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(71) Applicant: **JFE Steel Corporation**
Tokyo 100-0011 (JP)

(72) Inventors:
- **KAWASAKI, Yoshiyasu**
  Tokyo 100-0011 (JP)
- **MATSUDA, Hiroshi**
  Tokyo 100-0011 (JP)
- **YOKOTA, Takeshi**
  Tokyo 100-0011 (JP)
- **FUNAKAWA, Yoshimasa**
  Tokyo 100-0011 (JP)
- **SETO, Kazuhiro**
  Tokyo 100-0011 (JP)
- **MATSUBARA, Yukihiro**
  Tokyo 100-0011 (JP)

(74) Representative: **Ward, James Norman**
Haseltine Lake LLP
Bürkleinstrasse 10
80538 München (DE)

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

(57) Disclosed is a method comprising: preparing a steel slab with a predetermined chemical composition; subjecting the steel slab to hot rolling by heating it to a temperature of 1100-1300 °C, hot rolling it with a finisher delivery temperature of 800-1000 °C to form a hot-rolled steel sheet, and coiling the steel sheet at a mean coiling temperature of 200-500 °C; subjecting the steel sheet to pickling treatment; subjecting the steel sheet to annealing by retaining the steel sheet at a temperature of 740-840 °C for 10-900 s, and the cooling the steel sheet at a mean cooling rate of 5-30 °C/s to a cooling stop temperature of 150-350 °C; and subjecting the steel sheet to reheating treatment by reheating the steel sheet to a reheating temperature of higher than 350 °C and 550 °C or lower, and retaining the steel sheet at the reheating temperature for 10 s or more.

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Description

TECHNICAL FIELD

[0001] This disclosure relates to a high-strength steel sheet with excellent formability which is mainly suitable for automobile structural members and a method for manufacturing the same, and in particular, to provision of a high-strength steel sheet with high productivity that has a tensile strength (TS) of 780 MPa or more and that is excellent in ductility as well as in stretch flangeability and fatigue properties.

BACKGROUND

[0002] In order to secure passenger safety upon collision and to improve fuel efficiency by reducing the weight of automotive bodies, high-strength steel sheets reduced in thickness and having a tensile strength (TS) of 780 MPa or more have been increasingly applied to automobile structural members. Further, in recent years, examination has been made of applications of ultra-high-strength steel sheets with 980 MPa and 1180 MPa grade TS.

[0003] In general, however, strengthening of steel sheets leads to deterioration in formability. It is thus difficult to achieve both increased strength and excellent formability. Therefore, it is desirable to develop steel sheets with increased strength and excellent formability.

It is also desirable for steel sheets to have excellent fatigue properties since the travelable distance (total running distance) of automobiles depends on the fatigue strength of steel sheets applied to the automobile structural members.

[0004] To meet these demands, for example, JP2004218025A (PTL 1) describes "a high-strength steel sheet with excellent workability and shape fixability comprising: a chemical composition containing, in mass%, C: 0.06 % to 0.6 %, Si + Al: 0.5 % to 3 %, Mn: 0.5 % to 3 %, P: 0.15 % or less (exclusive of 0 %), and S: 0.02 % or less (inclusive of 0 %); and a structure that contains tempered martensite: 15 % or more by area to the entire structure, ferrite: 5 % to 60 % by area to the entire structure, and retained austenite: 5 % or more by volume to the entire structure, and that may contain bainite and/or martensite, wherein a ratio of the retained austenite transforming to martensite upon application of a 2 % strain is 20 % to 50 %.

[0005] JP2011195956A (PTL 2) describes "a high-strength thin steel sheet with excellent elongation and hole expansion formability, comprising: a chemical composition containing, in mass%, C : 0.05 % or more and 0.35 % or less, Si: 0.05 % or more and 2.0 % or less, Mn: 0.8 % or more and 3.0 % or less, P : 0.0010 % or more and 0.1 % or less, S : 0.0005 % or more and 0.05 % or less, N : 0.0010 % or more and 0.010 % or less, and Al: 0.01 % or more and 2.0 % or less, and the balance consisting of iron and incidental impurities; and a metallographic structure that includes a dominant phase of ferrite, bainite, or tempered martensite, and a retained austenite phase in an amount of 3 % or more and 30 % or less, wherein at a phase interface at which the austenite phase comes in contact with the ferrite phase, bainite phase, and martensite phase, a mean carbon concentration in the austenite phase is 0.6 % or more and 1.2 % or less, and austenite grains that satisfy Cgb/Cgc > 1.3 are present in the austenite phase in an amount of 50 % or more, where Cgc is a central carbon concentration and Cgb is a carbon concentration at grain boundaries of austenite grains.

[0006] JP201090475A (PTL 3) describes "a high-strength steel sheet comprising a chemical composition containing, in mass%, C : 0.17 % or more and 0.73 % or less, Si: 3.0 % or less, Mn: 0.5 % or more and 3.0 % or less, P: 0.1 % or less, S: 0.07 % or less, Al: 3.0 % or less, and N: 0.010 % or less, where Si + Al is 0.7 % or more, and the balance consisting of Fe and incidental impurities; and a structure that contains martensite: 10 % or more and 90 % or less by area to the entire steel sheet structure, retained austenite content: 5 % or more and 50 % or less, and bainitic ferrite in upper bainite: 5 % or more by area to the entire steel sheet structure, wherein the steel sheet satisfies conditions that 25 % or more of the martensite is tempered martensite, a total of the area ratio of the martensite to the entire steel sheet structure, the retained austenite content, and the area ratio of the bainitic ferrite in upper bainite to the entire steel sheet structure is 65 % or more, and an area ratio of polygonal ferrite to the entire steel sheet structure is 10 % or less (inclusive of 0 %), and wherein the steel sheet has a mean carbon concentration of 0.70 % or more in the retained austenite and has a tensile strength of 980 MPa or more.

[0007] JP2008174802A (PTL 4) describes "a high-strength cold-rolled steel sheet with a high yield ratio and having a tensile strength of 980 MPa or more, the steel sheet comprising, on average, a chemical composition that contains, by mass%, C : more than 0.06 % and 0.24 % or less, Si ≤ 0.3 %, Mn: 0.5 % to 2.0 %, P ≤ 0.06 %, S ≤ 0.005 %, Al ≤ 0.06 %, N ≤ 0.006 %, Mo: 0.05 % to 0.5 %, Ti: 0.03 % to 0.2 %, and V: more than 0.15 % and 1.2 % or less, and the balance consisting of Fe and incidental impurities, wherein the contents of C, Ti, Mo, and V satisfy $0.8 \leq (C/12)/\{(Ti/48) + (Mo/96) + (V/51)\} \leq 1.5$, and wherein an area ratio of ferrite phase is 95 % or more, and carbides containing Ti, Mo, and V with a mean grain size of less than 10 nm are diffused and precipitated, where Ti, Mo, and V contents represented by atomic percentage satisfy $V/(Ti + Mo + V) \geq 0.3$.

[0008] JP2010275627A (PTL 5) describes "a high-strength steel sheet with excellent workability comprising a chemical composition containing C : 0.05 mass% to 0.3 mass%, Si: 0.01 mass% to 2.5 mass%, Mn: 0.5 mass% to 3.5 mass%, P: 0.003 mass% to 0.100 mass%, S: 0.02 mass% or less, and Al: 0.010 mass% to 1.5 mass%, where a total of the Si and Al contents is 0.5 mass% to 3.0 mass%, and the balance consisting of Fe and incidental impurities; and a metallic structure that contains, by area, ferrite: 20 % or more, tempered martensite: 10 % to 60 %, and martensite: 0 % to 10 %, and that contains, by volume, retained austenite: 3 % to 10 %, where a ratio (m)/(f) of a Vickers hardness (m) of the tempered martensite to a Vickers hardness (f) of the ferrite is 3.0 or less.

[0009] JP4268079B (PTL 6) describes "an ultra-high-strength steel sheet exhibiting an excellent elongation in an ultra-high-strength range with a tensile strength of 1180 MPa or more, and having excellent hydrogen embrittlement resistance, the steel sheet comprising a chemical composition containing, in mass%, C : 0.06 % to 0.6 %, Si + Al: 0.5 % to 3 %, Mn: 0.5 % to 3 %, P : 0.15 % or less (exclusive of 0 %), S: 0.02 % or less (inclusive of 0 %), and the balance: Fe and incidental impurities; and a structure that contains tempered martensite: 15 % to 60 % by area to the entire structure, ferrite: 5 % to 50 % by area to the entire structure, retained austenite: 5 % or more by area to the entire structure, and massive martensite with an aspect ratio of 3 or less: 15 % to 45 %, where an area ratio of fine martensite having a mean grain size of 5 μm or less in the massive martensite is 30 % or more.

