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(54) HIGH-STRENGTH HOT-ROLLED STEEL SHEET AND METHOD FOR MANUFACTURING SAME

(57) There is provided a high-strength hot-rolled steel sheet having an excellent effect of suppressing the occurrence of cracking and wrinkling during bending.

A high-strength hot-rolled steel sheet has a chemical composition containing, by mass%, C: 0.02% to 0.23%, Si: 0.10% to 3.00%, Mn: 0.5% to 3.5%, P: 0.100% or less, S: 0.02% or less, and Al: 1.50 or less, the balance being Fe and incidental impurities, in which the total area fraction of martensite and bainite is 80% to 100%, the maximum orientation density of grains is less than 2.5 in a region extending from a position of 5 pm to a position of 10 pm from a surface in the thickness direction, and the maximum orientation density of grains is 2.5 or more in a region extending from a position of 50 μm to a position of 100 pm from the surface in the thickness direction.

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Description

Technical Field

[0001] The present invention relates to a high-strength hot-rolled steel sheet and a method for manufacturing the same, and in particular, to a high-strength hot-rolled steel sheet suitable as a material for automotive parts and a method for manufacturing the same.

Background Art

[0002] Steel sheets used for automotive parts are required to have higher strength from the viewpoints of improving crash safety and fuel economy of automobiles. In general, increasing the strength of steel sheets decreases the workability thereof; thus, steel sheets having high strength and excellent workability are required. Hot-rolled steel sheets having a tensile strength of more than 980 MPa are often subjected to forming processes, particularly bending processes for components such as frame parts. Thus, excellent bending workability is especially demanded. In bending processes, it is important to not only suppress significant cracking that greatly impair crash safety but also to suppress wrinkles from the perspectives of aesthetics and fatigue resistance. Various hot-rolled steel sheets have been developed to solve these problems.

[0003] Patent Literature 1 discloses a technique related to a method for manufacturing a cold rolled steel sheet having excellent ductility and bendability and having a tensile strength of 780 MPa or more by adjusting alloying elements to appropriate ranges, setting the volume fraction of ferrite to 60% to 80%, and controlling the ratio of the nano-hardness of ferrite to the nano-hardness of a low temperature transformed phase to a certain range. Patent Literature 2 discloses a technique related to a hot-dip galvanized steel sheet having improved bending workability obtained by setting the amount of C to 0.07 to 0.25 mass%, appropriately adjusting other alloying elements, and appropriately combining the area fraction of each phase of the steel sheet microstructure, the average grain size of the martensite phase, variations in Vickers hardness, and so forth. Patent Literature 3 discloses a technique related to a hot-rolled steel sheet having excellent ductility obtained by controlling misorientation in grains.

Citation List

Patent Literature

[0004]

- PTL 1: Japanese Unexamined Patent Application Publication No. 2009-167467
- PTL 2: International Publication No. 2016/129213
- PTL 3: Japanese Unexamined Patent Application Publication No. 2016-204690

Summary of Invention

Technical Problem

[0005] However, in Patent Literature 1, since a large amount of ferrite is contained, the yield strength (YS) is low, and it cannot necessarily be said that the steel sheet has strength needed for crash resistance. In addition, it cannot be said that the technique of Patent Literature 1 can be used to a hot-rolled steel sheet having a significantly different texture, and there is room for improvement. Patent Literature 2 discloses an improvement in a hot-dip galvanized steel sheet in which the occurrence of wrinkles (streak patterns) due to Mn segregation becomes a problem, and does not suggest anything about a hot-rolled steel sheet. In addition, it cannot be said that the technique of Patent Literature 2 can be used to a hot-rolled steel sheet having a significantly different texture, and there is room for improvement. In Patent Literature 3, while excellent ductility can be obtained by controlling the crystallographic orientation, no study has been made on wrinkles during bending, and there is room for improvement.

[0006] The present invention has been made to solve the above problems, and it is an object of the present invention to provide a high-strength hot-rolled steel sheet having an excellent effect of suppressing the occurrence of cracking and wrinkling during bending.

[0007] It is another object of the present invention to provide a method for manufacturing the high-strength hot-rolled steel sheet described above.

Solution to Problem

[0008] The inventors have conducted intensive studies on the conditions for the occurrence of wrinkles during bending. The inventors have found that the occurrence of cracking and wrinkling during bending is significantly suppressed by controlling the chemical composition and the texture of the surface layer of the steel sheet to specific ranges. These findings have led to the completion of the present invention.
[0009] In the present invention, the high strength means that the tensile strength (TS) is 980 MPa or more and the yield strength (YS) is 800 MPa or more.
[0010] In the present invention, the phrase "excellent effect of suppressing the occurrence of cracking and wrinkling during bending" indicates that R/t obtained by dividing the minimum bending radius R at which cracking and wrinkling do not occur during bending by the sheet thickness t is 3.0 or less.
[0011] The present invention has the following configurations.

[1] A high-strength hot-rolled steel sheet has a chemical composition containing, by mass%:

C: 0.02% to 0.23%,
Si: 0.10% to 3.00%,
Mn: 0.5% to 3.5%,
P: 0.100% or less,
S: 0.02% or less, and
Al: 1.50 or less, the balance being Fe and incidental impurities,
in which the total area fraction of martensite and bainite is 80% to 100%, the maximum orientation density of grains is less than 2.5 in a region extending from a position of 5 pm to a position of 10 pm from a surface in the thickness direction, and the maximum orientation density of grains is 2.5 or more in a region extending from a position of 50 μm to a position of 100 pm from the surface in the thickness direction.

[2] In the high-strength hot-rolled steel sheet described in [1], the chemical composition further contains one or more selected from, by mass%:

Cr: 0.005% to 2.0%,
Mo: 0.05% to 2.0%,
V: 0.05% to 1.0%,
Cu: 0.05% to 4.0%,
Ni: 0.005% to 2.0%,
Ti: 0.005% to 0.20%,
Nb: 0.005% to 0.20%,
B: 0.0003% to 0.0050%,
Ca: 0.0001% to 0.0050%,
REM: 0.0001% to 0.0050%,
Sb: 0.0010% to 0.10%, and
Sn: 0.0010% to 0.50%.

