during the secondary recrystallization annealing, allowing the selection mechanisms to operate and to produce a proper oriented final grains structure.

[0008] Primary recrystallized microstructure and second phases distribution are in their turn influenced by the upstream process and the attainment of the best metallurgical results is influenced in a complex manner by parameters distributed along the entire production process.

[0009] Proper precipitation of second phases is obtained by the presence in the alloy of controlled amounts of elements capable of forming them (S and/or Se and/or N together with Mn, Cu, Al, etc.), the heating of the slab before the hot-rolling up to very high temperatures ($>1350^\circ\text{C}$.), so as to dissolve a significant amount of the second phases, precipitated during casting in a coarse form, incapable of controlling the secondary recrystallization. After dissolution they can re-precipitate during the hot-rolling and the subsequent processes, in a form capable of controlling the secondary recrystallization.

[0010] Thanks to the teaching by Sakakura and Takuchi, as disclosed in U.S. Pat. No. 3,159,511; U.S. Pat. No. 3,287,183 and the further development by Barisoni et al. (U.S. Pat. No. 3,959,033) and Harase et al. (US48806) the technology for the production of highly oriented grains electrical steel (HGO), based on high temperature re-heating ($T > 1370^\circ\text{C}$.) of a slab containing sulphides and nitrides (namely MnS and AlN) and single stage cold rolling was developed. In this technology the high inhibition to the grain growth, due to the presence of AlN and MnS precipitated in fine form, allowed

the adoption of high reduction ratios during cold rolling, which as a consequence provided high degree of orientation of secondary grains, which in turn allowed to reach B800 values above 1,900 T.

[0011] In this technology the fine precipitation of sulphides is obtained during hot rolling, choosing the starting rolling temperature so that MnS, dissolved during slab reheating, are in strongly over-saturated solution; the fine second phase particles distribution is obtained thanks to the high density of dislocations generated by deformation, acting as nucleation site. The same mechanism cannot be adopted for the precipitation of nitrides, in fact when precipitation of nitrides happens during hot rolling, it is in coarse form, not suitable to control secondary recrystallization. This is due to the lower precipitation temperature of aluminium nitrides at the concentration used in this technology, if compared to the one of MnS, and to specific difference in the chemical-physical constants which controls the precipitation (diffusion coefficients, interface energy . . .) between AlN and MnS.

[0012] For this reason, nitrides precipitation during hot rolling is to be avoided and the precipitation in fine form of nitrides is obtained in the following annealing and quenching of the hot rolled strip, which in this technology is necessary. For the same reason, the strip needs to be rapidly cooled after hot rolling in order to prevent at maximum extent the precipitation of nitrides also during coiling; minor unavoidable precipitation during cooling is acceptable if the coiling temperature is below 600°C . In fact, coiling below the mentioned temperature guarantees the precipitation of residual nitrogen present in solid solution as silicon nitrides, preventing in this way the coarsening of aluminium nitrides during coiled strip cooling.

[0013] In spite of the considerable progress made, the technology still entails some drawback.

[0014] A first drawback is related to the control of secondary recrystallization phenomenon, which is quite delicate. Quite often in the industrial practice, due to fluctuations in process parameters it can become unstable, producing as a result finished product which contains fine grains with magnetically unfavourable orientation and determining as a consequence poor magnetic quality. One of the most critical point is the dissolution and re-precipitation of second phases (sulphides/selenides/nitrides) for the control of secondary recrystallization. It depends, besides the adopted temperature, on the chemical activities and consequently on concentration of constitutive elements (Al, N, Mn, S, Se . . .). In spite of the progress made in the steelmaking procedures, variation in concentration of elements is still possible, because of fluctuations in steelmaking procedures or because of accidental exposition of liquid steel to air during casting, which causes oxidation of Al and N pick-up. When it happens, fine grains can be present alone in the microstructure or mixed with properly secondarily recrystallized grains of proper orientation.

[0015] Another drawback is related to the abnormal growth of the grains in the slab microstructure. In fact, due to the very high temperature adopted in the reheating ($>1370^\circ\text{C}$.), some phenomena of selective secondary grain growth happens in the slab microstructure, producing strong microstructure heterogeneities, with some grains abnormally grown in comparison with others. These micro-structural heterogeneities are not completely overcome during conventional hot rolling and, without the adoption of adequate countermeasures, their inheritance remains down to finished product: fine grains of

unfavourable orientation appear together with properly secondary recrystallized grains. In this case fine grains are grouped in colonies elongated along rolling direction a few centimetres in width and a few decimetres in length, correspondent to the big grains grown in the slab microstructure (so called "streaks defect").

[0016] In order to prevent such phenomenon, complex hot rolling procedure has been developed which creates logistic problems in the slab managing, decreasing the hot rolling mill productivity. In this procedure the slab is subjected to a double re-heating, the first one at low temperature (~1150° C.), after which a "pre-rolling" for a total reduction of 25%-50% of the slab thickness is performed at a roughing mill. After that the slab, reduced in thickness, is subjected to a second passage through a reheating furnace at high temperature (>1370° C.).

[0017] A further drawback is related to brittleness of the hot rolled strip due to presence of silicon in concentration above 3%. The heterogeneities in the hot rolled strip microstructure favour the micro-cracks propagation enhancing such brittleness phenomena. This brittleness of the alloy negatively generates ruptures of the strip during the processing down to the finished product, especially during cold rolling, decreasing cold rolling productivity and yield.

[0018] Therefore, it remains the need to improve the technology and the characteristics of grain oriented electrical steel in order to overcome the above-mentioned drawbacks. A first object of the invention is a method for the production of hot-rolled steel strip comprising the following steps:

[0019] providing a steel slab comprising, in weight percentages: Si: 2.5 to 3.5%, C: 0.05 to 0.1%, Mn: 0.05 to 0.1%, Als: 0.015 to 0.026%, N: 0.0050 to 0.0100%, and further comprising S and/or Se so that S+ (32/79) Se is in an amount of 0.018 to 0.030%, and optionally comprising one or more elements chosen among Sb in an amount of 0.015 to 0.035%, Cu in an amount of 0.08% to 0.25%, Sn in an amount of 0.06% to 0.15%, P in an amount of 0.005% to 0.015%, the balance being iron and unavoidable impurities,

[0020] reheating said slab to a temperature between 1300° C. and 1430° C.,

[0021] roughing hot-rolling said slab to produce a blank having a thickness below 50 mm,

[0022] finishing hot-rolling of said blank to produce a hot rolled strip in three rolling passes or more, the temperature of said blank during the first pass being above 1150° C. and at least one rolling pass being performed with a reduction of 40% or more and being immediately followed by a holding of more than 20 sec, the average interpass holding temperature T_{av} , as defined by eq. 2 below, being settled between 1000 and 1200° C., the total finishing hot rolling time t (TFRT) being controlled so that the value of T_{av} for any portion of said strip further respects the under mentioned equation:

$$T_{av} > T_1 + \alpha_1(t-78) \quad [\text{eq. 1}]$$

[0023] with $T_1 = 992.2 + 1493(\text{Als})$ and $\alpha_1 = 1.204 + 24.9(\text{Als})$,

T_{av} and T_1 being expressed in ° C., t in seconds and Als in weight %,

[0024] cooling of said hot-rolled strip from the end rolling temperature to a temperature below 600° C. in less than 10 sec and

[0025] coiling of said hot-rolled strip.

The roughing hot rolling and finishing hot rolling are preferably performed using a reversible hot rolling mill.

The end hot rolling temperature T_{end} is preferably higher than $[T_1 + \alpha_1(t-78)] - 60^\circ \text{C}$.

According to a preferred embodiment, the reheating of the slab is performed at a temperature between 1350° C. and 1430° C.

Another object of the invention is a hot-rolled strip, obtainable by the method according to anyone of the modes above, comprising, in weight percentages: Si: 2.5 to 3.5%, C: 0.05 to 0.1%, Mn: 0.05 to 0.1%, Als: 0.015 to 0.026%, N: 0.0050 to 0.0100%, and further comprising S and/or Se so that S+ (32/79) Se is in an amount of 0.018 to 0.030%, and optionally comprising one or more elements chosen among Sb in an amount of 0.015 to 0.035%, Cu in an amount of 0.08% to 0.25%, Sn in an amount of 0.06% to 0.15%, P in an amount of 0.005% to 0.015%, the balance being iron and unavoidable impurities, comprising less than 0.0025% of nitrogen linked to aluminium under the form of AlN and presenting five different layers across the strip thickness composed of grains populations with different characteristics.

The hot-rolled strip comprises preferably outer layers 1 and 5, the zones extending from the surface to $\frac{1}{4}$ of strip thickness having a ferritic microstructure composed of more than 80% of equi-axial recrystallized grains with an average grain size d_{co} lower than 50 μm and preferably lower than 30 μm , and optionally, atop of at least one of the outer surface of said outer layers, coarse decarburised grains with an average grain size of at least 2 d_{co} .

According to a particular embodiment, the hot-rolled strip comprises intermediate layers 2 and 4, the zones extending from $\frac{1}{4}$ of the strip thickness to $\frac{3}{4}$ of strip thickness, as measured from the surface, having a ferritic microstructure composed of more than 80% of recrystallized grains with an average grain size d_{ca} lower than 80 μm and preferably lower than 50 μm , d_{ca} being such that: $d_{ca} > d_{co}$.