[0010] PTL 6 also describes a method for manufacturing the ultra-high-strength steel sheet comprising: heating and retaining a steel satisfying the aforementioned composition at a temperature from A_3 to 1100 °C for 10 s or more, and then cooling the steel at a mean cooling rate of 30 °C/s or higher to a temperature at or below Ms, and repeating this cycle at least twice; and heating and retaining the steel at a temperature from (A_3 - 25 °C) to A_3 for 120 s to 600 s, and then cooling the steel at a mean cooling rate of 3 °C/s or higher to a temperature at or above Ms and at or below Bs, at which the steel is retained for at least one second.

CITATION LIST

Patent Literature

[0011]

PTL 1: JP2004218025A
PTL 2: JP2011195956A
PTL 3: JP201090475A
PTL 4: JP2008174802A
PTL 5: JP2010275627A
PTL 6: JP4268079B

SUMMARY

(Technical Problem)

[0012] In fact, PTL 1 teaches the high-strength steel sheet has excellent workability and shape fixability, PTL 2 teaches the high-strength thin steel sheet has excellent elongation and hole expansion formability, PTL 3 teaches the high-strength steel sheet has excellent workability, in particular, excellent ductility and stretch flangeability. None of them however takes into account fatigue properties.

[0013] The high-strength cold-rolled steel sheet with a high yield ratio described in PTL 4 uses expensive elements, Mo and V, which results in increased costs and a low elongation (EL), which is as low as approximately 19 %.

[0014] The high-strength steel sheet described in PTL 5 exhibits, for example, TS of 980 MPa or more and TS x EL of approximately 24000 MPa·%, which remain, although may be relatively high when compared to general-use material, insufficient to meet the ongoing requirements for steel sheets.

[0015] The ultra-high tensile-strength steel sheet described in PTL 6 requires performing annealing treatment at least three times during its manufacture, resulting in low productivity in actual facilities.

[0016] It could thus be helpful to provide a method that can manufacture a high-strength steel sheet with high productivity that has a tensile strength (TS) of 780 MPa or more and that is excellent not only in ductility but also in stretch flangeability and fatigue properties, by performing a single annealing treatment at a ferrite-austenite dual phase region to form a fine structure that contains appropriate amounts of ferrite, bainitic ferrite, and retained austenite, and performing reheating following the annealing treatment so that an appropriate amount of tempered martensite is present in the structure.
It could also be helpful to provide a high-strength steel sheet manufactured by the method.
As used herein, the term "high-strength steel sheet" is intended to include high-strength galvanized steel sheets having a galvanized surface.

[0017] A steel sheet obtained according to the disclosure has the following target properties:

- Tensile strength (TS)
  780 MPa or more
- Ductility
  TS 780 MPa grade: EL ≥ 34 %
  TS 980 MPa grade: EL ≥ 27 %
  TS 1180 MPa grade: EL ≥ 23 %
- Balance between strength and ductility
  TS x EL ≥ 27000 MPa·%
- Stretch flangeability
  TS 780 MPa grade: λ ≥ 40 %
  TS 980 MPa grade: λ ≥ 30 %
  TS 1180 MPa grade: λ ≥ 20 %

$$\text{The maximum hole expansion ratio } \lambda\ (\%) = \{(D_f - D_0)/D_0\} \times 100,$$

where D_f is the hole diameter (mm) upon cracking and D_0 is the initial hole diameter (mm).

- Fatigue property
  fatigue limit strength ≥ 400 MPa, and fatigue ratio ≥ 0.40
  As used herein, the term "fatigue ratio" means a ratio of fatigue limit strength to tensile strength.

(Solution to Problem)

[0018] Upon carefully examining how to manufacture a steel sheet having TS of 780 MPa or more and excellent in ductility, stretch flangeability, and fatigue properties with high productivity, we discovered the following.

[0019]

(1) To obtain a steel sheet having a tensile strength (TS) of 780 MPa or more and excellent in ductility, stretch flangeability, and fatigue properties, it is important to prepare an appropriate chemical composition and to form a structure that contains appropriate amounts of ferrite, bainitic ferrite, and retained austenite, and in which fine retained austenite and fine bainitic ferrite are distributed.

(2) In addition, to form such a structure, it is important to provide the steel sheet with a structure prior to annealing treatment in which a single phase structure of martensite, a single phase structure of bainite, or a martensite-bainite mixed structure is dominantly present, while controlling annealing treatment conditions properly. In this respect, in order for the steel sheet to have such a pre-annealing structure without subjection to separate annealing treatment, it is important to perform appropriate slab reheating and optimize hot rolling conditions, in particular, to keep the mean coiling temperature (CT) following hot rolling low.

(3) Moreover, when cold rolling is performed after hot rolling, it is important to set a low rolling reduction such that the resulting structure of the hot-rolled steel sheet in which a single phase structure of martensite, a single phase structure of bainite, or a martensite-bainite mixed phase structure is dominantly present will remain intact as much as possible.

(4) Additionally, to improve stretch flangeability, it is important for the structure to contain an appropriate amount of tempered martensite and, to this end, it is of importance to keep the cooling stop temperature after annealing low and perform subsequent reheating treatment under proper conditions.

The disclosure is based on the aforementioned discoveries and further studies.

[0020] Specifically, the primary features of this disclosure are as described below.

1. A method for manufacturing a high-strength steel sheet, the method comprising: preparing a steel slab containing (consisting of), in mass%, C: 0.10 % or more and 0.35 % or less, Si: 0.50 % or more and 2.50 % or less, Mn: 2.00 % or more and less than 3.50 %, P: 0.001 % or more and 0.100 % or less, S: 0.0001 % or more and 0.0200 % or less, and N: 0.0005 % or more and 0.0100 % or less, and the balance consisting of Fe and incidental impurities; subjecting the steel slab to hot rolling by heating the steel slab to a temperature of 1100 °C or higher and 1300 °C or lower, hot rolling the steel slab with a finisher delivery temperature of 800 °C or higher and 1000 °C or lower to form a hot-rolled steel sheet, and coiling the hot-rolled steel sheet at a mean coiling temperature of 200 °C or higher and 500 °C or lower; subjecting the hot-rolled steel sheet to pickling treatment; subjecting the hot-rolled steel sheet to annealing by retaining the hot-rolled steel sheet at a temperature of 740 °C or higher and 840 °C or lower for 10

s or more and 900 s or less, and then cooling the hot-rolled steel sheet at a mean cooling rate of 5 °C/s or higher and 30 °C/s or lower to a cooling stop temperature of 150 °C or higher and 350 °C or lower; and subjecting the hot-rolled steel sheet to reheating treatment by reheating the hot-rolled steel sheet to a reheating temperature of higher than 350 °C and 550 °C or lower, and retaining the hot-rolled steel sheet at the reheating temperature for 10 s or more.

2. The method for manufacturing a high-strength steel sheet according to 1., the method further comprising prior to the annealing, cold rolling the hot-rolled steel sheet at a rolling reduction of less than 30 % to form a cold-rolled steel sheet, wherein in the annealing, the cold-rolled steel sheet is retained at a temperature of 740 °C or higher and 840 °C or lower for 10 s or more and 900 s or less, and cooled at a mean cooling rate of 5 °C/s or higher and 30 °C/s or lower to a cooling stop temperature of 150 °C or higher and 350 °C or lower, and in the reheating treatment, the cold-rolled steel sheet is reheated to a reheating temperature of higher than 350 °C and 550 °C or lower and retained at the reheating temperature for 10 s or more.

3. The method for manufacturing a high-strength steel sheet according to 1. or 2., the method further comprising after the reheating treatment, subjecting the hot-rolled steel sheet or the cold-rolled steel sheet to galvanizing treatment.

4. The method for manufacturing a high-strength steel sheet according to any of 1. to 3., wherein the steel slab further contains, in mass%, at least one element selected from the group consisting of Ti: 0.005 % or more and 0.100 % or less and B: 0.0001 % or more and 0.0050 % or less.