[3] A method for manufacturing a high-strength hot-rolled steel sheet includes heating a slab having the chemical composition described in [1] or [2], performing rough rolling, then performing finish rolling under conditions in which the total rolling reduction in a temperature range of 1,000°C or lower is 50% or more, the total number of passes in a temperature range of 1,000°C or lower is 3 passes or more, the final pass rolling temperature is 750°C to 900°C, and the total rolling reduction from the final pass rolling temperature to the final pass rolling temperature + 50°C is 35% or less, performing cooling under conditions in which a natural cooling time after completion of the finish rolling is 2.0 seconds or less and an average cooling rate to a temperature of 550°C is 50 °C/s or more, performing cooling at an average cooling rate of 100 °C/s or more in a temperature range of 300°C to 400°C, and performing coiling at 300°C or lower.

Advantageous Effects of Invention

[0012] According to the present invention, there is provided a high-strength hot-rolled steel sheet having an excellent effect of suppressing the occurrence of cracking and wrinkling during bending (hereinafter also referred to as "bending wrinkle resistance").
[0013] According to the present invention, there is provided a high-strength hot-rolled steel sheet that is suitable as a

material for automotive parts and that has excellent bending wrinkle resistance. The use of the high-strength hot-rolled steel sheet of the present invention enables the production of, for example, high-strength automotive parts having no cracks or wrinkles due to bending.

Description of Embodiments

[0014] A high-strength hot-rolled steel sheet and a method for manufacturing the high-strength hot-rolled steel sheet according to the present invention will be described in detail below. The present invention is not limited to the following embodiments.

<High-Strength Hot-Rolled Steel Sheet>

[0015] The high-strength hot-rolled steel sheet of the present invention may be a non-pickled hot-rolled steel sheet, which is as hot rolled, or a pickled hot-rolled steel sheet, which has been further pickled after hot rolling. The high-strength hot-rolled steel sheet of the present invention preferably has a thickness of 0.6 mm or more. The high-strength hot-rolled steel sheet of the present invention preferably has a thickness of 10.0 mm or less. When the high-strength hot-rolled steel sheet of the present invention is used as a material for automotive parts, the thickness is more preferably 1.0 mm or more. When the high-strength hot-rolled steel sheet of the present invention is used as a material for automotive parts, the thickness is more preferably 6.0 mm or less. The high-strength hot-rolled steel sheet of the present invention preferably has a width of 500 mm or more, more preferably 700 mm or more. The high-strength hot-rolled steel sheet of the present invention preferably has a width of 1,800 mm or less, more preferably 1,400 mm or less.

[0016] The high-strength hot-rolled steel sheet of the present invention has a specific chemical composition and a specific steel microstructure. Here, the chemical composition and the steel microstructure will be described in this order.

[0017] First, the chemical composition of the high-strength hot-rolled steel sheet of the present invention will be described. Here, "%" representing the component content of the chemical composition refers to "mass%".

[0018] The high-strength hot-rolled steel sheet of the present invention has a chemical composition containing, by mass%, C: 0.02% to 0.23%, Si: 0.10% to 3.00%, Mn: 0.5% to 3.5%, P: 0.100% or less, S: 0.02% or less, and Al: 1.50 or less, the balance being Fe and incidental impurities,

C: 0.02% to 0.23%

[0019] C is an element effective in forming and strengthening bainite and martensite to increase TS and YS. A C content of less than 0.02% does not sufficiently provide the effect and does not achieve a TS of 980 MPa or higher. A C content of more than 0.23% results in a marked development of the texture of the surface layer of the steel sheet, failing to achieve the desired bending wrinkle resistance. Accordingly, the C content is 0.02% to 0.23%. The C content is preferably 0.03% or more from the viewpoint of more stably obtaining a TS of 980 MPa or more, and is preferably 0.06% or more from the viewpoint of stably obtaining a TS of 1,180 MPa or more. From the viewpoint of bending wrinkle resistance, the C content is preferably 0.22% or less, more preferably 0.20% or less.

Si: 0.10% to 3.00%

[0020] Si is an element effective in increasing the strength of steel through solid solution strengthening and suppressing temper softening of martensite to increase TS and YS. Si is an element also effective in suppressing the occurrence of cracking and wrinkling at the time of bending. To provide the effect, the Si content needs to be 0.10% or more. On the other hand, a Si content of more than 3.00% results in excessive formation of polygonal ferrite, failing to obtain the steel microstructure of the present invention. Accordingly, the Si content is 0.10% to 3.00%. The Si content is preferably 0.20% or more. The Si content is preferably 2.00% or less, more preferably 1.50% or less.

Mn: 0.5% to 3.5%

[0021] Mn is an element effective in forming martensite and bainite to increase TS and YS. A Mn content of less than 0.5% does not sufficiently result in the effect, and polygonal ferrite or the like is formed, failing to form the microstructure of the present invention. On the other hand, a Mn content is more than 3.5% results in marked development of the texture of the surface layer of the steel sheet, failing to the desired bending wrinkle resistance. Accordingly, the Mn content is 0.5% to 3.5%. The Mn content is preferably 1.0% or more from the viewpoint of more stably obtaining a TS of 980 MPa or more. The Mn content is preferably 3.0% or less, more preferably 2.3% or less, from the viewpoint of bending wrinkle resistance.

P: 0.100% or Less

[0022] P causes embrittlement of the steel, thereby promoting bending cracking. Thus, the amount thereof is desirably minimized as much as possible. A P content of up to 0.100% is allowable in the present invention. Accordingly, the P content is 0.100% or less (excluding 0%). The P content is preferably 0.030% or less. Although the lower limit is not particularly specified, a P content of 0.001% or more is preferred because a P content of less than 0.001% leads to a decrease in production efficiency.