The hot-rolled strip comprises preferably a central layer, the central zone of the strip equal to $\frac{1}{3}$ of strip thickness, having an α -fiber texture with less than 60%, and preferably less than 50% of the area percentage of the layer with grains having a disorientation less than 20° from the α -fiber (<110> crystallographic direction parallel to rolling direction).

Another object of the invention is a method for the production of cold-rolled grain oriented magnetic strip comprising the following steps:

[0026] providing a hot-rolled strip obtained by the method according to anyone of the modes described above or a hot-rolled strip as described above,

[0027] optional cold rolling of said hot-rolled strip,

[0028] performing a first annealing of said strip during 40 to 300 sec, in one or more steps, the first step being performed at a temperature between 1050° C. and 1170° C. and optional further steps being performed at lower temperatures, and

[0029] cooling down said strip to a quenching start temperature between 750 and 940° C.,

[0030] quenching the strip to a temperature below 300° C.,

[0031] cold rolling said annealed strip, the reduction ratio of the last cold rolling down to final thickness being comprised between 80% and 95%,

[0032] performing a primary recrystallization annealing of the strip including a decarburization treatment so as to reach a carbon amount below 0.0030%,

[0033] applying an annealing separator onto the strip surface and

[0034] performing a secondary recrystallization annealing of the strip.

Preferably, the first annealing of the strip is performed in two steps, the strip being first held at a temperature between 1050° C. and 1170° C. during 10 to 60 s, and then cooled and held at a temperature between 800° C. and 950° C. during 40 to 240 sec.

The cold rolling of the annealed strip is preferably performed in three passes or more and the strip is held at a temperature between 170° C. and 300° C. after the first cold rolling pass. During the cold rolling of the annealed strip, the strip under rolling is held at a temperature between 170° C. and 300° C. in at least one interpass step after the first cold rolling pass. According to a preferred embodiment, the primary recrystallization annealing of the strip comprises an holding at a temperature between 780° C. and 900° C., during 60 to 300 sec, in an atmosphere consisting of N₂, H₂ and H₂O, the ratio between partial pressure of H₂O and partial pressure of H₂ being between 0.40 and 0.70.

The heating rate of the strip to reach said holding temperature between 780 and 900° C. is preferably at least 150° C./sec in the range between 200° C. and 700° C.

According to a preferred embodiment, the secondary recrystallization annealing comprises a heating of the strip to a temperature between 1000° C. and 1250° C. with a heating rate between 5° C./h and 40° C./h in an atmosphere consisting of N₂ and H₂, and then a holding of said strip during 5 to 30 h at this temperature in an atmosphere consisting of H₂.

[0035] The invention will now be described in more details, given as mere, non limiting examples, and referring to FIGS. 1 to 5 wherein:

[0036] FIGS. 1 to 3 illustrate the influence of TFRT and average holding temperature T_{av} on the magnetic induction at 800 A/m (B800) FIGS. 1 and 2 are related to two different values of soluble aluminium.

[0037] FIG. 4a) is an example of the through-thickness microstructure of a hot rolled strip according to the invention; FIG. 4b) is a schematic presentation of the different layers of FIG. 4a)

[0038] FIG. 5 illustrates the influence of the parameter $[T_1 + \alpha_1(t-78)] - T_{end}$ on the magnetic induction B800.

[0039] As will have been understood, the present inventors found out that the combination of the specific composition of the steel and the particular hot rolling procedure of the invention allows better control of the secondary recrystallization, decreasing its sensitivity to second phase distribution fluctuations and overcoming the occurrence of "streaks defect", without introducing complex pre-rolling procedures, and reducing the risk of breakage during cold rolling.

[0040] Such finishing hot rolling practice can for example be performed using a reversible hot rolling mill, also called Steckel mill, consisting of a single cage hot rolling mill with two coilers (each at any side of the cage) inside coil boxes at high temperature, where hot rolling is performed reversibly. This gives the additional advantage of reducing considerably the investment costs, necessary to start the production.

[0041] The composition of the steel is an essential part of the invention and will now be detailed, all percentages being weight percentages.

[0042] The amount of silicon is between 2.5 and 3.5%, and preferably between 2.90 and 3.3%. The addition of this element to the steel is essential and allows increasing the electric resistivity, decreasing in such way the iron losses. Silicon addition below the specified minimum limit does not produce suitable effect on iron losses reduction, while silicon contents above such mentioned maximum limit induces brittleness

phenomena which make the hot rolling and the following transformation down to finished product quite difficult to be performed.

[0043] The soluble aluminium amount (Als) is between 0.0150 and 0.0260%. In the frame of the present invention, Als is the aluminium soluble in acid, and is understood as being total aluminium minus aluminium bound as oxide. The addition of this essential element is necessary for the formation of proper amount of aluminium nitrides (AlN) suitable to control the secondary recrystallization. Aluminium amount below the minimum specified limit decreases the volume fraction of AlN so that secondary recrystallization becomes unstable. Its addition above the mentioned maximum limit provokes a coarse precipitation of AlN so that they are ineffective to control the grain growth during the secondary recrystallization annealing. In fact aluminium content above the mentioned limit increases the precipitation temperature of AlN, increasing in such way their driving force for precipitation during hot rolling. This makes impossible to maintain them in solution during hot rolling phase, producing as a consequence coarse precipitation of AlN.

[0044] The amount of nitrogen is between 0.0050 and 0.0100%. The addition of this essential element to the steel below the proposed minimum limit produces low volume fraction of nitrides, while nitrogen content above the mentioned upper limit is difficult to be obtained in conventional steelmaking operations, due its low solubility in steel, and may create a specific defect on the finished product occurrence, the so called "blister defect".

[0045] The amount of carbon in the hot-rolled steel is between 0.05 and 0.1%, but preferably under 0.08%. Its presence in the alloy has a positive effect on the magnetic characteristics. Carbon generates hard phases and fine carbides during the quenching process, thus increasing the strain hardening rate during the cold-rolling, in this way it improves the texture of cold rolled sheet, increasing the orientation of the Goss grains nuclei, which will produce better oriented Goss grains after secondary recrystallization. A carbon level below the mentioned lower limit does not produce the mentioned beneficial effects while carbon contents above the mentioned upper limit do not produce additional positive effects and increases the decarburization time unduly.

[0046] However carbides, by interacting with the walls of the magnetic domains in the finished product, generate dissipative phenomena which increase the iron losses, decreasing the magnetic quality of the strip. Carbon content has therefore to be decreased, preferably below 0.0030%, or most preferably below 0.0025% before the secondary recrystallization annealing takes place. This is done during the primary recrystallization annealing by performing such treatment under a specific decarburising atmosphere.

[0047] The amount of manganese is between 0.05 and 0.1%. Its addition below the mentioned limit produces insufficient volume fraction of sulphides and or selenides (MnS and MnSe) necessary for the proper control of secondary recrystallization, while manganese content above the mentioned upper limit increases the solubility product of the mentioned second phases and consequently provokes the coarse precipitation of the MnS/MnSe in a way ineffective to control the secondary recrystallization.

[0048] The amounts of sulphur and selenium must be so that S+(32/79)Se is between 0.0180 and 0.0300%. When their amount is below the lower limit, the volume fraction of sulphides and/or selenides becomes insufficient to produce sec-

ondary recrystallization, while contents above the upper limit produce brittleness phenomena due to sulphur and/or selenium segregation in the central part of the slab.

[0049] The steel according to the invention may also contain optionally one or more elements chosen among Sb in an amount of 0.015 to 0.035%, Cu in an amount of 0.08% to 0.25%, Sn in an amount of 0.06% to 0.15%, P in an amount of 0.005% to 0.015%.

[0050] Antimony can be used as a segregating element which can help in controlling grain growth during secondary recrystallization, in addition to AlN, MnS and/or MnSe.

[0051] Copper is able to form sulphides, alone or in combination with manganese. Its presence in the alloy contribute to have a distribution of sulphide second phase more suitable to control grain growth during secondary recrystallization annealing, improving the magnetic characteristics of the finished product. An addition below the minimum limit does not produce the mentioned positive effect, while above the maximum limit no further improvement of the magnetic characteristics are observed and cost of the alloys is unduly increased.

[0052] It has been observed that addition of tin and phosphorus in the proposed amounts improves the magnetic characteristics of the finished product. It has been hypothesized that this effect is due to the ability of tin to segregate on second phase particles surface, increasing their stability and favouring a fine precipitation, thus favouring the nucleation respect the particle growth. For phosphorus; it has been hypothesized that the described positive effect is due to its ability to segregate to grain boundaries, decreasing the grain boundary mobility, contributing, in this way to control the grain growth during secondary recrystallization annealing. Addition of tin and phosphorus amounts below the mentioned minimum limits do not produce the proposed positive effect, while concentrations above the mentioned maximum limits increase the brittleness of the alloy making the cold rolling difficult.

[0053] The method of production of a hot rolled steel strip according to the invention starts by reheating a slab having the above composition. Such a slab can be obtained by usual steelmaking methods such as continuous casting.

[0054] In order to carry out the hot rolling method, the slab has to be reheated at a high temperature, above 1300° C. The reheating temperature has to be above the level necessary to almost completely dissolve any sulphides and/or nitrides present in the steel, allowing having enough free nitrogen and free sulphur to generate second phases precipitates necessary to control secondary recrystallization.