5. The method for manufacturing a high-strength steel sheet according to any of 1. to 4., wherein the steel slab further contains, in mass%, at least one element selected from the group consisting of Al: 0.01 % or more and 1.00 % or less, Nb: 0.005 % or more and 0.100 % or less, Cr: 0.05 % or more and 1.00 % or less, Cu: 0.05 % or more and 1.00 % or less, Sb: 0.002 % or more and 0.200 % or less, Sn: 0.002 % or more and 0.200 % or less, Ta: 0.001 % or more and 0.100 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0005 % or more and 0.0050 % or less.

6. A high-strength steel sheet comprising: a steel chemical composition containing (consisting of), in mass%, C: 0.10 % or more and 0.35 % or less, Si: 0.50 % or more and 2.50 % or less, Mn: 2.00 % or more and less than 3.50 %, P: 0.001 % or more and 0.100 % or less, S: 0.0001 % or more and 0.0200 % or less, and N: 0.0005 % or more and 0.0100 % or less, and the balance consisting of Fe and incidental impurities; and a steel structure that contains a total of 30 % or more and 75 % or less by area of ferrite and bainitic ferrite, 5 % or more and 15 % or less by area of tempered martensite, and 8 % or more by volume of retained austenite, wherein the retained austenite has a mean grain size of 2 μm or less and the bainitic ferrite has a mean free path of 3 μm or less.

7. The high-strength steel sheet according to 6., wherein the steel chemical composition further contains, in mass%, at least one element selected from the group consisting of Ti: 0.005 % or more and 0.100 % or less and B: 0.0001 % or more and 0.0050 % or less.

8. The high-strength steel sheet according to 6. or 7., wherein the steel chemical composition further contains, in mass%, at least one element selected from the group consisting of Al: 0.01 % or more and 1.00 % or less, Nb: 0.005 % or more and 0.100 % or less, Cr: 0.05 % or more and 1.00 % or less, Cu: 0.05 % or more and 1.00 % or less, Sb: 0.002 % or more and 0.200 % or less, Sn: 0.002 % or more and 0.200 % or less, Ta: 0.001 % or more and 0.100 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0005 % or more and 0.0050 % or less.

(Advantageous Effect)

[0021] According to the disclosure, it becomes possible to manufacture a high-strength steel sheet having a tensile strength (TS) of 780 MPa or more and excellent in ductility, stretch flangeability, and fatigue properties with high productivity.

Also, a high-strength steel sheet manufactured by the method according to the disclosure is highly beneficial in industrial terms, because it can improve fuel efficiency when applied to, e.g., automobile structural members by a reduction in the weight of automotive bodies.

DETAILED DESCRIPTION

[0022] The present invention will be specifically described below. According to the method disclosed herein, a steel slab with a predetermined chemical composition is heated and hot rolled. At this point, it is important to keep the mean coiling temperature (CT) during hot rolling low so that the hot-rolled steel sheet is provided with a structure in which a single phase structure of martensite, a single phase structure of bainite, or a martensite-bainite mixed structure is dominantly present.

It is also important when cold rolling is performed after hot rolling to set as low a rolling reduction as possible so that the resulting structure of the hot-rolled steel sheet will remain intact as much as possible.

[0023] In this way, a single phase structure of martensite, a single phase structure of bainite, or a martensite-bainite mixed structure is dominantly present in the structure of the steel sheet before subjection to annealing treatment. Consequently, even when annealing treatment is performed just once at a ferrite-austenite dual phase region, it becomes possible to form a structure that contains appropriate amounts of ferrite, bainitic ferrite, and retained austenite, and in which fine retained austenite and fine bainitic ferrite are distributed.
In addition, by causing the cooling stop temperature after annealing to drop to 350 °C or lower and performing reheating treatment under proper conditions, the structure may contain an appropriate amount of tempered martensite.
As a result, it becomes possible to manufacture a high-strength steel sheet having a tensile strength (TS) of 780 MPa or more and excellent in ductility, stretch flangeability, and fatigue properties with high productivity.
[0024] Firstly, the reasons for the limitations on the chemical composition of the steel manufactured according to our methods are described.
When components are expressed in "%," this refers to "mass%" unless otherwise specified.

C: 0.10 % or more and **0.35 %** or less

[0025] C is an element that is important for increasing the strength of steel, has a high solid solution strengthening ability, and is essential for guaranteeing the presence of a desired amount of retained austenite to improve ductility.
[0026] If the C content is below 0.10 %, it becomes difficult to obtain the required amount of retained austenite. If the C content exceeds 0.35 %, however, the steel sheet is made brittle or susceptible to delayed fracture.
[0027] Therefore, the C content is 0.10 % or more and 0.35 % or less, preferably 0.15 % or more and 0.30 % or less, and more preferably 0.18 % or more and 0.26 % or less.

Si: 0.50 % or more and 2.50 % or less

[0028] Si is an element that is effective in suppressing decomposition of retained austenite to carbides. Si also exhibits a high solid solution strengthening ability in ferrite, and has the property of purifying ferrite by facilitating solute C diffusion from ferrite to austenite to improve ductility. Moreover, Si dissolved in ferrite improves strain hardenability and increases the ductility of ferrite itself. To obtain this effect, the Si content needs to be 0.50 % or more. If the Si content exceeds 2.50 %, however, an abnormal structure grows, causing ductility to deteriorate.
[0029] Therefore, the Si content is 0.50 % or more and 2.50 % or less, preferably 0.80 % or more and 2.00 % or less, and more preferably 1.20 % or more and 1.80 % or less.

Mn: 2.00 % or more and less than 3.50 %

[0030] Mn is effective in guaranteeing strength. Mn also improves hardenability to facilitate formation of a multi-phase structure. Moreover, Mn acts to suppress formation of ferrite and pearlite during a cooling process after hot rolling, and thus is an effective element in causing the hot-rolled sheet to have a structure in which a low temperature transformation phase (bainite or martensite) is dominantly present. To obtain this effect, the Mn content needs to be 2.00 % or more. If the Mn content is 3.50 % or more, however, Mn segregation becomes significant in the sheet thickness direction, leading to deterioration of fatigue properties.
[0031] Therefore, the Mn content is 2.00 % or more and less than 3.50 %, preferably 2.00 % or more and 3.00 % or less, and more preferably 2.00 % or more and 2.80 % or less.

P: 0.001 % or more and 0.100 % or less

[0032] P is an element that has a solid solution strengthening effect and can be added depending on a desired strength. P also facilitates transformation to ferrite, and thus is an effective element in forming a multi-phase structure. To obtain this effect, the P content needs to be 0.001 % or more. If the P content exceeds 0.100 %, however, weldability degrades and, when a galvanized layer is subjected to alloying treatment, the alloying rate decreases, impairing galvanizing quality.
[0033] Therefore, the P content is 0.001 % or more and 0.100 % or less, and preferably 0.005 % or more and 0.050 % or less.

S: 0.0001 % or more and 0.0200 % or less

[0034] S segregates to grain boundaries, makes the steel brittle during hot working, and forms sulfides to reduce local deformability. Therefore, the S content needs to be 0.0200 % or less. Under manufacturing constraints, however, the S content is necessarily 0.0001 % or more.
[0035] Therefore, the S content is 0.0001 % or more and 0.0200% or less, and preferably 0.0001 % or more and

0.0050 % or less.

N: 0.0005 % or more and 0.0100 % or less

[0036] N is an element that deteriorates the anti-aging property of steel. Deterioration of the anti-aging property becomes more pronounced, particularly when the N content exceeds 0.0100 %. Under manufacturing constraints, the N content is necessarily 0.0005 % or more, although smaller N contents are more preferable.

[0037] Therefore, the N content is 0.0005 % or more and 0.0100 % or less, and preferably 0.0005 % or more and 0.0070 % or less.

[0038] In addition to the above basic components, at least one element selected from the group consisting of Ti and B may also be included. In particular, when the steel contains both Ti and B in appropriate amounts, the resulting hot-rolled sheet may be provided more advantageously with a structure in which a single phase structure of martensite, a single phase structure of bainite, or a martensite-bainite mixed structure is dominantly present.

Ti: 0.005 % or more and 0.100 % or less

[0039] Ti forms fine precipitates during hot rolling or annealing to increase strength. In addition, Ti precipitates as TiN with N, and may thus suppress precipitation of BN when B is added to the steel, thereby effectively bringing out the effect of B as described below. To obtain this effect, the Ti content needs to be 0.005 % or more. If the Ti content exceeds 0.100 %, however, strengthening by precipitation works excessively, leading to deterioration of ductility. Therefore, the Ti content is preferably 0.005 % or more and 0.100 % or less, and more preferably 0.010 % or more and 0.080 % or less.