S: 0.02% or Less

[0023] S causes embrittlement of the steel, thereby promoting bending cracking. Thus, the amount thereof is preferably minimized as much as possible. A S content of up to 0.02% is allowable in the present invention. Accordingly, the S content is 0.02% or less (excluding 0%). The S content is preferably 0.0050% or less, more preferably 0.0030% or less. Although the lower limit is not particularly specified, a S content of 0.0002% or more is preferred because a S content of less than 0.0002% leads to a decrease in production efficiency.

Al: 1.50 or Less

[0024] Al acts as a deoxidizing agent and is preferably added in a deoxidization step. From the viewpoint of using Al as a deoxidizing agent, the Al content is preferably 0.01% or more. On the other hand, a large amount of Al contained results in the formation of a large amount of polygonal ferrite, failing to obtain the steel microstructure of the present invention. An Al content of up to 1.5% is allowable in the present invention. Accordingly, the Al content is 1.5% or less (excluding 0%). The Al content is preferably 0.50% or less, more preferably 0.30% or less, still more preferably 0.10% or less.

[0025] The balance is Fe and incidental impurities.

[0026] The above components are the basic chemical composition of the high-strength hot-rolled steel sheet of the present invention. In the present invention, the following elements may be further contained as appropriate.

[0027] One or more Selected from Cr: 0.005% to 2.0%, Mo: 0.05% to 2.0%, V: 0.05% to 1.0%, Cu: 0.05% to 4.0%, Ni: 0.005% to 2.0%, Ti: 0.005% to 0.20%, Nb: 0.005% to 0.20%, B: 0.0003% to 0.0050%, Ca: 0.0001% to 0.0050%, REM: 0.0001% to 0.0050%, Sb: 0.0010% to 0.10%, and Sn: 0.0010% to 0.50%

[0028] Cr, Mo, V, Cu, and Ni are elements effective in forming martensite to contribute to an increase in strength. To provide the effect, when Cr, Mo, V, Cu, and Ni are contained, the amounts of individual elements contained are preferably equal to or higher than their respective lower limits described above. When the amounts of individual elements of Cr, Mo, V, Cu, and Ni contained are more than their respective upper limits mentioned above, the texture of the surface layer of the steel sheet may develop, failing to provide the desired bending wrinkle resistance. The Cr content is more preferably 0.1% or more. The Cr content is more preferably 1.0% or less. The Mo content is more preferably 0.1% or more. The Mo content is more preferably 0.5% or less. The V content is more preferably 0.1% or more. The V content is more preferably 0.5% or less. The Cu content is more preferably 0.1% or more. The Cu content is more preferably 0.6% or less. The Ni content is more preferably 0.1% or more. The Ni content is more preferably 0.6% or less.

[0029] Ti and Nb are elements effective in forming carbides to increase the strength of steel. To provide the effect, when Ti and Nb are contained, the amounts of individual elements contained are preferably equal to or higher than their respective lower limits described above. On the other hand, when the amounts of individual Ti and Nb contained are more than their respective upper limits mentioned above, the texture of the surface layer of the steel sheet may develop, failing to provide the desired bending wrinkle resistance. The Ti content is more preferably 0.01% or more. The Ti content is more preferably 0.15% or less. The Nb content is more preferably 0.01% or more. The Nb content is more preferably 0.15% or less.

[0030] B is an element effective in increasing the hardenability of a steel sheet and forming martensite to contribute to an increase in strength. To provide the effect, when B is contained, the B content is preferably 0.0003% or more. On the other hand, a B content of more than 0.0050% may result in the increase of B-containing compounds to decrease the hardenability, failing to provide the steel microstructure of the present invention. Accordingly, when B is contained, the B content is preferably 0.0003% to 0.0050%. The B content is more preferably 0.0005% or more. The B content is more preferably 0.0040% or less.

[0031] Ca and REM are elements effective in improving workability due to their contribution to the shape control of inclusions. To provide the effect, when Ca and REM are contained, the individual amounts thereof are preferably set to Ca: 0.0001% to 0.0050% and REM: 0.0001% to 0.0050%. When each of the Ca content and the REM content is more than the corresponding upper limit described above, the amount of inclusions may increase to deteriorate workability. The Ca content is more preferably 0.0005% or more. The Ca content is more preferably 0.0030% or less. The REM content is more preferably 0.0005% or more. The REM content is more preferably 0.0030% or less. REM is a general term for Sc, Y, and 15 elements ranging from lanthanum (La) with atomic number 57 to lutetium (Lu) with atomic number 71, and the REM content used here refers to the total amount of these elements contained.

[0032] Sb is an element effective in suppressing denitrification, deboronization, and so forth to inhibit a decrease in the strength of steel. To provide the effect, when Sb is contained, the Sb content is preferably 0.0010% to 0.10%. An Sb content of more than the upper limit described above may lead to embrittlement of the steel sheet. The Sb content is more preferably 0.0050% or more. The Sb content is more preferably 0.050% or less.

[0033] Sn is an element effective in suppressing pearlite to inhibit a decrease in the strength of steel. To provide the effect, when Sn is contained, the Sn content is preferably 0.0010% to 0.50%. A Sn content of more than the upper limit described above may lead to embrittlement of the steel sheet. The Sn content is more preferably 0.0050% or more. The Sn content is more preferably 0.050% or less.

[0034] Even if the amounts of individual Cr, Mo, V, Cu, Ni, Ti, Nb, B, Ca, REM, Sb, and Sn contained are less than the respective lower limits described above, the effects of the present invention are not impaired. Accordingly, when the amounts of these elements contained are less than the respective lower limits described above, these elements are treated as being contained as incidental impurities. Incidental impurities other than these elements include N, Na, Mg, Zr, Hf, Ta, W, etc. and are contained in an amount of 0.020% or less in total.

[0035] The steel microstructure of the high-strength hot-rolled steel sheet of the present invention will be described below.