[0055] It is preferred to set a minimum value of 1350° C. for the reheating temperature so as to ensure having a complete dissolution even in the presence of possible heterogeneities in the second phase precipitation in the slab due to fluctuation in casting conditions before reheating.

[0056] Reheating temperatures above the upper limit of 1430° C. do not produce additional advantages, increasing the energy consumption and decreasing the yield of reheating process due to the oxidation of the slab.

In the present invention, the hot rolling is divided in two phases: "roughing hot rolling" until the blank thickness is below 50 mm and "finishing hot rolling" from this thickness to the final thickness, which is usually between 1 and 3 mm. After the roughing hot rolling, a blank thickness above the upper maximum limit makes difficult to fulfil the proposed conditions for the following finishing hot rolling because the total finishing reduction rate became too high and conse-

quently the total rolling time is increased above the total maximum limit. The roughing rolling can be performed in any roughing stand but is preferably performed in a reversible rolling mill.

[0057] Once the slab has been roughed down to below 50 mm, it is then submitted to finishing hot rolling, which is also preferably performed in a reversible hot rolling mill. According to the invention, the finishing hot rolling is performed in three rolling passes or more. It is preferred to have three or five rolling passes, a most preferred embodiment being to have three rolling passes. The total reduction ratio depends of the thickness of the slab.

[0058] The start temperature of finishing hot rolling (i.e. temperature of the blank measured on the run-in table just before the first finishing hot rolling pass) must be above 1150° C. in order to avoid the beginning of any second phase precipitation before the hot rolling starts, which would cause a coarsening of sulphides and/or selenides.

[0059] It is even preferred to have a starting finishing rolling temperature above 1180° C.; it helps to control fluctuations in distribution of precipitating elements, produced by fluctuation in distribution of solubility product through the blank, due to segregation of precipitating elements.

[0060] During finish hot rolling, it is essential that at least one rolling pass is performed with a reduction ratio of 40% or more, this rolling pass being immediately followed by a holding for more than 20 sec; thus, the interpass time between said pass and the following one has to be higher than 20 sec and during this time the blank has to be held at high temperature. The average interpass holding temperature T_{av} (as defined by eq. 2 below) settled between 1000° C. and 1200° C., the total finishing hot rolling time (or "TFRT") have to be controlled so that the value of T_{av} for any portion of said strip further respects the under mentioned equation:

$$T_{av} > T_1 + \alpha_1(t - 78) \quad [\text{eq. 1}]$$

[0061] with $T_1 = 992.2 + 1493(Al_s)$ and $\alpha_1 = 1.204 + 24.9(Al_s)$,

[0062] T_{av} and T_1 being expressed in ° C., t in seconds and Al_s in weight %.

In the frame of the present invention, TFRT is considered to be the time interval between entry of the strip in the first finishing rolling pass and exit out of the last finishing rolling pass. When hot rolling is performed using a reversible rolling mill, due to the inversions of the strip direction in the different passes, TFRT will vary along the strip length. Being x the abscissa defined along the strip length, the total rolling time will be figured out from the hot rolling data as depending on x : $t(x)$. For the same reason, the holding time τ_i of the strip in the interpass i between rolling pass i and $i+1$ is depending on x : $\tau_i(x)$. It has also to be kept in mind that, due to cooling on rougher run-out table and to contact with cold coiling drum in case of reversible rolling mill, the different part of the strip under rolling are held at different temperatures between consecutive rolling passes; i.e. the holding temperature T_i of the strip in the interpass i between rolling pass i and $i+1$ is depending on x : $T_i(x)$. This is why the average interpass holding temperature T_{av} has also to be determined for each part of the strip located at an abscissa x along the length of the strip. In the frame of the present invention, it is defined as:

$$T_{av}(x) = \frac{\sum_{i=1}^{i=N-1} \tau_i(x) T_i(x)}{\sum_{i=1}^{i=N-1} \tau_i(x)} \quad [\text{eq. } 2]$$

[0063] with N being the number of finishing rolling passes, $T_i(x)$ being the holding temperature of the part of the strip of abscissa x when it is located in the interpass i between two rolling passes, $\tau_i(x)$ being the holding time of the part of the strip of abscissa x when it is located in the interpass between two rolling passes. The way how to measure the interpass holding temperature depends on the specific furnace used to perform the holding. There also is the possibility that the holding temperature during the time interval $\tau_i(x)$ is not constant, being so a function of time t beside of the abscissa x: $T_i(t; x)$. In this case the interpass holding temperature $T_i(x)$ will be determined averaging this variable temperature according to the following equation.

$$T_i(x) = \frac{1}{\tau_i(x)} \int_{t=0}^{\tau_i(x)} T_i(t; x) dt \quad [\text{eq. } 3]$$

The inventors, while not willing to be bound by any specific measuring method, point out that in the examples 1, 2 and 3 and as well as in the experiments used to determine the graphs in FIGS. 1, 2 and 3, where a reversible hot rolling mill has been used, the above eq. 3 has been estimated by averaging the entry and exit Temperature of the strip in the coiling furnaces, and by assuming a linear variation of the temperature of the strip $T_i(t; x)$ during holding time. This linear approximation is justified by the small difference in the measured entry and exit temperature: less than 20° C. for most length of the strip. Only for the head part of the strip, the difference between entry and exit temperature is about 50° C. According to a preferred embodiment of the invention, the end hot rolling temperature T_{end} (i.e. the temperature measured on the run-out table just after the last hot rolling pass), is an important parameter related to the magnetic quality of the finished product. The inventors have found that, assumed that the previous specifications for Tav and TFRT are fulfilled, if in addition T_{end} is higher than $[T_1 + \alpha_1(t-78)] - 60^\circ \text{ C.}$ (with T_1 , α_1 , t, as defined above), or what is equivalent, if $[T_1 + \alpha_1(t-78)] - T_{end}$ is lower than 60° C., the magnetic quality of the finished product has superior characteristics with B800 being superior or equal to 1920 mT, or 1.92 T. If instead, always assuming that the previous specifications for Tav and TFRT are fulfilled, $[T_1 + \alpha_1(t-78)] - T_{end}$ (with T_1 , α_1 , t, as defined above) is higher than 60° C., the magnetic quality of the finished product has “conventional” characteristics quality: 1900 mT $\leq$ B800 < 1920 mT.

The reason why this particular finishing hot rolling leads to good magnetic properties, quite stable in case of method parameters fluctuation, and to a reduced brittleness of the strip, also preventing the streaks defect formation, is still object of study. Nevertheless, the inventors have observed that the rolling pass at high reduction ratio followed by a holding at high temperature induces a recrystallization during finishing hot rolling, which, produces a hot band with finer and more recrystallized grain compared to what is known to be obtained in the state of art for a conventional finishing hot rolling procedure, which does not include any intermediate recrystallization step. The inventors think that this peculiar microstructure, better described below, plays a role in the

obtaining of good and stable magnetic quality and in the preventing of strip brittleness and of streaks defect.

[0064] It is not yet completely understood as well why the average interpass holding temperature and the total finishing rolling time have to be linked by the relation represented by equation 1 to obtain good and stable magnetic quality of the strip. Nevertheless, the inventors observed that when the blank during hot rolling is held at high temperature (so that Tav ranges between 1000° C. and 1200° C.) during a total finishing hot rolling time above what is expected from eq. 1, the precipitation and coarsening of nitrides is promoted, making impossible to get a fine precipitation of nitrides during annealing and quenching of the hot rolled strip.

[0065] The inventors also observed that an high average interpass holding temperatures towards the higher limit of the range 1000° C.-1200° C. decrease the driving force for precipitation, allowing longer rolling time without promoting precipitation of nitrides, as expected according to Eq. 1. For holding temperatures below 1000° C. the driving force for precipitation is so high that it happens irrespectively of the chosen holding time. On the other side, average interpass holding temperatures above 1200° C. are difficult to reach and it does not provide additional advantages.

[0066] It has also been observed that a lower amount of soluble aluminium Al_s decreases the driving force for precipitation, allowing larger time/temperature domains in which materials with good magnetic properties are obtained. This reflects in the decreasing of the slope of the straight line correspondent to eq. 1 in t, Tav cartesian domain with the decreasing of Als.

[0067] Even if the reason why T_{end} , in particular the difference between the minimum average holding temperature as defined above and $T_{end}([T_1 + \alpha_1(t-78)] - T_{end})$, is an important parameter in order to guarantee the finished product has a superior magnetic quality, has not been completely understood, the inventors have nevertheless observed that, provided that the previous specifications for Tav and TFRT are fulfilled, if the difference $([T_1 + \alpha_1(t-78)] - T_{end})$ is higher than 60° C., then a minor amount of precipitation of AlN starts in any case on the run-out table and the magnetic quality of the finished product, although still having a B800 $\geq$ 1900 mT, starts to deteriorate. If instead the said difference is lower than 60° C., no precipitation on the runout table is observed and the magnetic quality of the finished product is superior with B800 $\geq$ 1920 mT.

[0068] To better illustrate the influence of those parameters, equation 1 is drawn on FIGS. 1 and 2, for two particular Al_s values, together with the experimental data which allowed to determine it.