B: 0.0001 % or more and 0.0050 % or less

[0040] B has the effect of suppressing ferrite-pearlite transformation during a cooling process after hot rolling so that the hot-rolled sheet has a structure in which a low temperature transformation phase (bainite or martensite), in particular martensite is dominantly present. B is also effective in increasing the strength of steel. To obtain this effect, the B content needs to be 0.0001 % or more. However, excessively adding B beyond 0.0050 % forms excessive martensite, raising a concern that ductility might decrease due to a rise in strength.

[0041] Therefore, the B content is preferably 0.0001 % or more and 0.0050 % or less, and more preferably 0.0005 % or more and 0.0030 % or less.

Mn content/B content: 2100 or less

[0042] In particular for a low-Mn chemical composition, ferrite-pearlite transformation develops during a cooling process after hot rolling, which tends to cause ferrite and/or pearlite to be present in the structure of the hot-rolled sheet. As such, to bring out the above-described addition effect of B sufficiently, it is preferred that the Mn content divided by the B content (Mn content/B content) equals 2100 or less, and more preferably 2000 or less. No lower limit is particularly placed on the Mn content/B content, yet a preferred lower limit is approximately 300.

[0043] In addition to the above components, at least one element selected from the group consisting of the following may also be included:

Al: 0.01 % or more and 1.00 % or less, Nb: 0.005 % or more and 0.100 % or less, Cr: 0.05 % or more and 1.00 % or less, Cu: 0.05 % or more and 1.00 % or less, Sb: 0.002 % or more and 0.200 % or less, Sn: 0.002 % or more and 0.200 % or less, Ta: 0.001 % or more and 0.100 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0005 % or more and 0.0050 % or less.

A1: 0.01 % or more and 1.00 % or less

[0044] Al is an element that is effective in forming ferrite and improving the balance between strength and ductility. To obtain this effect, the Al content needs to be 0.01 % or more. On the other hand, an A1 content exceeding 1.00 % leads to deterioration of surface characteristics.

[0045] Therefore, when Al is added to steel, the Al content is 0.01 % or more and 1.00 % or less, and preferably 0.03 % or more and 0.50 % or less.

Nb: 0.005 % or more and 0.100 % or less

[0046] Nb forms fine precipitates during hot rolling or annealing to increase strength. To obtain this effect, the Nb content needs to be 0.005 % or more. If the Nb content exceeds 0.100 %, however, formability deteriorates.

[0047] Therefore, when Nb is added to steel, the Nb content is 0.005 % or more and 0.100 % or less.

Cr: 0.05 % or more and 1.00 % or less, Cu: 0.05 % or more and 1.00 % or less

[0048] Cr and Cu not only serve as solid-solution-strengthening elements, but also act to stabilize austenite in a cooling process during annealing, facilitating formation of a multi-phase structure. To obtain this effect, the Cr and Cu contents each need to be 0.05 % or more. If the Cr and Cu contents both exceed 1.00 %, formability deteriorates.

[0049] Therefore, when Cr and Cu are added to steel, respective contents are 0.05 % or more and 1.00 % or less.

Sb: 0.002 % or more and 0.200 % or less, Sn: 0.002 % or more and 0.200 % or less

[0050] Sb and Sn may be added as necessary for suppressing decarbonization of a region extending from the surface layer of the steel sheet to a depth of about several tens of micrometers, which is caused by nitriding and/or oxidation of the steel sheet surface. Suppressing such nitriding or oxidation is effective in preventing a reduction in the amount of martensite formed in the steel sheet surface and guaranteeing strength. To obtain this effect, the Sb and Sn contents each need to be 0.002 % or more. However, excessively adding any of these elements beyond 0.200 % leads to deterioration of toughness. Therefore, when Sb and Sn are added to steel, respective contents are 0.002 % or more and 0.200 % or less.

Ta: 0.001 % or more and 0.100 % or less

[0051] As is the case with Ti and Nb, Ta forms alloy carbides or alloy carbonitrides, and contributes to increasing the strength of steel. It is also believed that Ta has the effect of significantly suppressing coarsening of precipitates when partially dissolved in Nb carbides or Nb carbonitrides to form complex precipitates, such as (Nb, Ta) (C, N), and providing a stable contribution to increasing strength through strengthening by precipitation. This precipitate-stabilizing effect can be obtained when the Ta content is 0.001 % or more. However, excessively adding Ta beyond 0.100 % fails to further increase the precipitate-stabilizing effect, but instead increases alloy costs. Therefore, when Ta is added to steel, the Ta content is 0.001 % or more and 0.100 % or less.

Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, REM: 0.0005 % or more and 0.0050 % or less

[0052] Ca, Mg, and REM are elements that are used for deoxidation, and are effective in causing spheroidization of sulfides and mitigating the adverse effect of sulfides on local ductility and stretch flangeability. To obtain this effect, Ca, Mg, and REM each need to be added to steel in an amount of 0.0005 % or more. However, excessively adding Ca, Mg, and REM beyond 0.0050 % leads to increased inclusions and the like, causing defects on the steel sheet surface and internal defects.

[0053] Therefore, when Ca, Mg, and REM are added to steel, respective contents are 0.0005 % or more and 0.0050 % or less.

[0054] The balance other than the above components consists of Fe and incidental impurities.

[0055] The following provides a description of manufacturing conditions in the method according to the disclosure.

The method for manufacturing a high-strength steel sheet according to the disclosure comprises: preparing a steel slab with the aforementioned chemical composition; subjecting the steel slab to hot rolling by heating the steel slab to a temperature of 1100 °C or higher and 1300 °C or lower, hot rolling the steel slab with a finisher delivery temperature of 800 °C or higher and 1000 °C or lower to form a hot-rolled steel sheet, and coiling the hot-rolled steel sheet at a mean coiling temperature of 200 °C or higher and 500 °C or lower; subjecting the hot-rolled steel sheet to pickling treatment; optionally cold rolling the hot-rolled steel sheet at a rolling reduction below 30 % to form a cold-rolled steel sheet; subjecting the hot-rolled or cold-rolled steel sheet to annealing by retaining the steel sheet at a temperature of 740 °C or higher and 840 °C or lower for 10 s or more and 900 s or less, and then cooling the steel sheet at a mean cooling rate of 5 °C/s or higher and 30 °C/s or lower to a cooling stop temperature of 150 °C or higher and 350 °C or lower; and subsequently subjecting the hot-rolled or cold-rolled steel sheet to reheating treatment by reheating the steel sheet to a reheating temperature of higher than 350 °C and 550 °C or lower, and retaining the steel sheet at the reheating temperature for 10 s or more.

In the above steps, the temperatures, such as the finisher delivery temperature, the mean coiling temperature, and the like, all represent temperatures measured at the steel sheet surface. The mean cooling rate is also calculated from temperatures measured at the steel sheet surface.

The following explains the reasons for the limitations placed on the manufacturing conditions.

Steel slab heating temperature: 1100 °C or higher and 1300 °C or lower

[0056] Precipitates that are present at the time of heating of a steel slab will remain as coarse precipitates in the resulting steel sheet, making no contribution to strength. Thus, remelting of any Ti- and Nb-based precipitates precipitated during casting is required.

[0057] In this respect, if a steel slab is heated at a temperature below 1100 °C, it is difficult to cause sufficient melting of carbides, leading to problems such as an increased risk of trouble during hot rolling resulting from increased rolling load. In addition, for obtaining a smooth steel sheet surface, it is necessary to scale-off defects on the surface layer of the slab, such as blow hole generation, segregation, and the like, and to reduce cracks and irregularities on the steel sheet surface. Therefore, the steel slab heating temperature needs to be 1100 °C or higher.

[0058] If the steel slab heating temperature exceeds 1300 °C, however, scale loss increases as oxidation progresses. Therefore, the steel slab heating temperature needs to be 1300 °C or lower.

[0059] For this reason, the steel slab heating temperature is 1100 °C or higher and 1300 °C or lower, and preferably 1150 °C or higher and 1250 °C or lower.