[0036] In the steel microstructure of the high-strength hot-rolled steel sheet of the present invention, the total area fraction of martensite and bainite is 80% to 100%, the maximum orientation density of grains is less than 2.5 in a region extending from a position of 5 pm to a position of 10 pm from a surface in the thickness direction, and the maximum orientation density of grains is 2.5 or more in a region extending from a position of 50 μm to a position of 100 pm from the surface in the thickness direction.

Total Area Fraction of Martensite and Bainite: 80 % to 100%

[0037] In the present invention, in order to achieve high TS, high YS, and excellent bending wrinkle resistance, the microstructure is mainly composed of martensite and bainite. When the total area fraction of martensite and bainite is less than 80%, the desired TS, YS, or bending wrinkle resistance cannot be achieved. Accordingly, the total area fraction of martensite and bainite is 80% to 100%. The total area fraction is preferably 90% to 100%, more preferably 95% to 100%. The area fraction of each phase can be determined by a method described in Examples.

Maximum Orientation Density of Grains in Region Extending from Position of 5 pm to Position of 10 pm from Surface in Thickness Direction (5- to 10-μm Surface Layer Region): less than 2.5

[0038] By randomizing the orientation of grains in the outermost surface layer, the occurrence of cracking and wrinkling during bending can be suppressed. To provide the effect, the maximum orientation density of grains needs to be less than 2.5 in a region extending from a position of 5 pm to a position of 10 pm from a surface in the thickness direction (5- to 10-μm surface layer region). Accordingly, the maximum orientation density of the grains in the 5- to 10-μm surface layer region is less than 2.5. The maximum orientation density of the grains in the 5- to 10-μm surface layer region is preferably less than 2.4, more preferably less than 2.3. The lower limit of the maximum orientation density of the grains in the 5- to 10-μm surface layer region is preferably 1.0 or more, more preferably 1.2 or more. The maximum orientation density of the grains in the 5- to 10-μm surface layer region can be determined by a method described in Examples.

Maximum Orientation Density of Grains in Region Extending from Position of 50 μm to Position of 100 μm from Surface in Thickness Direction (50- to 100-μm Surface Layer Region): 2.5 or More

[0039] By developing the texture of grains in a region immediately below the outermost layer and making it non-random, the occurrence of cracking and wrinkling during bending can be suppressed. Although the details are not clear, the reason for this is presumably that the surface layer of the steel sheet serving as a starting point of cracking and wrinkling during bending is restricted to a deformation mode in which cracking and wrinkling are less likely to occur during bending because layers having different crystallographic orientation biases are adjacent to each other. To provide the effect, it is necessary to set the maximum orientation density of the grains to less than 2.5 in the 5- to 10-μm surface layer region and to set the maximum orientation density of grains to 2.5 or more in a region extending from a position of 50 μm to a position of 100 pm from the surface in the thickness direction (50- to 100-pm surface layer region). Accordingly, the maximum orientation density of the grains is 2.5 or more in the 50-to 100-pm surface layer region. The maximum orientation density of the grains is preferably 2.6 or more, more preferably 2.7 or more, in the 50- to 100-pm surface layer region. The upper limit of the maximum orientation density of the grains is preferably 6.0 or less, more preferably 5.0 or less, in the 50- to 100-pm surface layer region. The maximum orientation density of the grains in the 50- to 100-

pm surface layer region can be determined by a method described in Examples.

<Method for Manufacturing High-Strength Hot-Rolled Steel Sheet>

[0040] A high-strength hot-rolled steel sheet of the present invention is manufactured by heating a slab having the chemical composition described above, subjecting the slab to rough rolling, performing finish rolling under conditions in which the total rolling reduction in a temperature range of 1,000°C or lower is 50% or more, the total number of passes in a temperature range of 1,000°C or lower is 3 passes or more, the final pass rolling temperature is 750°C to 900°C, and the total rolling reduction from the final pass rolling temperature to the final pass rolling temperature + 50°C is 35% or less, performing cooling under conditions in which a natural cooling time after completion of the finish rolling is 2.0 seconds or less and an average cooling rate to a temperature of 550°C is 50 °C/s or more, performing cooling at an average cooling rate of 100 °C/s or more in a temperature range of 300°C to 400°C, and performing coiling at 300°C or lower.

[0041] A detailed description will be given below. The temperature described above is the surface temperature at the central portion of the width of the steel sheet, and the average cooling rate described above is the average cooling rate at the surface of the central portion of the width of the steel sheet. The average cooling rate is [(cooling start temperature - finish cooling temperature)/cooling time from the cooling start temperature to the finish cooling temperature] unless otherwise specified.

[0042] A steel having the above-described chemical composition is obtained by a known steelmaking method using, for example, a converter, an electric arc furnace, or a vacuum melting furnace, and is cast by a known method, such as a continuous casting method or an ingot making-slabbing method to form a cast slab. The slab is directly heated or once cooled and then heated and subjected to rough rolling. The rough rolling conditions do not have to be specified, and can be performed in the usual manner. After performing rough rolling, finish rolling is performed under predetermined conditions.

Total Rolling Reduction in Temperature Range of 1,000°C or Lower: 50% or More

[0043] In the finish rolling of the hot rolling, the maximum orientation densities of the grains in the 5- to 10-μm surface layer region and the 50- to 100-pm surface layer region of the present invention can be obtained by setting the total rolling reduction in a temperature range of 1,000°C or lower to 50% or more. Accordingly, the total rolling reduction in the temperature range of 1,000°C or lower in the finish rolling is 50% or more. The rolling reduction is preferably 60% or more. Although the upper limit of the rolling reduction is not particularly specified, when the rolling reduction is too large, the texture inside the steel sheet may develop to impair workability. Thus, the rolling reduction is preferably 95% or less.