[0069] On FIG. 1, the experimental data related to different steel samples containing 0.0250% $\pm$ 0.0010% Als. The B800 of each single sample is represented as a function of average interpass holding temperature Tav and total finishing rolling time t with the following symbols:

[0070] grey circles for B800 > 1.900 T and

[0071] white triangles for B800 < 1.900 T.

[0072] All the samples were hot rolled and transformed to the finished product according to the teaching of present invention, except for what concern Tav and TFRT, whose values are represented in the graph. On the same graph, the straight line is delimiting the invention domain, represented by [eq. 1] above.

So closed circles, which are above the line, are inside the present invention while open triangles which are below the line, represent comparative examples.

[0073] On FIG. 2, the experimental data related to a samples containing 0.0190% $\pm$ 0.0010 Al_s .

[0074] It can be seen that, for a given amount of soluble aluminium, increasing the total rolling time imposes to increase the average holding temperature. Moreover, increasing the soluble aluminium amount imposes to shorten the total rolling time or to increase the average holding temperature.

[0075] The manufacturing conditions according to the invention make it also possible to obtain very stable magnetic properties along the length of a strip: FIG. 3 illustrates the magnetic properties of samples that have been extracted in different positions along the length of a strip of chemical composition fulfilling the teaching of the present invention (Als measured on the strip: $0.0247\% \pm 0.0010\%$), finishing hot rolled by a reversible hot rolling mill, having as a consequence local variations in TFRT and T_{av} along the strip length, represented by the losange marks and continuous line in the graph. In the conditions of the invention, even in spite of the variation of TFRT and T_{av} along the length, the magnetic properties remain high and quasi-constant. By comparison, when the conditions of the invention are not fulfilled, B800 drops very sharply. The length of the part hot rolled strip which can fall outside the invention limit, at hot rolled strip tail, during a normal rolling operation at conventional reversible hot rolling mill, is usually very short and it is usually cut away in the normal scrapping operation performed for other reasons during the production process.

[0076] Once the finish hot rolling is done, the cooling of the hot-rolled strip from the end rolling temperature to a temperature below 600°C . has to be done in less than 10 sec to avoid early precipitation of nitrides.

[0077] The end hot rolling temperature T_{end} is the temperature measured on the run-out table just after last rolling pass.

[0078] The coiling is performed next at a maximum temperature of 600°C . There again, coiling above the mentioned maximum limit produces a hot rolled strip with a coarse precipitation of AlN unsuitable to control secondary recrystallization.

[0079] On the contrary, the coiling at a temperature according to the invention produces a hot rolled strip where the nitrogen is captured by precipitation as silicon nitrides, which can be re-dissociated in the subsequent annealing of the hot rolled strip and nitrogen can be so re-precipitated as fine aluminium nitrides.

[0080] The hot rolled band obtained through this method shows specific characteristics as can be seen on FIG. 4a) showing a micrograph of sample n° 15 of the under examples and on FIG. 4b) schematizing the layers structure across the thickness. "RD" and "ND" on FIG. 4a) stand respectively for the Rolling Direction and the Normal Direction of the band. This fully ferritic microstructure presents a higher degree of recrystallization compared to what is known in the state of art when the hot rolling is conducted without holding the strip at high temperature in the interpass between consecutive hot rolling passes. This microstructure shows specific features:

[0081] It presents five different layers composed of grains with different characteristics; the thickness of the layers being, going from upper to lower surface: $\frac{1}{6}$, $\frac{1}{6}$, $\frac{1}{3}$, $\frac{1}{6}$, $\frac{1}{6}$, of the hot rolled strip thickness (FIG. 4);

[0082] the outer layers, referred as 1 and 5 on FIG. 4b) have the following characteristics: from the surface to $\frac{1}{6}$ of strip thickness, the microstructure is composed of more than 80% (preferably more than 90%), expressed in area percentage, of equiaxial recrystallized grains with an average ferritic grain size $d_{\alpha\alpha}$ lower than $50\text{ }\mu\text{m}$ and preferably lower than $30\text{ }\mu\text{m}$; equiaxial means preferentially a ratio between minor and major dimensions of grains in a range of 0.8 to 1.

[0083] the intermediate layers 2 and 4 present the following characteristics: from a distance going from $\frac{1}{6}$ to $\frac{5}{6}$ of strip thickness, the microstructure is composed of more than 80% (preferably more than 90%), expressed in area percentage, of recrystallized grains with an average grain size $d_{\alpha\alpha}$ lower than $80\text{ }\mu\text{m}$, preferably lower than $50\text{ }\mu\text{m}$, and, in any case bigger than the average grain size measured in layers 1 and 5 respectively, which means that $d_{\alpha\alpha} > d_{\alpha\alpha}$;

[0084] the central layer 3 presents the following characteristics: on a thickness equal to $\frac{1}{3}$ of the strip, centred on the mid-thickness of the strip, the microstructure presents an α -fiber texture with less than 50% of area percentage of the layer with grains having a disorientation less than 20° from the α -fiber ($\langle 110 \rangle$ crystallographic direction parallel to rolling direction), which is representative of the recrystallization state of the strip.

[0085] At the outmost part of layers 1 and 5 (near the surface of the strip) coarse grains, bigger than two times the average grain size $d_{\alpha\alpha}$ of the grains measured in layers 1 and 5, may be sometimes present at one or both surfaces of the strip. FIGS. 4a-b) illustrate an example wherein these surface grains evidenced as sub-layers 6 and 7 are present on both sides of the sheet, which are probably due to a superficial decarburization occurring incidentally during the interpass holding at high temperature. When these surface coarse grains are present, they are not considered in the grain size calculation.

The inventors characterised the microstructure with "Orientation Imaging Microscopy" (OIM) technique. Grain size was determined based on diameter of circle of equivalent area respect the grains; the grains area was determined by 5° tolerance angle criterion (see "Electron Backscattered Diffraction in Materials Science" Kluwer Academic/Plenum Publishers, New York, 2000, ISBN 0-306-46487-X for details on the used techniques). Drawing in FIG. 4a was obtained with such technique.

The average grain sizes in the outer layers 1 and 5 are not necessarily equal to each other and for that reason $d_{\alpha\alpha}$ is measured as the average grain size of both layers all together. The same criterion applies to the measurement of the average grain size of the intermediate layers 2 and 4, $d_{\alpha\alpha}$, for the same reason.

[0086] Although the reason why the application of the method described in the present application can produce such peculiar microstructure is not completely clarified, the present inventors retain it is linked to the recrystallization of the microstructure which happens during holding at a high temperature after a reduction greater than 40% one or more time between consecutive rolling passes, the average interpass holding temperature being settled between 1000°C . and 1200°C .

[0087] It is still difficult to connect the characteristics of this microstructure with the final properties of the cold-rolled product. However, the present inventors, while not willing to be bound by any theory, believe that the fine grains layers at the surface or near the surface may be favourable towards toughness characteristics, those fine grains preventing the micro cracks generated during cold rolling to propagate along the strip thickness.

[0088] Moreover the present inventors also retain the strong recrystallization of the microstructure obtained with this method is also responsible for the avoidance of the streaks defect without introducing the pre-rolling procedure and for the improved stability of the magnetic quality.

[0089] Whatever its structure, the hot-rolled band contains MnS and/or MnSe precipitated in fine form suitable to control

the secondary recrystallization. Nitrogen is precipitated in SiN or in other low temperature stable compounds; in minor part it is also precipitated as AlN but less than 0.0025% and preferably less than 0.0015% of nitrogen is precipitated as AlN in the hot rolled strip.

[0090] When the above limit is not respected, the precipitation of AlN is coarse and cannot be re-dissociated in the subsequent steps of the method, meaning that the second phase precipitation during the recrystallization steps will be insufficient to control secondary recrystallization and so to get good magnetic properties.

[0091] The above described hot rolled strip can be considered a product itself, which can be used as starting product for the production of cold rolled grain oriented electrical steel following the teaching, well known by the man skilled in the art, for the production of Grain Oriented electrical steel based on MnS and AlN inhibitors completely dissolved during hot rolling and re-precipitated during the process.

[0092] Anyhow, inventors have found that among the possible routes, known in the state of art, the best of the results are obtained following the process described below.

[0093] After the hot-rolling has been completed, the strip can be optionally cold-rolled and then annealed during 40 to 300 seconds in one or more steps, the first step being performed at 1050-1170° C. and optional further steps being performed at lower temperatures.

[0094] Annealing directly after hot rolling or after this first cold rolling has different purposes. It is first necessary to dissolve the silicon nitrides, precipitated during last part of cooling and coiling of the hot rolled strip, and to re-precipitate them in form of AlN. Such precipitation of AlN happens both during the heating stage of this annealing, simultaneously with silicon nitrides dissolution and during cooling before quenching.

[0095] It is also necessary during the holding at high temperature that the dissolution of silicon nitrides is completed and that AlN is partially dissolved. High temperature holding is also necessary to form a certain amount of gamma phase which is useful to form some martensite during quenching.

[0096] Annealing temperatures and times as well as starting quenching temperatures outside the mentioned ranges, do not provide the proper fine distribution of carbides and nitrides so that the magnetic quality of the finished product is worsened.