[0060] A steel slab is preferably made with continuous casting to prevent macro segregation, yet may be produced with other methods such as ingot casting or thin slab casting. The steel slab thus produced may be cooled to room temperature and then heated again according to the conventional method. Alternatively, there can be employed without problems what is called "energy-saving" processes, such as hot direct rolling or direct rolling in which either a warm steel slab without being fully cooled to room temperature is charged into a heating furnace, or a steel slab undergoes heat retaining for a short period and immediately hot rolled. Further, a steel slab is subjected to rough rolling under normal conditions and formed into a sheet bar. When the heating temperature is low, the sheet bar is preferably heated using a bar heater or the like prior to finish rolling from the viewpoint of preventing troubles during hot rolling.

Finisher delivery temperature in hot rolling: 800 °C or higher and 1000 °C or lower

[0061] The heated steel slab is hot rolled through rough rolling and finish rolling to form a hot-rolled steel sheet. At this point, when the finisher delivery temperature exceeds 1000 °C, the amount of oxides (scales) generated suddenly increases and the interface between the steel substrate and oxides becomes rough, which tends to impair the surface quality after pickling and cold rolling. In addition, any hot-rolling scales remaining after pickling adversely affect ductility. Further, grain size increases excessively and fatigue properties deteriorate.

[0062] On the other hand, if the finisher delivery temperature is below 800 °C, rolling load and burden increase, rolling is performed more often in a state in which recrystallization of austenite does not occur, and an abnormal texture develops. As a result, the final product has a significant planar anisotropy, and not only does the material properties become less uniform, but also the ductility itself deteriorate.

[0063] Therefore, the finisher delivery temperature in hot rolling needs to be 800 °C or higher and 1000 °C or lower, and preferably 820 °C or higher and 950 °C or lower.

Mean coiling temperature after hot rolling: 200 °C or higher and 500 °C or lower

[0064] Setting of mean coiling temperature after the hot rolling is very important for the method according to the disclosure.

[0065] Specifically, when the mean coiling temperature after the hot rolling is above 500 °C, ferrite and pearlite form during cooling and retaining processes after the hot rolling. Consequently, it becomes difficult to provide the hot-rolled sheet with a structure in which a single phase structure of martensite, a single phase structure of bainite, or a martensite-bainite mixed structure is dominantly present, making it difficult to impart a desired ductility to the steel sheet obtained after annealing or to balance its strength and ductility. If the mean coiling temperature after the hot rolling is below 200 °C, the hot-rolled steel sheet is degraded in terms of shape, deteriorating productivity. Therefore, the mean coiling temperature after the hot rolling needs to be 200 °C or higher and 500 °C or lower, preferably 300 °C or higher and 450 °C or lower, and more preferably 350 °C or higher and 450 °C or lower.

[0066] Finish rolling may be performed continuously by joining rough-rolled sheets during the hot rolling. Rough-rolled sheets may be coiled on a temporary basis. At least part of finish rolling may be conducted as lubrication rolling to reduce rolling load in hot rolling. Conducting lubrication rolling in such a manner is effective from the perspective of making the shape and material properties of a steel sheet uniform. In lubrication rolling, the coefficient of friction is preferably 0.10 or more and 0.25 or less.

[0067] The hot-rolled steel sheet thus produced is subjected to pickling. Pickling enables removal of oxides from the steel sheet surface, and is thus important to ensure that the high-strength steel sheet as the final product has good chemical convertibility and a sufficient quality of coating. Pickling may be performed in one or more batches.

Rolling reduction in cold rolling: less than 30 %

[0068] Additionally, the hot-rolled steel sheet may be subjected to cold rolling to form a cold-rolled steel sheet. When cold rolling is performed, rolling reduction in cold rolling is of great importance.

[0069] Specifically, if the rolling reduction is 30 % or more, a low temperature transformation phase is broken in the structure of the hot-rolled sheet. Consequently, it becomes difficult to provide the steel sheet obtained after the annealing with a structure that contains appropriate amounts of ferrite, bainitic ferrite, and retained austenite, and in which fine retained austenite and fine bainitic ferrite are distributed, making it difficult to ensure ductility, balance strength and ductility, or guarantee good fatigue properties. Therefore, the rolling reduction in cold rolling is less than 30 %, preferably 25 % or less, and more preferably 20 % or less. No lower limit is particularly placed on the rolling reduction in cold rolling. It may be greater than 0 %. The number of rolling passes and the rolling reduction per pass are not particularly limited, and the effect of the disclosure may be obtained with any number of rolling passes and any rolling reduction per pass.

Annealing temperature: 740 °C or higher and 840 °C or lower

[0070] An annealing temperature below 740 °C cannot ensure formation of a sufficient amount of austenite during the annealing. Consequently, a desired amount of retained austenite cannot be obtained in the end, making it difficult to yield good ductility and to balance strength and ductility. On the other hand, an annealing temperature above 840 °C is within a temperature range of austenite single phase, and a desired amount of fine retained austenite cannot be produced in the end, which makes it difficult again to ensure good ductility and to balance strength and ductility.

[0071] Therefore, the annealing temperature is 740 °C or higher and 840 °C or lower, and preferably 750 °C or higher and 830 °C or lower.

Annealing treatment holding time: 10 s or more and 900 s or less

[0072] A annealing treatment holding time shorter than 10 s cannot ensure formation of a sufficient amount of austenite during the annealing. Consequently, a desired amount of retained austenite cannot be obtained in the end, making it difficult to yield good ductility and to balance strength and ductility. On the other hand, an annealing treatment holding time longer than 900 s causes grain coarsening, a desired amount of fine retained austenite cannot be produced in the end, making it difficult to ensure good ductility and to balance strength and ductility. This also inhibits productivity.

[0073] Therefore, the annealing treatment holding time is 10 s or more and 900 s or less, preferably 30 s or more and 750 s or less, and more preferably 60 s or more and 600 s or less.

Mean cooling rate to a cooling stop temperature of 150 °C or higher and 350 °C or lower: 5 °C/s or higher and 30 °C/s or lower

[0074] If the mean cooling rate to a cooling stop temperature of 150 °C or higher and 350 °C or lower is below 5 °C/s, a large amount of ferrite is produced during cooling, making it difficult to guarantee a desired strength. On the other hand, if the mean cooling rate is above 30 °C/s, a low temperature transformation phase forms excessively, degrading ductility.

[0075] Therefore, the mean cooling rate to a cooling stop temperature of 150 °C or higher and 350 °C or lower is 5 °C/s or higher and 30 °C/s or lower, and preferably 10 °C/s or higher and 30 °C/s or lower.

[0076] The cooling in the annealing is preferably performed by gas cooling; however, furnace cooling, mist cooling, roll cooling, water cooling, and the like can also be employed in combination.

[0077] In addition, if the cooling stop temperature is above 350 °C, it is higher than the martensite transformation starting temperature (Ms), with the result that tempered martensite is not produced when reheating treatment is performed subsequently, hard and fresh martensite (martensite not tempered) remains in the resulting structure, and hole expansion formability (stretch flangeability) ends up deteriorating. On the other hand, if the cooling stop temperature is below 150 °C, austenite transforms to martensite in a large amount, and a desired amount of retained austenite cannot be obtained in the end, making it difficult to obtain good ductility and to balance strength and ductility.
Therefore, the cooling stop temperature is 150 °C or higher and 350 °C or lower, and preferably 180 °C or higher and 320 °C or lower.

Reheating temperature: higher than 350 °C and 550 °C or lower

[0078] If the reheating temperature is above 550 °C, decomposition of retained austenite occurs, and a desired amount of retained austenite cannot be obtained in the end, making it difficult to yield good ductility and balance strength and ductility. On the other hand, if the heating temperature is 350 °C or lower, a desired amount of tempered martensite cannot be obtained, making it difficult to ensure hole expansion formability (stretch flangeability).

[0079] Therefore, the reheating temperature is higher than 350 °C and 550 °C or lower, and preferably 370 °C or higher and 530 °C or lower.

Holding time at reheating temperature: 10 s or more

[0080] If the holding time at the reheating temperature is shorter than 10 s, there is insufficient time for the concentration of C (carbon) into austenite to progress, making it difficult to ensure a desired amount of retained austenite in the end. Therefore, the holding time at the reheating temperature is 10 s or more. However, a holding time longer than 600 s does not increase the amount of retained austenite and ductility does not significantly improve, where the effect reaches a plateau. Therefore, the holding time at the reheating temperature is preferably 600 s or less, more preferably 30 s or more and 500 s or less, and still more preferably 60 s or more and 400 s or less.