Total Number of Passes in Temperature Range of 1,000°C or Lower: 3 Passes or More

[0044] The rolling reduction in the temperature range of 1,000°C or lower in the finish rolling can be divided into multiple times to reduce the rolling reduction per pass, thereby randomizing the grains in the 5- to 10-μm surface layer region. In the present invention, the maximum orientation density of the grains in the 5- to 10-μm surface layer region of the present invention can be obtained by setting the total number of passes to 3 or more in the temperature region of 1,000°C or lower. The total number of passes is preferably 4 passes or more. The total number of passes is preferably, but not particularly limited to, 10 passes or less.

Final Pass Rolling Temperature: 750°C to 900°C

[0045] When the rolling temperature in the final finishing pass of the hot rolling (finishing delivery temperature) is lower than 750°C, a large amount of undesirable microstructure, such as ferrite, is formed, thereby failing to obtain the microstructure of the present invention. On the other hand, a rolling temperature of higher than 900°C leads to insufficient development of the texture of the surface layer of the steel sheet, failing to obtain the maximum orientation density of the grains in the 50- to 100-pm surface layer region of the present invention. Accordingly, the final pass rolling temperature (finishing delivery temperature) is 750°C to 900°C. The rolling temperature is preferably 770°C or higher. The rolling temperature is preferably 880°C or lower.

Total Rolling Reduction from Final Pass Rolling Temperature to Final Pass Rolling Temperature + 50°C: 35% or Less

[0046] A high rolling reduction in the vicinity of the final pass temperature results in recrystallization to cause insufficient development of the texture of the surface layer of the steel sheet, thereby failing to obtain the maximum orientation density of the grains in the 50- to 100-pm surface layer region of the present invention. To obtain the maximum orientation density of the grains in the 50- to 100-pm surface layer region of the present invention, the total rolling reduction in the temperature range of the final pass rolling temperature to the final pass rolling temperature + 50°C needs to be 35% or less. Accordingly, the total rolling reduction from the final pass rolling temperature to the final pass rolling temperature + 50°C is 35% or less. The total rolling reduction is preferably 30% or less. Although the lower limit is not particularly specified, the total rolling reduction is preferably 5% or more because an excessive low total rolling reduction may cause shape defects etc.

Natural Cooling Time After Finish Rolling: 2.0 Seconds or Less

[0047] A natural cooling time after the finish rolling of more than 2.0 seconds results in the promotion of the recovery of dislocations immediately below the surface layer, thereby failing to obtain the maximum orientation density of the grains in the 50- to 100-pm surface layer region of the present invention. Accordingly, the natural cooling time after the finish rolling is 2.0 seconds or less. The natural cooling time is preferably 1.5 seconds or less. The lower limit of the natural cooling time is not particularly specified. However, when the natural cooling time is 0.1 seconds or more, the recovery of dislocations in the surface layer of the steel sheet is further enhanced to more easily obtain the maximum orientation density of the grains in the 5- to 10-μm surface layer region of the present invention. Thus, the natural cooling time is preferably 0.1 seconds or more. The natural cooling refers to exposure to the atmosphere (air cooling) without performing active cooling (accelerated cooling) by pouring water or the like.

Average Cooling Rate in Temperature Range up to 550°C: 50 °C/s or More

[0048] When the average cooling rate from the start of cooling after the completion of the finish rolling to 550°C is lower than 50 °C/s, ferrite and pearlite are formed to fail to obtain the steel microstructure of the present invention. Accordingly, the average cooling rate from the start of cooling (the start temperature of accelerated cooling) to 550°C is 50 °C/s or more. The average cooling rate is preferably 80 °C/s or more. The upper limit of the average cooling rate is not particularly specified. However, the average cooling rate is preferably 1,000 °C/s or less from the viewpoint of the shape stability of the steel sheet and so forth. The cooling start temperature is, for example, a finishing delivery temperature (final pass rolling temperature).

Average Cooling Rate in Temperature Range of 300°C to 400°C: 100 °C/s or More

[0049] When the average cooling rate in the temperature range of 300°C to 400°C is less than 100 °C/s, bainite transformation or martensite transformation occurs in a state where the driving force is low, thereby failing to obtain the maximum orientation density of the grains in the 50- to 100-pm surface layer region of the present invention. Accordingly, the average cooling rate in the temperature range of 300°C to 400°C is 100 °C/s or more. The average cooling rate is preferably 150 °C/s or more. The upper limit of the average cooling rate is not particularly specified. However, the average cooling rate is preferably 1,000 °C/s or less from the viewpoint of the shape stability of the steel sheet and so forth.

Coiling Temperature: 300°C or Lower

[0050] A coiling temperature of higher than 300°C results in a low driving force for transformation, thereby failing to obtain the maximum orientation density of the grains in the 50- to 100-pm surface layer region of the present invention. Accordingly, the coiling temperature is 300°C or lower. The coiling temperature is preferably 280°C or lower, more preferably 250°C or lower. After the coiling, the coil is cooled to room temperature, for example.

[0051] There are no particular limitations other than the conditions of the production method described above. However, it is preferable to appropriately adjust the conditions as described below for the manufacture. For example, the heating temperature of the slab is preferably 1,100°C or higher from the viewpoints of, for example, segregation removal and dissolution of precipitates, and is preferably 1,300°C or lower from the viewpoint of, for example, energy efficiency. The finish rolling is preferably performed in four or more passes from the viewpoint of, for example, reducing coarse grains that cause a decrease in workability.

[0052] The high-strength hot-rolled steel sheet of the present invention has a tensile strength (TS) of 980 MPa or more and a yield strength (YS) of 800 MPa or more. TS is preferably 1,180 MPa or more. YS is preferably 900 MPa or more. Although not particularly limited, TS is preferably 1,570 MPa or less, and YS is preferably 1,300 MPa or less. The high-strength hot-rolled steel sheet of the present invention has excellent bending wrinkle resistance and an R/t of 3.0 or less. R/t is preferably 2.8 or less. TS, YS, and R/t are each obtained by a method described in Examples.