[0097] First holding annealing temperature below the mentioned lower limits does not guarantee the proper dissolution of nitrides, as well as the formation of the proper quantity of gamma phase necessary to form martensite during quenching. First holding annealing temperature, as well as time, above the maximum limit produces coarsening of sulphides by Oswald ripening, which makes their size distribution less suitable to control the secondary recrystallization, producing a worsening of the magnetic quality.

[0098] In a preferred embodiment of the invention, the annealing of the strip after hot rolling or after the first cold rolling is carried out in a double stage holding temperature, with a first holding at a temperature comprised in the range 1050° C.-1170° C., during 10-60 seconds, followed by a cooling down to a second holding temperature in the range 800° C.-950° C. during 40-240 seconds, followed by cooling down to a starting quenching temperature in the range 750° C.-940° C.

[0099] This double stage annealing allows a better control of the distribution of nitrides and hard phases and also an easier control of the starting quenching, less dependent on the possible fluctuations of the annealing line speed. The presence of the lower temperature holding, during which the

precipitation of the main part AlN is performed, guarantees a better control of the size distribution of AlN.

[0100] Choosing a second holding temperature above the maximum mentioned limit partially leaves in solution an excessive quantity of nitrides, so that they are precipitated in uncontrolled way during cooling before quenching, worsening the second phase distribution and consequently losing the advantage of performing the double stage holding. When the second holding temperature is below the minimum mentioned limit, it becomes difficult to initiate the quenching process at the temperatures highlighted, which are those yielding the maximum density of fine carbides and carbon in solid solution.

[0101] After this annealing, the strip is cooled down to 750-940° C. and further quenched at a temperature below 300° C. This quenching of the strip is necessary to generate fine carbides and hard phases useful to increase the work hardening during cold rolling. Preferably, the quenching time is less than 30 s.

[0102] Next step is cold rolling of the annealed strip, which is necessary, besides the thickness reduction of the strip, to cold harden the strip in order to provide a suitable microstructure and texture after recrystallization. The reduction ratio of the last cold rolling, down to final thickness, must be between 80 and 95%. Below, the minimum value of 80%, the obtained magnetic properties after secondary recrystallization are poor. Above the maximum value of 95%, unstable secondary recrystallization is obtained and too fine grains appear in the finished product with consequently poor magnetic quality. The latter is probably due to the very fine grain size produced in the decarburized strip which corresponds to a very high driving force to growth during following secondary recrystallization annealing. The produced distribution of fine second phases is not able to control such high driving force to growth, producing an unstable secondary recrystallization.

[0103] In the frame of the present invention, this "cold-rolling" describes a step performed on a cold-rolling mill.

[0104] In a preferred embodiment of the invention, the cold rolling operation is performed in three passes or more and the strip is held at a temperature comprised between 170 and 300° C., in at least one interpass step, after the first cold rolling pass. The function of this holding within the proposed temperature interval is to favour the migration of carbon in solid solution onto the dislocations generated by the rolling process, thereby favouring the generation of new dislocations. This is reflected on the magnetic quality of the final product, showing a more homogeneous and better-oriented grain. Holding temperatures lower than the minimum value does not allow the phenomenon of carbon migration onto the dislocations to occur in a sufficiently effective manner. Temperatures higher than the maximum limit yield no significant improvements and entail phenomena of rapid degradation of the lubricant utilised, making it difficult to industrialise the method.

[0105] After cold rolling the strip, a primary recrystallization is carried out simultaneously with a decarburization so as to reach a carbon amount below 0.0030% and preferably below 0.0025%.

[0106] In a preferred embodiment, this recrystallization is performed at a temperature comprised between 780° C. and 900° C. during 60 to 300 sec, in an atmosphere consisting of N₂, H₂ and H₂O, the ratio between partial pressure of H₂O and partial pressure of H₂ being between 0.40 and 0.70.

[0107] Temperatures and time lower than the minimum limits cause a non-optimal recrystallization of the sheet that worsens the magnetic characteristics, whereas temperatures higher than the maximum limits, as well as ratios between water and hydrogen partial pressure higher than the maxi-

imum value indicated, cause an excessive oxidation of the sheet surface, worsening the magnetic characteristics, as well as the surface quality of the final product. Ratios between water and hydrogen partial pressure below the minimum value indicated produce insufficient decarburization of the strip.

[0108] In a more preferred embodiment, this recrystallization is carried out with a heating rate of at least 150° C./sec in the temperature range comprised between 200° C. and 700° C.

[0109] After this primary recrystallization step, an annealing separator, usually made of MgO is applied to the strip surface and a secondary recrystallization is performed.

[0110] According to a preferred embodiment of the invention, the secondary recrystallization annealing is carried out by first heating the strip to a temperature between 1000° C. and 1250° C. with a heating rate between 5° C./h and 40° C./h and in an atmosphere consisting of N₂ and H₂, and then holding the strip during 5 to 30 h at this temperature in an atmosphere consisting of H₂.

[0111] Heating rates higher than the maximum indicated cause a too rapid evolution of the distribution of second phases formed during the hot-rolling, required for controlling the secondary recrystallization, so that the latter is not adequately controlled and the result is a worsening of the magnetic characteristics of the final product. Heating rates lower than the minimum one proposed does not produce special advantage and unnecessarily lengthen of the annealing times. Holding temperatures lower than the minimum one proposed does not allow the purification process for the elimination of nitrogen; sulphur and/or selenium to take place in a correct manner, whereas temperatures higher than the maximum proposed entail a worsening of the surface quality of the final product. With the aid of the following examples, herein-after a description of embodiments will be provided, aimed at making better understood the objects, features, advantages and application modes thereof.

[0112] The following examples are to be construed as illustrative of the invention and not limitative of its scope.

EXAMPLES

Example 1

[0113] Three steels of chemical composition shown in the following table 1 in weight percentages were industrially cast by continuous casting, the balance being iron and unavoidable impurities. First heat had an Als amount around 250 ppm and second and third had an Als amount around 190 ppm.

TABLE 1

chemical composition of the heats								
Heat	C	Mn	Si	S	Als	N	Cu	Sn
1	0.0754	0.060	3.13	0.023	0.0247	0.0086	0.110	0.079
2	0.0691	0.056	3.03	0.028	0.0194	0.0094	0.094	0.078
3	0.0754	0.060	3.10	0.024	0.0188	0.0074	0.105	0.081

[0114] The produced slabs were reheated at 1420° C. during 30 min, roughed and finished using a reversible hot rolling mill. The finishing hot rolling was performed in 3 passes.

[0115] In the interpass between consecutive hot rolling passes, the strip was held, at least once, for a time variable along the strip length, but in any case greater than 20 s, at a

temperature in the range 1000-1200° C. depending on coil and on the position along the coil length.

[0116] After last hot rolling pass, the coils were cooled to a temperature less than 600° C. in less than 10 seconds and coiled. From some of the hot rolled strips, samples were taken changing the sampling position along the coil length. The Al_s analysis was repeated on the strip samples; for all the samples the measured value was in agreement with table 1 values within ±0.0010%.

[0117] Different hot rolling parameters, together with the average holding temperature Tav and TFRT t figured out the different samples, from hot rolling data, are represented in table 2 and table 3, respectively for high and low Als heats. The minimum calculated value for Tav given by equation 1 was calculated and the difference ΔT between the real values of Tav and this minimum, has been also indicated in the tables.

[0118] Microstructural examinations were performed on polished surfaces of hot rolled sheets, on plane section perpendicular to the transverse direction of rolling. Hot rolled sheets manufactured according to the invention display a five layer disposal as described above. Less than 0.0015% of nitrogen bound to aluminium under the form of AlN was measured in the hot rolled samples manufactured according to the invention.

[0119] The different samples were then transformed into finished product performing a double stage annealing of the hot rolled strip, with a first holding at 1100° C. for 15 sec, followed by a cooling down to 900° C. in 15 sec, holding at 900° C. for 60 sec, cooling down to 800° C. and final quenching to room temperature with water.

[0120] The annealed strips were cold rolled to 0.30 mm in five passes, at the intermediate thicknesses of 1.0 mm, 0.7 mm and 0.5 mm, the temperature of the strip has being maintained at 250° C. for 10 nm.

[0121] No breakage of samples was observed in the conditions of the invention during cold rolling.

[0122] Decarburization was performed at 840° C. for 200 sec in an H₂/N₂/H₂O atmosphere with a ratio between, partial pressure of H₂O and partial pressure of H₂ of 0.55, reaching a carbon amount below 0.0025%. The heating rate in the temperature range between 200 and 700° C. was 40° C./sec.

[0123] After decarburization, the strips were coated with an annealing separator constituted mainly of MgO and then subjected to a secondary recrystallization annealing with the following cycle:

[0124] heating from 25° C. to 1210° C. with an heating rate of 10° C./h in a atmosphere consisting of H₂/N₂ in a volume ratio of 3:1,

[0125] holding at 1210° C. for 15 h in pure hydrogen, then

[0126] cooling down from 1210° C. to 600° C. in pure hydrogen atmosphere,

[0127] cooling down from 600° C. to 25° C. in pure nitrogen atmosphere.

[0128] B800 measured on such samples is gathered in Tables 2 and 3. The measurement was made according to standard UNI EN 10107 and IEC 404-2. No "streaks" defect was recorded in the conditions of the invention.