[0081] Cooling after the holding is not particularly limited, and any method may be used to implement cooling to a desired temperature.

[0082] The steel sheet thus obtained may be subjected to galvanizing treatment such as hot-dip galvanizing.

[0083] For example, when hot-dip galvanizing is performed, the above-described steel sheet subjected to the annealing treatment is immersed in a galvanizing bath at 440 °C or higher and 500 °C or lower for hot-dip galvanizing, after which coating weight adjustment is performed using gas wiping or the like. For hot-dip galvanizing, a galvanizing bath with an Al content of 0.10 % or more and 0.22 % or less is preferably used. When a galvanized layer is subjected to alloying treatment, the alloying treatment is performed in a temperature range of 470 °C to 600 °C after hot-dip galvanizing. If alloying treatment is performed at a temperature above 600 °C, untransformed austenite transforms to pearlite, where the presence of a desired volume fraction of retained austenite cannot be ensured and ductility may degrade. Therefore, when a galvanized layer is subjected to alloying treatment, the alloying treatment is preferably performed in a temperature range of 470 °C to 600 °C. Electrogalvanized plating may also be performed.

[0084] Moreover, when skin pass rolling is performed after the heat treatment, the skin pass rolling is preferably performed with a rolling reduction of 0.1 % or more and 1.0 % or less. A rolling reduction below 0.1 % provides only a small effect and complicates control, and hence 0.1 % is the lower limit of the favorable range. On the other hand, a rolling reduction above 1.0 % significantly degrades productivity, and thus 1.0 % is the upper limit of the favorable range.

[0085] The skin pass rolling may be performed on-line or off-line. Skin pass may be performed in one or more batches with a target rolling reduction. No particular limitations are placed on other manufacturing conditions, yet from the perspective of productivity, the aforementioned series of processes such as annealing, hot-dip galvanizing, and alloying treatment on a galvanized layer are preferably carried out on a CGL (Continuous Galvanizing Line) as the hot-dip galvanizing line. After the hot-dip galvanizing, wiping may be performed for adjusting the coating amounts.

[0086] The following describes the microstructure of a steel sheet manufactured by the method according to the disclosure.

Total area ratio of ferrite and bainitic ferrite: 30 % or more and 75 % or less

[0087] A high-strength steel sheet manufactured by the method according to the disclosure comprises a multi-phase structure in which retained austenite having an influence mainly on ductility and, more preferably, a small amount of martensite affecting strength are diffused in a structure in which soft ferrite with high ductility is dominantly present. In addition, bainitic ferrite forms adjacent to ferrite and retained austenite/martensite, and reduces the difference in hardness between ferrite and retained austenite and between ferrite and martensite to suppress the occurrence of cracking during hole expansion test and of fatigue cracking during fatigue test.

[0088] To ensure sufficient ductility, the total area ratio of ferrite and bainitic ferrite needs to be 30 % or more. On the other hand, to secure strength, the total area ratio of ferrite and bainitic ferrite needs to be 75 % or less. For better ductility, the total area ratio of ferrite and bainitic ferrite is preferably 35 % or more and 70 % or less.

[0089] Bainitic ferrite is effective in ensuring better hole expansion formability and better fatigue properties since, as described above, it forms adjacent to ferrite and retained austenite/martensite and has the effect of reducing the difference in hardness between ferrite and retained austenite and between ferrite and martensite to suppress the occurrence of cracking during hole expansion test and of fatigue cracking during fatigue test. Therefore, the area ratio of bainitic ferrite is preferably 5 % or more. On the other hand, to secure stable strength, the area ratio of bainitic ferrite is preferably 25 % or less.

[0090] As used herein, the term "bainitic ferrite" means such ferrite that is produced during the process of annealing at a temperature of 740 °C or higher and 840 °C or lower, followed by cooling to and holding at a temperature of 600 °C or lower, and that has a high dislocation density as compared to normal ferrite.

While the main example of ferrite is acicular ferrite, ferrite may include polygonal ferrite and non-recrystallized ferrite. To ensure good ductility, however, it is preferred that the area ratio of polygonal ferrite is 20 % or less and the area ratio of non-recrystallized ferrite is 5 % or less. The area ratios of polygonal ferrite and of non-recrystallized ferrite may be 0 %.

[0091] The area ratios of ferrite and bainitic ferrite can be determined by polishing a cross section of a steel sheet taken in the sheet thickness direction to be parallel to the rolling direction (L-cross section), etching the cross section with 3 vol.% nital, and averaging the results from observing ten locations at 2000 times magnification under an SEM (scanning electron microscope) at a position of sheet thickness x 1/4 (a position at a depth of one-fourth of the sheet thickness from the steel sheet surface) and calculating the area ratios of ferrite and bainitic ferrite for the ten locations with Image-Pro, available from Media Cybernetics, Inc., using the structure micrographs imaged with the SEM.

In the structure micrographs, ferrite and bainitic ferrite appear as a gray structure (base steel structure), while retained austenite and martensite as a white structure.

[0092] Identification of ferrite and bainitic ferrite is made by EBSD (Electron Back Scatter Diffraction) measurement. Specifically, a crystal grain (phase) that includes a sub-boundary with a grain boundary angle of smaller than 15° is identified as bainitic ferrite, for which the area ratio is calculated and used as the area ratio of bainitic ferrite. The area ratio of ferrite can be calculated by subtracting the area ratio of bainitic ferrite from the area ratio of the above-described gray structure.

Area ratio of tempered martensite: 5 % or more and 15 % or less

[0093] To ensure good hole expansion formability (stretch flangeability), the area ratio of tempered martensite needs to be 5 % or more. For better hole expansion formability (stretch flangeability), it is preferred that the area ratio of tempered martensite is 8 % or more. If the area ratio of tempered martensite exceeds 15 %, however, it becomes difficult to obtain a sufficient amount of retained austenite. This results in a difficulty in obtaining good ductility and balancing strength and ductility. Therefore, the area ratio of tempered martensite needs to be 15 % or less.

[0094] Here, tempered martensite can be identified by determining whether cementite or retained austenite is included in martensite (tempered martensite is martensite containing cementite or retained austenite). The area ratio of tempered martensite can be determined by polishing an L-cross section of a steel sheet, etching the cross section with 3 vol.% nital, and averaging the results from observing ten locations at 2000 times magnification under an SEM (scanning electron microscope) at a position of sheet thickness x 1/4 and calculating the area ratios of ferrite and bainitic ferrite for the ten locations with Image-Pro, available from Media Cybernetics, Inc., using the structure micrographs imaged with the SEM.

Volume fraction of retained austenite: 8 % or more

[0095] To ensure good ductility and balance strength and ductility, the volume fraction of retained austenite needs to be 8 % or more. For obtaining better ductility and achieving a better balance between strength and ductility, it is preferred that the volume fraction of retained austenite is 10 % or more. No upper limit is particularly placed on the volume fraction of retained austenite, yet it is around 35 %.

[0096] The volume fraction of retained austenite is calculated by determining the x-ray diffraction intensity of a plane of sheet thickness x 1/4, which is exposed by polishing the steel sheet surface to a depth of one-fourth of the sheet thickness. Using an incident x-ray beam of MoKα, the intensity ratio of the peak integrated intensity of the {111}, {200}, {220}, and {311} planes of retained austenite to the peak integrated intensity of the {110}, {200}, and {211} planes of ferrite is calculated for all of the twelve combinations, the results are averaged, and the average is used as the volume fraction of retained austenite.

Mean grain size of retained austenite: 2 μm or less

[0097] Refinement of retained austenite grains contributes to improving the ductility and fatigue properties of the steel sheet. Accordingly, to ensure good ductility and fatigue properties, retained austenite needs to have a mean grain size of 2 μm or less. For better ductility and fatigue properties, it is preferred that retained austenite has a mean grain size of 1.5 μm or less. No lower limit is particularly placed on the mean grain size, yet it is around 0.1 μm.

[0098] The mean grain size of retained austenite can be determined by averaging the results from observing twenty locations at 15000 times magnification under a TEM (transmission electron microscope) and averaging the equivalent circular diameters calculated from the areas of retained austenite grains identified with Image-Pro, as mentioned above, using the structure micrographs imaged with the TEM.