EXAMPLES

[0053] Steels having respective chemical compositions given in Table 1 were obtained by steelmaking in a vacuum melting furnace and formed into slabs. The slabs were heated to 1,250°C, subjected to rough rolling, and subjected to finish rolling, natural cooling, cooling (accelerated cooling), and coiling, under respective conditions given in Table 2, thereby producing hot-rolled steel sheets. The total number of passes of the finish rolling was 7 passes. The resulting hot-rolled steel sheets were subjected to microstructure observation and evaluation of tensile properties and bending wrinkle resistance in accordance with the following test methods.

Microstructure Observation

[0054] The area fractions of martensite and bainite are the fractions of the areas of the respective microstructures to the observed area. For the area fraction of martensite, a sample was cut out from the resulting hot-rolled steel sheet. A cross section in the thickness direction and parallel to the rolling direction was polished and then etched in 3% nital. A position 1/4 of the thickness was photographed in three visual fields at a magnification of $\times$1,500 with a scanning electron microscope (SEM). The area fraction of each microstructure was determined from the image data of the obtained secondary electron image using Image-Pro available from Media Cybernetics, Inc., and the average area fraction of the three visual fields was defined as the area fraction of each microstructure. In the image data, upper bainite is distinguished as black or dark gray containing carbide or linear interface-containing martensite, lower bainite is distinguished as black, dark gray, gray, or light gray containing oriented carbide, martensite is distinguished as black, dark gray, gray, or light gray containing carbide having multiple orientations, or white or light gray with free of carbide, and retained austenite is distinguished as white or light gray with free of carbide. Martensite and retained austenite cannot be distinguished from each other, in some cases. Thus, retained austenite was determined by a method described below, and the area fraction of martensite was determined by subtracting the area fraction of retained austenite from the total area fraction of martensite and retained austenite determined from the SEM image. In the present invention, the martensite may be any of fresh martensite, autotempered martensite, tempered martensite, etc. The bainite may be any bainite, such as upper bainite, lower bainite, or tempered bainite. A higher degree of tempering of the microstructure results in a contrast image in which the matrix appears blacker. For this reason, the color of the matrix is a guide. In the present invention, identification was based on the comprehensive assessment of the amount of carbide, the form of the microstructure, etc. Then, the microstructures were classified into those having similar characteristics, including microstructures described below. Carbides appear white dots or lines. Although basically not contained in the present invention, ferrite is a black or dark gray microstructure having no or little carbide inside or having no martensite with a linear interface. Pearlite can be distinguished as a black and white lamellar or partially interrupted lamellar microstructure. The area fraction of retained austenite was determined as follows: An annealed steel sheet was ground to a position 1/4 of the thickness + 0.1 mm and then chemically polished by 0.1 mm. For the polished surface, the integrated intensities of reflections from the (200), (220), and (311) planes of fcc iron (austenite) and the (200), (211), and (220) planes of bcc iron (ferrite) were measured with an X-ray diffractometer using MoKα1 radiation. The volume fraction was determined from the intensity ratio of the integrated intensity of reflection from the planes of fcc iron to the integrated intensity of reflection from the planes of bcc iron. This volume fraction was used as the area fraction of the retained austenite.

[0055] The total area fraction was determined using the obtained area ratios of the respective microstructures. Table 3 presents the results. In Table 3, "V (M + B)" means the total area fraction of martensite and bainite, and "V (O)" means the total area fraction of other microstructures (microstructures other than martensite or bainite).

Maximum Orientation Density of Grains

[0056] Crystallographic orientations in a region extending from a position of 5 pm to a position of 10 pm from a surface and a region extending from a position of 50 μm to a position of 100 pm from the surface of the steel sheet were determined by an electron backscatter diffraction (EBSD) method for a cross section of the same sample used for the microstructure observation, the cross section being in the thickness direction and perpendicular to the rolling direction. The range of each of Φ1, Φ2, and Φ was set to 0 to 90, the resolution of each was set to 5, and the orientation distribution function (ODF) was calculated to determine the maximum orientation density of grains in the field of view. This was performed at five points in each of the region extending from the position of 5 μm to the position of 10 pm from the surface and the region extending from the position of 50pm to the position of 100 pm from the surface of the steel sheet. The individual averages thereof were used as the maximum orientation densities of grains in respective 5- to 10-μm surface layer region and 50- to 100-pm surface layer region. With respect to the five points in the region extending from the position of 5 μm to the position of 10 pm from the surface of the steel sheet, five measurement regions each measuring 5 μm in the thickness direction $\times$ 1,000 pm in the width direction were used, a position 7.5 pm from the surface of the steel sheet in the thickness direction being centered, and the centers of the measurement regions in the width direction being spaced at 1,000 μm. With respect to the five points in the region extending from the position of 50 μm to the position of 100 pm from the surface of the steel sheet, five measurement regions each measuring 5 μm in the thickness direction × 1,000 pm in the width direction were used, a position 75 pm from the surface of the steel sheet in the thickness direction being centered, and the centers of the measurement regions in the thickness direction being spaced at 10 pm (in other words, the centers of the measurement regions being located at positions 55 pm, 65 pm, 75 pm, 85 pm, and 95 pm from the surface of the steel sheet). The EBSD measurement was performed at an accelerating voltage of 30 kV and a step size of 0.05 μm.

Tensile Test

[0057] JIS No. 5 test pieces for a tensile test (JIS Z 2201) were sampled from the resulting hot-rolled steel sheets in a direction parallel to the rolling direction. The tensile test was performed in accordance with JIS Z 2241 at a strain rate of 10^{-3}/s to determine TS and YS (0.2% proof stress). In the present invention, a TS of 980 MPa or more and a YS of 800 MPa or more were regarded as acceptable.