TABLE 2

Hot rolling conditions of the strips of heat 1															
Heat		Rough blank gauge [mm]	Start temperature of finishing rolling T [° C.]	Strip gauge [mm]	Coiling Temperature [° C.]	Number of passes	Reduction ratio [%]			TFRT t (sec)	Tav [° C.]	EQ1 [° C.]	ΔT [° C.]	B800 [T]	
1	1	24	1104	2.3	600	3	62.5	53.3	45.2	158	1054	1175	-121	1.675	Comparative
2	1	24	1136	2.3	570	3	62.5	53.3	45.2	154	1073	1167	-94	1.717	
3	1	26	1163	2.3	600	3	59.6	60	45.2	163	1089	1184	-95	1.730	
4	1	24	1159	2.3	600	3	62.5	53.3	45.2	127	1100	1118	-18	1.846	
5	1	26	1249	2.3	595	3	59.6	60	45.2	86	1025	1044	-19	1.850	
6	1	24	1172	2	560	3	62.5	55.6	50.0	120	1150	1107	43	1.948	Invention
7	1	24	1246	2.3	550	3	62.5	53.3	45.2	86	1101	1043.6	57	1.961	
8	1	24	1247	2.3	565	3	56.3	60	45.2	86	1078	1043.6	34	1.952	

TABLE 3

Hot rolling conditions of the strips of heats 2 and 3															
Heat		Rough blank gauge [mm]	Start temperature of finishing rolling [° C.]	Strip gauge [mm]	Coiling Temperature [° C.]	Number of passes	Reduction ratio [%]			TFRT t (sec)	Tav [° C.]	EQ1 [° C.]	ΔT [° C.]	B800 [T]	
9	2	22,3	<u>1092</u>	2,3	500	3	59,6	55,6	42,5	191	<u>1017</u>	1212	<u>-195</u>	<u>1,599</u>	Comparative
10	2	22	<u>1105</u>	2	540	3	59,1	55,6	50,0	176	<u>1034</u>	1186	<u>-152</u>	<u>1,626</u>	
11	3	24	<u>1091</u>	2,3	555	3	62,5	53,3	45,2	160	<u>1047</u>	1157	<u>-110</u>	<u>1,709</u>	
12	3	26	<u>1149</u>	2,3	573	3	59,6	60	45,2	164	<u>1087</u>	1164	<u>-77</u>	<u>1,774</u>	
13	2	24	<u>1167</u>	2	557	3	62,5	55,6	50,0	135	<u>1102</u>	1117	<u>-15</u>	<u>1,869</u>	
14	2	24	1204	2,3	528	3	62,5	53,3	45,2	87	1060	1036	24	1,945	Invention
15	3	26	1250	2,3	567	3	59,6	60	45,2	87	1080	1035	45	1,957	
16	3	26	1211	2,3	561	3	59,6	60	45,2	126	1150	1101	49	1,957	
17	3	24	1244	2,3	600	3	56,2	60	45	85	1085	1032	53	1,958	
18	3	24	1189	2,3	581	3	56,2	60	45	124	1145	1097	48	1,951	

Example 2

[0129] A steel of chemical composition shown in table 4 in weight percentages was industrially cast by continuous casting, the balance being iron and unavoidable impurities.

TABLE 4

chemical composition of the heat								
Heat	C	Mn	Si	S	Als	N	Cu	Sn
4	0.0686	0.056	2.96	0.024	0.0186	0.0076	0.110	0.083

A slab from this cast was hot rolled according to the following cycle:

- [0130] slab reheating at 1410° C. during 35 minutes
- [0131] roughing hot rolling down to 21 mm in seven passes with a finish rolling temperature of 1250° C.,
- [0132] finishing hot rolling using a reversible hot rolling mill, with a starting rolling temperature of 1185° C., in three passes (reduction ratios: 57.3%, 55.6% and 42.5%) to produce a strip of 2.3 mm thickness and
- [0133] cooling to a temperature less than 600° C. in less than 10 seconds and coiling at a temperature of 550° C.

[0134] In the interpass between consecutive hot rolling passes, the strip was held at least once for a time variable along the strip length, but in any case greater than 20 sec at a temperature in the range 1000-1200° C. depending on coil and on the position along the coil length.

[0135] Samples were taken in the middle of the length of the strip. From the hot rolling data, the total finishing rolling time t and average holding temperature Tav were figured out for such samples. the Als analysis was repeated on the strip samples; for all the samples the measured value was in agreement with Table 4 value within ±0.0010%:

[0136] t=126 sec

[0137] Tav=1115° C.

[0138] Applying the equation 1, the minimum value to be respected by Tav is 1100° C., meaning that these samples are according to the invention.

[0139] The five layers structure was observed as previously described.

[0140] Samples were then annealed according to one of the following cycles:

[0141] A. annealing in one step at holding temperature of 1125° C. during 100 sec, cooling down to 915° C., then quenching in water to reach a temperature of 50° C., or

[0142] B. annealing in two steps with a first holding temperature of 1125° C. during 30 sec, cooling down to 925° C. in 15 sec, second holding at 925° C. during 165 sec, cooling down to 800° C., then quenching in water to reach a temperature of 50° C.

After annealing, all samples were transformed into finished cold-rolled product according to the following steps:

[0143] cold rolling down in five passes to 0.30 mm; at intermediate thicknesses of 1.00 mm, 0.75 mm and 0.5 mm, samples under rolling were held at 250° C. for 10 minutes.

[0144] first recrystallization with decarburization with single holding temperature of 840° C. during 200 sec;
 [0145] coating with annealing separator based on dried slurry mainly constituted of MgO;
 [0146] box annealing with following cycle:
 [0147] heating from room temperature to 1200° C. at 10° C./h in an atmosphere consisting of H₂/N₂ in a volume ratio of 3:1,
 [0148] holding at 1200° C. during 15 hours in pure H₂
 [0149] cooling from 1200° C. to 600° C. in pure. H₂
 [0150] cooling from 600° C. to 50° C. in pure N₂.
 [0151] After box annealing the magnetic characteristics were measured. B800 and power losses P17 were measured according to standard UNI EN 10107 and IEC 404-2. Results are reported in the following table. No “streaks” defect was recorded.

TABLE 5

magnetic properties		
Properties	Annealing of hot-rolled strip	
	Cycle A	Cycle B
B ₈₀₀ [T]	1.905	1.945
P ₁₇ [w/kg]	1.095	0.99

It can be seen from this trial that cycle B allows to get an improved value of induction for the final product over cycle A. This is also the case for the loss value which is improved for cycle B compared to cycle A.

Example 3

[0152] A slab of the heat n° 4 was hot rolled in the following conditions:

[0153] slab reheating at 1420° C. during 30 minutes,
 [0154] roughing hot rolling down to 21 mm in seven passes with a finish rolling temperature of 1250° C.,
 [0155] finishing hot rolling using a reversible hot rolling mill, with a starting rolling temperature of 1188° C., in three passes (reduction ratios: 57.3%, 55.6% and 42.5%) to produce a strip of 2.3 mm thickness and
 [0156] cooling to a temperature less than 600° C. in less than 10 seconds and coiling at a temperature of 550° C.
 [0157] In the interpass between consecutive hot rolling passes, the strip was held at least once for a time variable along the strip length, but in any case greater than 20 sec at a temperature in the range 1000-1200° C. depending on coil and on the position along the coil length.
 [0158] Samples were taken in the middle of the length of the strip. From the hot rolling data, the total finishing rolling time t and average holding temperature Tav were figured out for such sampling position:
 [0159] t=122 sec
 [0160] Tav=1110° C.

[0161] Applying the equation 1, the minimum value to be respected by Tav is 1093° C., meaning that this sample is according to the invention.

[0162] After hot rolling, the samples were annealed with a single step annealing at 1105° C. during 90 sec, a cooling down to 920° C. and a water quenching down to a temperature of 40° C.

[0163] After annealing, the samples were cold rolled down in several passes to 0.30 mm, held at 210° C. for 10 min. at three different interpass thicknesses. The Als analysis was repeated on the strip samples; for all the samples the measured value was in agreement with Table 4 value within ±0.0010%. No breakages happened during cold rolling of samples within the teachings of present invention.

[0164] After cold rolling, samples were recrystallized and decarburized according to one of the following cycles:

[0165] A) heating from room temperature to 840° C. with a heating rate of 25° C./sec in the range between 200 and 700° C., holding at 840° C. during 180 sec in an atmosphere consisting of H₂/N₂/H₂O with a ratio between partial pressures P(H₂O)/P(H₂) equal to 0.55, followed by a second holding at 860° C. in an atmosphere consisting of H₂/N₂/H₂O with a ratio P(H₂O)/P(H₂) equal to 0.010,

[0166] B) heating from room temperature to 840° C. with a heating rate of 400° C./sec in the range between 200 and 700° C.; holding at 840° C. during 180 sec, in an atmosphere consisting of H₂/N₂/H₂O with a ratio between partial pressures P(H₂O)/P(H₂) equal to 0.55, followed by a second holding at 860° C. in an atmosphere consisting of H₂/N₂/H₂O with a ratio P(H₂O)/P(H₂) equal to 0.010.

[0167] Then, all samples were coated with an annealing separator based on dried slurry mainly constituted of MgO and annealed in a box annealing device with the same cycle used in example 2.