Mean free path of bainitic ferrite: 3 μm or less

[0099] The mean free path of bainitic ferrite is very important. Specifically, bainitic ferrite forms in the process of cooling to and holding at a temperature of 600 °C or lower following the annealing in a temperature range of 740 °C to 840 °C.

In this respect, bainitic ferrite forms adjacent to ferrite and retained austenite, and has the effect of reducing the difference in hardness between ferrite and retained austenite to suppress the occurrence of fatigue cracking and propagation of cracking. It is thus more advantageous if bainitic ferrite is densely distributed, in other words, if bainitic ferrite has a small mean free path.

[0100] To ensure good fatigue properties, bainitic ferrite needs to have a mean free path of 3 μm or less. For better fatigue properties, it is preferred that bainitic ferrite has a mean free path of 2.5 μm or less. No lower limit is particularly placed on the mean free path, yet it is around 0.5 μm.

[0101] The mean free path (L_{BF}) of bainitic ferrite can be calculated by:

$$L_{BF} = \frac{d_{BF}}{2}\left(\frac{4\pi}{3f}\right)^{\frac{1}{3}} - d_{BF}$$

L_{BF}: mean free path of bainitic ferrite (μm)
d_{BF}: mean grain size of bainitic ferrite (μm)
f: area ratio of bainitic ferrite (%) ÷ 100

[0102] The mean grain size of bainitic ferrite can be determined by averaging the areas of grains by dividing the area of bainitic ferrite in the measured region calculated by EBSD (Electron Back Scatter Diffraction) measurement by the number of bainitic ferrite grains in the measured region to identify an equivalent circle diameter.

[0103] In addition to ferrite and bainitic ferrite, tempered martensite, and retained austenite, the microstructures according to the disclosure may include carbides such as martensite, pearlite, cementite, and the like, as well as other microstructures well known as steel sheet microstructures. Any microstructure that has an area ratio of 15 % or less may be used without detracting from the effect of the disclosure.

EXAMPLES

[0104] Steels having the chemical compositions presented in Table 1, each with the balance consisting of Fe and incidental impurities, were prepared by steelmaking in a converter and formed into slabs by continuous casting. The steel slabs thus obtained were heated under the conditions presented in Table 2, and subjected to hot rolling, followed by pickling treatment. For Steel Nos. 1, 3-6, 8, 9, 12, 14, 16-19, 21, 24, 26, 29, 31, 33, 35, 37, 38, 40, 42, 43, 47, 50, 51, 53, 56, and 60 presented in Table 2, cold rolling was not performed, and annealing treatment was conducted under the conditions presented in Table 2 to produce high-strength hot-rolled steel sheets (HR). For Steel Nos. 2, 7, 10, 11, 13, 15, 20, 22, 23, 25, 27, 28, 30, 32, 34, 36, 39, 41, 44-46, 48, 49, 52, 54, 55, 57-59, and 61 presented in Table 2, cold rolling was performed, and annealing treatment was conducted under the conditions presented in Table 2 to produce high-strength cold-rolled steel sheets (CR). Moreover, some were subjected to galvanizing treatment to obtain hot-dip galvanized steel sheets (GI), galvannealed steel sheets (GA), and electrogalvanized steel sheets (EG).
Used as hot-dip galvanizing baths were a zinc bath containing 0.19 mass% of A1 for GI and a zinc bath containing 0.14 mass% of A1 for GA, in each case the bath temperature was 465 °C. The coating weight per side was 45 g/m^2 (in the case of both-sided coating), and the Fe concentration in the coated layer of each hot-dip galvannealed steel sheet (GA) was 9 mass% or more and 12 mass% or less.

[0105] The Ac_1 transformation temperature (°C) presented in Table 1 was calculated by:

$$Ac_1 \text{ transformation temperature (°C)} = 751 - 16 \times (\%C) + 11 \times (\%Si) - 28 \times (\%Mn) - 5.5 \times (\%Cu) + 13 \times (\%Cr)$$

[0106] Where (%X) represents content (in mass%) of an element X in steel.

Table 1

Table 1

Steel ID	Chemical composition (mass%)																		Ac_1 transformation temperature (°C)	Remarks
	C	Si	Mn	P	S	N	B	Ti	Al	Nb	Cr	Cu	Sb	Sn	Ta	Ca	Mg	REM		
A	0.112	1.62	2.38	0.021	0.0020	0.0032	-	-	-	-	-	-	-	-	-	-	-	-	700	Conforming steel
B	0.182	1.24	2.11	0.019	0.0019	0.0030	-	-	-	-	-	-	-	-	-	-	-	-	703	Conforming steel
C	0.211	1.28	2.14	0.014	0.0018	0.0032	-	-	-	-	-	-	-	-	-	-	-	-	705	Conforming steel
D	0.232	0.73	2.34	0.025	0.0022	0.0030	-	-	-	-	-	-	-	-	-	-	-	-	690	Conforming steel
E	0.224	1.02	2.13	0.029	0.0016	0.0032	-	-	-	-	-	-	-	-	-	-	-	-	702	Conforming steel
F	0.218	1.48	2.09	0.016	0.0024	0.0033	-	-	-	-	-	-	-	-	-	-	-	-	709	Conforming steel
G	0.228	1.55	2.16	0.018	0.0019	0.0034	-	-	-	-	-	-	-	-	-	-	-	-	704	Conforming steel
H	0.200	1.48	2.34	0.022	0.0021	0.0030	-	-	-	-	-	-	-	-	-	-	-	-	699	Conforming steel
I	0.182	1.39	2.86	0.028	0.0019	0.0029	-	-	-	-	-	-	-	-	-	-	-	-	683	Conforming steel
J	0.064	1.51	2.89	0.027	0.0018	0.0028	-	-	-	-	-	-	-	-	-	-	-	-	686	Comparative steel
K	0.232	0.24	2.78	0.023	0.0021	0.0030	-	-	-	-	-	-	-	-	-	-	-	-	672	Comparative steel
L	0.213	1.43	1.72	0.028	0.0028	0.0028	-	-	-	-	-	-	-	-	-	-	-	-	715	Comparative steel
M	0.202	1.34	2.22	0.018	0.0024	0.0034	-	-	0.380	-	-	-	-	-	-	-	-	-	700	Conforming steel
N	0.198	1.22	2.11	0.031	0.0022	0.0031	-	0.034	-	-	-	-	-	-	-	-	-	-	707	Conforming steel
O	0.188	1.24	2.25	0.016	0.0026	0.0032	-	-	-	0.041	-	-	-	-	-	-	-	-	709	Conforming steel
P	0.234	1.48	2.41	0.028	0.0018	0.0030	-	-	-	-	0.22	-	-	-	-	-	-	-	712	Conforming steel
Q	0.203	1.46	2.21	0.015	0.0024	0.0029	-	-	-	-	-	0.25	-	-	-	-	-	-	701	Conforming steel
R	0.221	1.49	2.18	0.024	0.0019	0.0033	-	-	-	-	-	-	0.0051	-	-	-	-	-	703	Conforming steel
S	0.187	1.56	2.34	0.019	0.0028	0.0034	-	-	-	-	-	-	-	0.0046	-	-	-	-	710	Conforming steel
T	0.189	1.45	2.03	0.024	0.0018	0.0029	-	-	-	-	-	-	-	-	0.0039	-	-	-	707	Conforming steel
U	0.199	1.32	2.09	0.025	0.0017	0.0044	-	-	-	0.041	-	-	0.0060	-	-	-	-	-	704	Conforming steel
V	0.202	1.38	2.12	0.018	0.0026	0.0036	-	-	-	0.020	-	-	-	0.0062	-	-	-	-	704	Conforming steel
W	0.211	1.46	2.28	0.028	0.0025	0.0042	-	-	-	0.034	-	-	-	-	0.0055	-	-	-	709	Conforming steel
X	0.213	1.24	2.42	0.019	0.0022	0.0044	-	-	-	-	-	-	-	-	-	0.0024	-	-	707	Conforming steel
Y	0.197	1.44	2.21	0.024	0.0019	0.0036	-	-	-	-	-	-	-	-	-	-	0.0016	-	702	Conforming steel
Z	0.198	1.63	2.09	0.020	0.0017	0.0032	-	-	-	-	-	-	-	-	-	-	-	0.0020	707	Conforming steel

Underlined if outside of the appropriate range.