Bend Test (Bending Wrinkle Resistance)

[0058] Test pieces having widths of 30 mm and lengths of 100 mm were sampled from the resulting hot-rolled steel sheets and subjected to bending with a 90° V-bending punch. The presence or absence of cracking and wrinkling on the outer surfaces of the bends was checked visually or using a magnifier. The minimum bending radius R at which no cracking or wrinkling was observed in three test pieces (N = 3) was determined and divided by the thickness t of the sheet to calculate R/t. Table 3 presents "wrinkling R/t", which is a value obtained by dividing the minimum bending radius R at which wrinkling is not observed by the thickness t, and "cracking R/t", which is a value obtained by dividing the minimum bending radius R at which cracking is not observed by the thickness t. In the present invention, an R/t of 3.0 or less was acceptable (when "wrinkling R/t" and "cracking R/t" presented in Table 3 were both 3.0 or less, the sample was evaluated as acceptable). Note that cracking from the end surface was excluded from the determination.

[Table 1]

Steel	Chemical composition (mass%)							Remarks
	C	Si	Mn	P	S	Al	Others	
A	0.02	0.10	3.3	0.014	0.0022	0.034	-	Acceptable steel
B	0.22	0.50	2.5	0.003	0.0007	0.031	Cr: 0.30	Acceptable steel
C	0.07	1.00	1.6	0.015	0.0025	0.025	Mo: 0.30, B: 0.0020	Acceptable steel
D	0.11	0.30	2.0	0.022	0.0012	0.041	V: 0.20	Acceptable steel
E	0.09	0.60	2.4	0.009	0.0028	0.017	Cu: 0.20, Ca: 0.0020, Sn: 0.050	Acceptable steel
F	0.14	0.80	2.5	0.018	0.0015	0.044	Nb: 0.030, REM: 0.0010, Sb: 0.020	Acceptable steel
G	0.19	1.50	0.7	0.006	0.0004	0.068	Ni: 0.70, Ti: 0.080, B: 0.0020	Acceptable steel
H	0.01	0.50	1.5	0.012	0.0018	0.031	Cr: 0.30	Comparative steel
I	0.25	0.50	1.5	0.010	0.0013	0.035	Ti: 0.050, B: 0.0010	Comparative steel
J	0.10	3.10	1.8	0.018	0.0009	0.025	Nb: 0.020, Ni: 0.50	Comparative steel
K	0.10	0.05	1.8	0.015	0.0012	0.043	Ni: 0.40, Cu: 0.30, B: 0.0035	Comparative steel
L	0.10	0.50	0.4	0.014	0.0022	0.038	Cr: 0.30, Mo: 0.30	Comparative steel
M	0.10	0.50	3.7	0.008	0.0013	0.030	-	Comparative steel
* Underlined portions indicate that the values are outside the scope of the present invention.								

[Table 2]

Steel sheet No.	Steel	Finish rolling				Natural cooling time after finish rolling (s)	Average cooling rate from start of cooling to 550°C (°C/s)	Average cooling rate from 300 °C to 400°C (°C/s)	Coiling temperature (°C)	Remarks
		Total rolling reduction at 1 ,000°C or lower (%)	Total number of passes at 1 ,000°C or lower	Total rolling reduction from final pass rolling temperature to final pass rolling temperature + 50°C (%)	Final pass rolling temperature (°C)					
1	A	70	4	28	850	1.0	200	200	25	Inventive example
2		45	4	28	850	1.0	200	200	25	Comparative example
3	B	50	3	34	880	1.5	60	120	290	Inventive example
4		50	2	34	880	1.5	60	120	290	Comparative example
5	C	70	4	13	820	1.0	100	500	150	Inventive example
6		70	4	13	720	1.0	100	500	150	Comparative example
7		70	4	27	920	1.0	100	500	150	Comparative example
8	D	70	4	12	780	0.5	150	200	200	Inventive example
9		70	4	12	780	0.5	30	200	200	Comparative example
10	E	70	5	31	850	0.2	80	200	200	Inventive example
11		70	5	31	850	2.2	80	200	200	Comparative example

(continued)

Steel sheet No.	Steel	Finish rolling				Natural cooling time after finish rolling (s)	Average cooling rate from start of cooling to 550°C (°C/s)	Average cooling rate from 300 °C to 400°C (°C/s)	Coiling temperature (°C)	Remarks
		Total rolling reduction at 1,000°C or lower (%)	Total number of passes at 1,000°C or lower	Total rolling reduction from final pass rolling temperature to final pass rolling temperature + 50°C (%)	Final pass rolling temperature (°C)					
12	F	85	5	28	890	1.8	80	200	250	Inventive example
13	F	85	5	28	890	1.8	80	80	250	Comparative example
14	G	70	4	27	900	0.8	80	400	250	Inventive example
15	G	70	4	27	900	0.8	80	<1	350	Comparative example
16	H	70	4	28	760	1.5	200	200	200	Comparative example
17	I	70	4	21	880	1.5	150	200	200	Comparative example
18	J	70	4	13	850	1.5	60	200	200	Comparative example
19	K	70	4	13	850	1.5	80	200	200	Comparative example
20	L	70	4	12	850	1.5	80	200	200	Comparative example
21	M	70	4	18	850	1.5	80	200	200	Comparative example
22	A	70	4	37	850	1.0	200	200	25	Comparative example
23	B	70	4	45	850	1.5	60	120	290	Comparative example

* Underlined portions indicate that the values are outside the scope of the present invention.

[Table 3]