[0168] The magnetic characteristics were then measured. B800 and power losses P17 were measured according to standard UNI EN 10107 and IEC 404-2. Results are reported in the following table. No “streaks” defect was recorded

TABLE 6

magnetic properties		
Properties	Primary recrystallization	
	Cycle A	Cycle B
B ₈₀₀ [T]	1.920	1.925
P ₁₇ [w/kg]	1.08	1.03

It can be seen from this trial that cycle B allows to get an improved value of induction for the final product over cycle A. This is also the case for the loss value which is improved for cycle B compared to cycle A. This is due to the heating rate between 200 and 700° C. which allows to further improve the magnetic properties of the strip when set above 150° C./sec.

Example 4

[0169] Four casts of chemical composition shown in the following table 7 in weight percentages were industrially cast by continuous casting, the balance being iron and unavoidable impurities. Heats 5 and 6 have an Als amount around 250 ppm, heats 7 and 8 have an Als amount around 190 ppm.

TABLE 7

chemical composition of the heats								
Heat	C	Mn	Si	S	Als	N	Cu	Sn
5	0.0728	0.057	3.00	0.020	0.0253	0.0066	0.098	0.079
6	0.0754	0.060	3.13	0.023	0.0230	0.0086	0.110	0.080
7	0.0673	0.057	3.05	0.027	0.0192	0.088	0.096	0.079
8	0.0750	0.060	3.11	0.023	0.0190	0.075	0.100	0.080

[0170] The produced slabs were reheated at 1415° C. during 30 min, roughed and finished using a Steckel reversible hot rolling mill. The finishing hot rolling was performed in 3 passes.

[0171] In the interpass between consecutive hot rolling passes, the strip was held at least once for a time variable along the strip length, but in any case greater than 20 sec at a temperature in the range 1000-1200° C. depending on coil and on the position along the coil length.

[0172] After last hot rolling pass, the coils were cooled to a temperature less than 600° C. in less than 10 seconds and coiled. From some of the hot rolled strips, samples were taken changing the sampling position along the coil length.

[0173] Different hot rolling parameters, together with the average holding temperature T_{av} and total finishing hot rolling time $TFRT$ figured out for the different samples, from hot rolling data, are represented in table 8 and table 9, respectively for high and low Als heats. The value $(T_1 + \alpha_1(t-78))$ from equation 1, i.e. "EQ1", has been calculated, and the difference ΔT between the real values of T_{av} and EQ1, has been indicated in the tables.

[0174] The end hot rolling temperature T_{end} is reported in the table. The difference between EQ1 and T_{end} , i.e. $(EQ1 - T_{end})$ is also reported in the table.

Less than 0.0015% of nitrogen bound to aluminium under the form of AlN was measured in the hot rolled samples manufactured according to the invention.

[0175] The different samples were then transformed into finished product performing a double stage annealing of the hot rolled strip, with a first holding at 1100° C. for 15 sec, followed by a cooling down to 900° C. in 15 sec, holding at 900° C. for 60 sec, cooling down to 800° C. and final quenching to room temperature with water.

[0176] The annealed strips were cold rolled to 0.30 mm in five passes, at the intermediate thicknesses of 1.0 mm, 0.7 mm and 0.5 mm, the temperature of the strip has been maintained at 250° C. for 10 min.

[0177] No breakage of samples was observed in the conditions of the invention during cold rolling.

[0178] Decarburization was performed at 840° C. for 200 sec in an $H_2/N_2/H_2O$ atmosphere with a ratio between partial pressure of H_2O and partial pressure of H_2 of 0.55, reaching a carbon amount below 0.0025%. The heating rate in the temperature range between 200 and 700° C. was 40° C./sec.

[0179] After decarburization, the strips were coated with an annealing separator constituted mainly of MgO and then subjected to a secondary recrystallization annealing with the following cycle:

[0180] heating from 25° C. to 1210° C. with an heating rate of 10° C./h in a atmosphere consisting of H_2/N_2 in a volume ratio of 3:1,

[0181] holding at 1210° C. for 15 h in pure hydrogen, in order

[0182] cooling down from 1210° C. to 600° C. in pure hydrogen atmosphere, cooling down from 600° C. to 25° C. in pure nitrogen atmosphere

B800 measured on such samples is displayed in a Tables 8 and 9. The measurement was made according to standard UNI EN 10107 and IEC 404-2. No "streaks" defect was recorded in the conditions of the invention.

In table 8, samples n° 1-6 have been manufactured with start temperature of finishing rolling, lower than 1150° C., and with T_{av} lower than $(T_1 + \alpha_1(t-78))$, i.e. EQ1 in table 8. As a consequence, the value of B800 is well below 1900 mT for these samples.

Samples 8 and 9 corresponding to the range of the invention, display B800 value equal or greater than 1900 mT.

However, the magnetic properties can be still increased when the difference between the EQ1 and the end rolling temperature T_{end} is lower than 60° C., as may be seen on FIG. 5 reporting the value of B800 of the finished product for the different samples fulfilling the invention, as a function of $[(T_1 + \alpha_1(t-78)) - T_{end}]$

Thus, samples n° 10-17 in table 8 display superior magnetic properties with B800 higher than 1920 mT.

In table 9, the samples 18-23 have been manufactured with inadequate start temperature of finishing rolling and T_{av} . Thus, the value of B800 is lower than 1900 mT. Samples 24-26 and 32-33 satisfy to the conditions of invention and display B800 value greater than or equal to 1900 mT.

B800 value higher than 1920 mT is obtained with samples 27-31 when $[(T_1 + \alpha_1(t-78)) - T_{end}]$ is lower than 60° C.

TABLE 8

Hot rolling conditions of the strips of heat 5, 6										
Sample n°.	Heat	Start temperature of finishing rolling [° C.]	Thickness at the end of roughing step [mm]	Final hot strip thickness [mm]	Coiling temperature [° C.]	Number of Steckel mill passes	Reduction ratios [%]			TFRT t [s]
1	5	1181	22.8	2.3	520	3	60.5	55.6	42.5	94
2	5	1093	22.9	2.3	543	3	60.7	55.6	42.5	177
3	5	1096	22.3	2.3	577	3	59.6	55.6	42.5	175
4	5	1112	24	2.3	579	3	62.5	55.6	42.5	176
5	6	1136	24	2.3	570	3	62.5	53.3	45.2	154
6	6	1104	24	2.3	600	3	62.5	53.3	45.2	158
7	6	1145	24	2.3	577	3	56.3	60	45.2	161
8	5	1173	22.9	2.3	600	3	60.7	55.6	42.5	100

TABLE 8-continued

Hot rolling conditions of the strips of heat 5, 6										
9	5	1188	24.2	2.3	500	3	62.8	55.6	42.5	100
10	5	1211	24	2	600	3	62.5	55.6	50.0	98
11	5	1172	24	2	560	3	62.5	55.6	50.0	120
12	5	1151	21.2	2.3	576	3	57.5	55.6	42.5	135
13	6	1191	24	2.3	570	3	62.5	53.3	45.2	127
14	6	1246	24	2.3	550	3	62.5	53.3	45.2	86
15	6	1204	26	2.3	566	3	59.6	60	45.2	125
16	6	1247	24	2.3	565	3	56.3	60	45.2	86
17	6	1203	24	2.3	569	3	56.3	60	45.2	123

$\Delta T [^{\circ} \text{C.}] = T_{\text{av}} - T_{\text{EQ1}}$							
Sample n°.	$T_{\text{av}} [^{\circ} \text{C.}]$	$T_{\text{end}} [^{\circ} \text{C.}]$	$T_{\text{EQ1}} [^{\circ} \text{C.}]$	T_{EQ1}	$T_{\text{EQ1}} - T_{\text{end}} [^{\circ} \text{C.}]$	$B_{800} [\text{mT}]$	
1	<u>1018</u>	933	1059	-41	<u>126</u>	1718	Comparative
2	<u>1024</u>	1011	1212	-188	<u>200</u>	1587	
3	<u>1023</u>	1008	1208	-185	<u>200</u>	1610	
4	<u>1045</u>	1034	1210	-165	<u>176</u>	1592	
5	<u>1073</u>	955	1162	-89	<u>207</u>	1717	
6	<u>1054</u>	950	1169	-115	<u>218</u>	1675	
7	<u>1084</u>	975	1174	-90	<u>199</u>	1723	
8	1080	942	1070	10	<u>129</u>	1900	Invention
9	1095	951	1070	25	<u>119</u>	1902	
10	1110	1042	1067	43	25	1936	Preferred range of the invention
11	1150	1104	1107	43	3	1948	
12	1140	1095	1135	5	39	1925	
13	1141	1143	1114	27	-29	1925	
14	1101	1071	1041	60	-30	1961	
15	1144	1135	1110	34	-25	1938	
16	1078	1079	1041	37	-39	1952	
17	1135	1130	1106	29	-23	1925	

Underlined values in the columns of start temperature of finishing rolling, and Tav are outside of the range of invention

Underlined values in the column ($T_{\text{EQ1}} - T_{\text{end}}$) indicate values outside of a preferred range of the invention.