Steel sheet No.	Steel microstructure				Mechanical properties				Remarks
	V(M+B) (%)	V (O) (%)	Maximum orientation density of grains in 5- to 10-μm surface layer region	Maximum orientation density of grains in 50- to 100-μm surface layer region	TS (MPa)	YS (MPa)	Wrinkling R/t	Cracking R/t	
1	100	0	2.3	3.1	994	944	2.5	<2.5	Inventive example
2	100	0	2.6	2.4	989	930	3.2	<3.2	Comparative example
3	99	1	2.2	2.9	1536	1275	2.8	<2.8	Inventive example
4	98	2	2.5	2.7	1541	1248	3.3	<3.3	Comparative example
5	100	0	2.3	3.5	1183	1041	<1.5	1.5	Inventive example
6	35	65	2.4	3.9	726	472	<0.2	0.2	Comparative example
7	100	0	2.1	2.1	1215	1130	4.0	<4.0	Comparative example
8	90	10	2.4	4.6	1298	1064	<1.8	1.8	Inventive example
9	68	32	2.3	3.9	984	748	<0.5	0.5	Comparative example
10	98	2	2.0	2.8	1234	1123	2.7	2.7	Inventive example
11	99	1	1.9	2.4	1231	1108	3.2	<3.2	Comparative example
12	99	1	2.0	2.7	1383	1231	2.8	<2.8	Inventive example
13	98	2	2.0	2.4	1347	1212	3.5	3.5	Comparative example
14	98	2	2.2	2.6	1450	1189	2.8	2.8	Inventive example
15	95	5	2.3	2.3	1376	1101	3.7	<3.7	Comparative example
16	92	8	2.4	4.1	945	765	2.2	<2.2	Comparative example
17	98	2	2.7	3.0	1588	1334	3.3	3.3	Comparative example
18	64	36	2.2	2.9	956	660	<1.2	1.2	Comparative example

(continued)

Steel sheet No.	Steel microstructure				Mechanical properties				Remarks
	V(M +B) (%)	V (O) (%)	Maximum orientation density of grains in 5- to 10-μm surface layer region	Maximum orientation density of grains in 50- to 100-μm surface layer region	TS (MPa)	YS (MPa)	Wrinkling R/t	Cracking R/t	
19	100	0	2.2	2.8	1272	1145	3.2	<3.2	Comparative example
20	78	22	1.9	2.6	913	794	<0.5	0.5	Comparative example
21	99	1	2.8	3.3	1280	1152	4.0	<4.0	Comparative example
22	100	0	2.1	1.9	983	924	4.0	4.0	Comparative example
23	99	1	2.0	1.8	1516	1258	4.2	<4.2	Comparative example
* Underlined portions indicate that the values are outside the scope of the present invention.									

[0059] The high-strength steel sheets obtained in all inventive examples have excellent bending wrinkle resistance. In contrast, in comparative examples, which are outside the scope of the present invention, one or more of the desired strength and bending wrinkle resistance are not obtained. Industrial Applicability

[0060] According to the present invention, it is possible to provide a high-strength hot-rolled steel sheet having a TS of 980 MPa or more and a YS of 800 MPa or more and having excellent bending wrinkle resistance. When the high-strength steel sheet of the present invention is used for automotive parts, the steel sheet can greatly contribute to the improvements of the crash safety and fuel economy of automobiles.

Claims

1. A high-strength hot-rolled steel sheet having a chemical composition comprising, by mass%:

C: 0.02% to 0.23%,
Si: 0.10% to 3.00%,
Mn: 0.5% to 3.5%,
P: 0.100% or less,
S: 0.02% or less, and
Al: 1.50 or less, the balance being Fe and incidental impurities,
wherein a total area fraction of martensite and bainite is 80% to 100%, a maximum orientation density of grains is less than 2.5 in a region extending from a position of 5 pm to a position of 10 pm from a surface in a thickness direction, and the maximum orientation density of grains is 2.5 or more in a region extending from a position of 50 μm to a position of 100 pm from the surface in the thickness direction.

2. The high-strength hot-rolled steel sheet according to Claim 1, wherein the chemical composition further contains one or more selected from, by mass%:

Cr: 0.005% to 2.0%,
Mo: 0.05% to 2.0%,
V: 0.05% to 1.0%,
Cu: 0.05% to 4.0%,

Ni: 0.005% to 2.0%,
Ti: 0.005% to 0.20%,
Nb: 0.005% to 0.20%,
B: 0.0003% to 0.0050%,
Ca: 0.0001% to 0.0050%,
REM: 0.0001% to 0.0050%,
Sb: 0.0010% to 0.10%, and
Sn: 0.0010% to 0.50%.

3. A method for manufacturing a high-strength hot-rolled steel sheet, comprising:

heating a slab having the chemical composition according to Claim 1 or 2;
performing rough rolling;
then performing finish rolling under conditions in which a total rolling reduction in a temperature range of 1,000°C or lower is 50% or more, a total number of passes in a temperature range of 1,000°C or lower is 3 passes or more, a final pass rolling temperature is 750°C to 900°C, and a total rolling reduction from the final pass rolling temperature to the final pass rolling temperature + 50°C is 35% or less;
performing cooling under conditions in which a natural cooling time after completion of the finish rolling is 2.0 seconds or less, and an average cooling rate to a temperature of 550°C is 50 °C/s or more;
performing cooling at an average cooling rate of 100 °C/s or more in a temperature range of 300°C to 400°C; and
performing coiling at 300°C or lower.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2022/013739

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; ***C21D 8/02***(2006.01)i; ***C21D 9/46***(2006.01)i; ***C22C 38/06***(2006.01)i; ***C22C 38/60***(2006.01)i
FI: C22C38/00 301W; C21D8/02 A; C21D9/46 T; C22C38/06; C22C38/60

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C38/00-38/60; C21D8/02; C21D9/46

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2022
Registered utility model specifications of Japan 1996-2022
Published registered utility model applications of Japan 1994-2022

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2020/110843 A1 (NIPPON STEEL CORP.) 04 June 2020 (2020-06-04)	1-3
A	JP 2009-132988 A (NIPPON STEEL CORP.) 18 June 2009 (2009-06-18)	1-3
A	WO 2019/103121 A1 (NIPPON STEEL CORP.) 31 May 2019 (2019-05-31)	1-3
A	WO 2019/031583 A1 (NIPPON STEEL & SUMITOMO METAL CORP.) 14 February 2019 (2019-02-14)	1-3
A	JP 2015-160986 A (JFE STEEL CORP.) 07 September 2015 (2015-09-07)	1-3

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 May 2022	**07 June 2022**

Name and mailing address of the ISA/JP	Authorized officer
Japan Patent Office (ISA/JP) **3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915** **Japan**	Telephone No.

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2022/013739

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Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

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- WO 2016129213 A **[0004]**
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