TABLE 9

Hot rolling conditions of the strips of heat 7, 8										
Sample n.	Heat	Start temperature of finishing rolling [$^{\circ} \text{C.}$]	Thickness at the end of roughing step [mm]	Final hot strip thickness [mm]	Coiling temperature [$^{\circ} \text{C.}$]	Number of Steckel mill passes	Reduction ratios [%]			TFRT t [s]
18	7	<u>1092</u>	22.3	2.3	500	3	59.6	55.6	42.5	191
19	7	<u>1104</u>	22.8	2.3	548	3	60.5	55.6	42.5	174
20	7	<u>1110</u>	24.2	2.3	508	3	62.8	55.6	42.5	175
21	7	<u>1120</u>	24	2	558	3	62.5	55.6	50	173
22	7	<u>1167</u>	24	2	557	3	62.5	55.6	50	135
23	8	<u>1149</u>	26	2.3	573	3	59.6	60	45.2	164
24	7	1184	22.3	2.3	510	3	59.6	55.6	42.5	100
25	7	1211	24	2	532	3	62.5	55.6	50	96
26	7	1207	22	2	581	3	59.1	55.6	50	98
27	8	1204	24	2.3	528	3	62.5	53.3	45.2	87
28	8	1250	26	2.3	567	3	59.6	60	45.2	87
29	8	1211	26	2.3	561	3	59.6	60	45.2	126
30	8	1244	24	2.3	600	3	56.2	60	45	85
31	8	1189	24	2.3	581	3	56.2	60	45	124
32	8	1185	21.2	2.3	464	3	57.5	55.6	42.5	87
33	8	1185	21.1	2.3	521	3	57.3	55.6	42.5	88

$\Delta T (^{\circ} \text{C.}) = T_{\text{av}} - T_{\text{EQ1}}$							
Sample n.	$T_{\text{av}} [^{\circ} \text{C.}]$	$T_{\text{end}} [^{\circ} \text{C.}]$	$T_{\text{EQ1}} [^{\circ} \text{C.}]$	T_{EQ1}	$T_{\text{EQ1}} - T_{\text{end}} (^{\circ} \text{C.})$	$B_{800} [\text{mT}]$	
18	<u>1017</u>	999	1211	-194	<u>212</u>	1599	Comparative
19	<u>1034</u>	1015	1182	-148	<u>167</u>	1625	
20	<u>1031</u>	1013	1184	-153	<u>171</u>	1626	
21	<u>1050</u>	1041	1181	-131	<u>140</u>	1638	
22	<u>1115</u>	1103	1117	-2	<u>14</u>	1869	
23	<u>1087</u>	961	1165	-78	<u>204</u>	1774	
24	1065	952	1058	7	<u>106</u>	1903	Invention
25	1085	963	1051	34	<u>88</u>	1900	
26	1060	972	1055	5	<u>83</u>	1900	Preferred range of the
27	1060	1053	1036	24	-17	1941	
28	1080	1086	1036	44	-50	1957	

TABLE 9-continued

Hot rolling conditions of the strips of heat 7, 8							
29	1150	1131	1101	49	-30	1957	invention
30	1085	1078	1032	53	-46	1958	
31	1145	1129	1098	47	-31	1951	Invention
32	1056	914	1036	20	<u>122</u>	1903	
33	1056	939	1037	19	<u>98</u>	1900	

Underlined values in the columns of start of finishing rolling temperature and Tav are outside of the range of invention

Underlined values in the column (EQ1 - T_{end}) indicate values outside of a preferred range of the invention.

1. A method for the production of hot-rolled steel strip comprising the successive following steps, in this order:

providing a steel slab comprising, in weight percentages:

Si: 2.5 to 3.5%,

C: 0.05 to 0.1%,

Mn: 0.05 to 0.1%,

Als: 0.015 to 0.026%,

N: 0.0050 to 0.0100%,

and further comprising S and/or Se so that S+ (32/79) Se is in an amount of 0.018 to 0.030%,

optionally comprising one or more elements chosen among Sb in an amount of 0.015 to 0.035%, Cu in an amount of 0.08% to 0.25%, Sn in an amount of 0.06% to 0.15%, P in an amount of 0.005% to 0.015%,

the balance being iron and unavoidable impurities, reheating said slab to a temperature between 1300° C. and 1430° C.,

roughing hot-rolling said slab to produce a blank having a thickness below 50 mm,

finishing hot-rolling of said blank to produce a hot rolled strip in three rolling passes or more, the temperature of said blank during the first pass being above 1150° C. and at least one rolling pass being performed with a reduction of 40% or more and being immediately followed by a holding of more than 20 sec,

the average interpass holding temperature Tav being settled between 1000 and 1200° C., the total finishing hot rolling time t being controlled so that the value of Tav for any portion of said strip further respects the under mentioned equation:

$$T_{av} > T_1 + \alpha_1(t-78) \quad [\text{eq. 1}]$$

with $T_1 = 992.2 + 1493(\text{Als})$ and $\alpha_1 = 1.204 + 24.9(\text{Als})$,

T_{av} and T₁ being expressed in ° C., t in seconds and Al, in weight %, and

cooling of said hot-rolled strip from the finish rolling temperature to a temperature below 600° C. in less than 10 sec, and

coiling of said hot-rolled strip.

2. A method according to claim 1, wherein the roughing and finishing hot rolling is performed using a reversible hot rolling mill.

3. A method according to claim 1, wherein the end hot rolling temperature T_{end} is higher than $([Ti + \alpha_1(t-78)] - 60^\circ \text{C.})$

4. A method according to claim 1, wherein said reheating of the slab is performed at a temperature between 1350° C. and 1430° C.

5. A hot-rolled steel strip, to comprising, in weight percentages:

Si: 2.5 to 3.5%,

C: 0.05 to 0.1%,

Mn: 0.05 to 0.1%,

Als: 0.015 to 0.026%,

N: 0.0050 to 0.0100%,

and further comprising S and/or Se so that S+ (32/79) Se is in an amount of 0.018 to 0.030%,

optionally comprising one or more elements chosen among Sb in an amount of 0.015 to 0.035%, Cu in an amount of 0.08% to 0.25%, Sn in an amount of 0.06% to 0.15%, P in an amount of 0.005% to 0.015%, the balance being iron and unavoidable impurities, and

comprising less than 0.0025% of nitrogen linked to aluminium under the form of AlN and presenting five different layers across the strip thickness composed of grains populations with different characteristics.

6. A hot-rolled strip according to claim 5, further comprising outer layers 1 and 5, the zones extending from the surface to 1/6 of strip thickness having a ferritic microstructure composed of more than 80% of equi-axial recrystallized grains with an average grain size d_{αα} lower than 50 μm and preferably lower than 30 μm, and optionally, atop of at least one of the outer surface of said outer layers, coarse decarburised grains with an average grain size of at least 2d_{αα}.

7. A hot-rolled strip according to claim 5, further comprising intermediate layers 2 and 4, the zones extending from 1/6 of the strip thickness to 2/6 of strip thickness, as measured from the surface, having a ferritic microstructure composed of more than 80% of recrystallized grains with an average grain size d_{αα} lower than 80 μm and preferably lower than 50 μm, d_{αα} being such that d_{αα} > d_{αα}.

8. A hot-rolled strip according to claim 5, further comprising a central layer, the central zone of the strip equal to 1/3 of strip thickness, having an α-fiber texture with less than 60% and preferably less than 50% of the area percentage of the layer with grains having a disorientation less than 20° from the α-fiber (<110> crystallographic direction parallel to rolling direction)

9. A method for the production of cold-rolled grain oriented magnetic strip comprising the successive following steps, in this order:

providing a hot-rolled strip obtained by the method according to claim 1,

optional cold rolling of said hot-rolled strip,

performing a first annealing of said strip during 40 to 300 sec, in one or more steps, the first step being performed at a temperature between 1050° C. and 1170° C. and optional further steps being performed at lower temperatures,

cooling down said strip to a quenching start temperature between 750 and 940° C.,

quenching the strip to a temperature below 300° C.,

cold rolling said annealed strip, the reduction ratio of the last cold rolling down to final thickness being between 80% and 95%,

performing a primary recrystallization annealing of the strip including a decarburization treatment so as to reach a carbon amount below 0.0030%,
applying an annealing separator onto the strip surface, and performing a secondary recrystallization annealing of the strip.

10. A method according to claim 9, wherein said first annealing of the strip is performed in two steps, the strip being first held at a temperature between 1050° C. and 1170° C. during 10 to 60 s, and then cooled and held at a temperature between 800° C. and 950° C. during 40 to 240 sec.

11. A method according to claim 9, wherein during said cold rolling of said annealed strip, said strip under rolling is held at a temperature between 170° C. and 300° C. in at least one interpass step after the first cold rolling pass.

12. A method according to claim 9, wherein the primary recrystallization annealing of the strip comprises a holding at a temperature between 780° C. and 900° C., during 60 to 300 sec, in an atmosphere consisting of N₂, H₂ and H₂O, the ratio between partial pressure of H₂O and partial pressure of H₂ being between 0.40 and 0.70.

13. A method according to claim 12, wherein the heating rate of the strip to reach said holding temperature between 780 and 900° C. is at least 150° C./sec in the range between 200° C. and 700° C.

14. A method according to claim 9, wherein the secondary recrystallization annealing comprises a heating of the strip to a temperature between 1000° C. and 1250° C. with a heating rate between 5° C./h and 40° C./h in an atmosphere consisting of N₂ and H₂, and then a holding of said strip during 5 to 30 h at this temperature in an atmosphere consisting of H₂.

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