Table 1 (cont'd)

Table 1 (cont'd)

Steel ID	Chemical composition (mass%)																		Ac$_1$ transformation temperature	Remarks
	C	Si	Mn	P	S	N	B	Ti	Al	Nb	Cr	Cu	Sb	Sn	Ta	Ca	Mg	REM	(°C)	
AA	0.178	1.42	2.30	0.012	0.0015	0.0033	0.0019	0.021	-	-	-	-	-	-	-	-	-	-	699	Conforming steel
AB	0.252	1.01	2.11	0.018	0.0022	0.0041	0.0012	0.018	-	-	-	-	-	-	-	-	-	-	699	Conforming steel
AC	0.181	1.49	2.61	0.019	0.0021	0.0032	0.0011	0.023	-	-	-	-	-	-	-	-	-	-	691	Conforming steel
AD	0.143	0.98	2.79	0.012	0.0016	0.0035	0.0026	0.032	-	-	-	-	-	-	-	-	-	-	681	Conforming steel
AE	0.112	1.39	2.33	0.021	0.0024	0.0039	0.0021	0.026	-	-	-	-	-	-	-	-	-	-	699	Conforming steel
AF	0.109	1.21	2.18	0.019	0.0021	0.0033	-	-	-	-	-	-	-	-	-	-	-	-	702	Conforming steel
AG	0.115	1.30	2.86	0.028	0.0019	0.0034	0.0030	0.018	-	-	-	-	-	-	-	-	-	-	683	Conforming steel
AH	0.113	0.89	2.12	0.015	0.0018	0.0030	-	-	-	-	-	-	-	-	-	-	-	-	700	Conforming steel
AI	0.126	0.97	2.83	0.024	0.0021	0.0029	0.0025	0.030	-	-	-	-	-	-	-	-	-	-	680	Conforming steel
AJ	0.121	2.30	2.89	0.019	0.0028	0.0028	-	-	-	-	-	-	-	-	-	-	-	-	693	Conforming steel
AK	0.308	1.22	2.10	0.024	0.0024	0.0030	0.0015	0.028	-	-	-	-	-	-	-	-	-	-	701	Conforming steel
AL	0.295	1.44	2.41	0.022	0.0022	0.0028	-	-	-	-	-	-	-	-	-	-	-	-	695	Conforming steel
AM	0.293	1.22	2.69	0.021	0.0026	0.0034	0.0035	0.015	-	-	-	-	-	-	-	-	-	-	684	Conforming steel
AN	0.131	1.33	2.38	0.022	0.0018	0.0037	0.0018	0.060	-	-	-	-	-	-	-	-	-	-	697	Conforming steel
AO	0.177	1.47	2.79	0.006	0.0024	0.0032	-	-	-	-	-	-	-	-	-	-	-	-	686	Conforming steel
AP	0.190	1.40	2.68	0.017	0.0007	0.0041	0.0020	0.025	-	-	-	-	-	-	-	-	-	-	688	Conforming steel
AQ	0.228	1.32	2.47	0.007	0.0006	0.0040	-	-	-	-	-	-	-	-	-	-	-	-	693	Conforming steel

Underlined if outside of the appropriate range.

[0107] Table 2

Table 2

No.	Steel ID	Slab heating temp. (°C)	Hot-rolling, conditions		Cold-rolling conditions	Annealing treatment conditions				Reheating treatment conditions		Type*	Remarks
			Finisher delivery temp. (°C)	Mean coiling temp. (°C)	Rolling reduction (%)	Annealing temp. (°C)	Annealing holding time (s)	Mean cooling rate (°C/s)	Cooling stop temp. (°C)	Reheating temp. (°C)	Reheating holding time (s)		
1	A	1250	910	400	cold rolling not performed	770	120	17	220	400	190	HR	Example
2	B	1260	890	440	13.0	790	150	20	190	500	340	GI	Example
3	C	1230	870	410	cold rolling not performed	780	140	22	200	420	210	HR	Example
4	C	890	900	400	cold rolling not performed	810	200	15	230	430	150	HR	Comparative example
5	C	1420	910	420	cold rolling not performed	800	240	16	200	450	130	HR	Comparative example
6	C	1220	640	380	cold rolling not performed	810	280	17	190	390	210	HR	Comparative example
7	C	1230	1120	490	6.0	800	180	17	220	400	290	CR	Comparative example
8	C	1240	910	120	cold rolling not performed	790	300	18	240	400	210	GI	Comparative example
9	C	1260	890	630	cold rolling not performed	790	250	22	250	420	230	HR	Comparative example
10	C	1230	900	420	46.2	820	200	17	280	500	240	CR	Comparative example

(continued)

No.	Steel ID	Slab heating temp. (°C)	Hot-rolling, conditions		Cold-rolling conditions	Annealing treatment conditions				Reheating treatment conditions		Type*	Remarks
			Finisher delivery temp. (°C)	Mean coiling temp. (°C)	Rolling reduction (%)	Annealing temp. (°C)	Annealing holding time (s)	Mean cooling rate (°C/s)	Cooling stop temp. (°C)	Reheating temp. (°C)	Reheating holding time (s)		
11	C	1230	920	450	13.0	<u>660</u>	280	15	240	480	180	EG	Comparative example
12	C	1220	860	470	cold rolling not performed	<u>900</u>	100	16	200	490	210	HR	Comparative example
13	C	1240	870	460	5.3	780	5	17	170	460	290	CR	Comparative example
14	C	1250	900	480	cold rolling not performed	790	<u>1200</u>	17	300	440	260	HR	Comparative example
15	C	1260	910	500	8.7	800	180	<u>72</u>	260	420	190	EG	Comparative example
16	C	1250	900	480	cold rolling not performed	810	220	17	70	400	160	GI	Comparative example
17	C	1230	860	460	cold rolling not performed	800	240	15	<u>550</u>	450	170	HR	Comparative example
18	C	1240	900	450	cold rolling not performed	810	180	14	220	<u>270</u>	150	HR	Comparative example
19	C	1200	870	420	cold rolling not performed	820	150	12	200	<u>620</u>	200	HR	Comparative example
20	C	1230	890	400	8.0	810	300	18	230	420	<u>5</u>	GA	Comparative example

(continued)

No.	Steel ID	Slab heating temp. (°C)	Hot-rolling conditions		Cold-rolling conditions	Annealing treatment conditions				Reheating treatment conditions		Type*	Remarks
			Finisher delivery temp. (°C)	Mean coiling temp. (°C)	Rolling reduction (%)	Annealing temp. (°C)	Annealing holding time (s)	Mean cooling rate (°C/s)	Cooling stop temp. (°C)	Reheating temp. (°C)	Reheating holding time (s)		
21	C	1240	880	450	cold rolling not performed	790	180	20	220	500	950	GI	Example
22	D	1220	890	460	11.1	770	180	24	200	480	480	CR	Example
23	E	1230	900	420	11.1	790	200	24	240	380	260	CR	Example
24	F	1240	910	480	cold rolling not performed	760	240	22	220	400	270	GA	Example
25	G	1230	880	500	6.3	790	190	20	190	460	190	CR	Example
26	H	1220	860	470	cold rolling not performed	760	150	22	200	450	170	EG	Example
27	I	1210	880	490	8.7	820	100	19	220	480	150	CR	Example
28	J	1200	860	500	8.0	760	180	22	240	430	190	CR	Comparative example
29	K	1230	890	470	cold rolling not performed	820	150	17	230	400	510	EG	Comparative example
30	L	1230	890	460	4.3	800	170	16	210	420	200	CR	Comparative example
31	M	1250	900	420	cold rolling not performed	820	200	18	200	480	450	GI	Example
32	N	1240	890	450	5.3	750	90	16	210	500	510	CR	Example

(continued)

No.	Steel ID	Slab heating temp. (°C)	Hot-rolling conditions		Cold-rolling conditions	Annealing treatment conditions				Reheating treatment conditions		Type*	Remarks
			Finisher delivery temp. (°C)	Mean coiling temp. (°C)	Rolling reduction (%)	Annealing temp. (°C)	Annealing holding time (s)	Mean cooling rate (°C/s)	Cooling stop temp. (°C)	Reheating temp. (°C)	Reheating holding time (s)		
33	O	1240	880	460	cold rolling not performed	780	120	27	220	450	180	HR	Example
34	P	1250	860	400	5.6	790	180	26	240	410	520	CR	Example
35	Q	1230	890	440	cold rolling not performed	800	80	17	190	400	400	EG	Example
36	R	1220	860	400	5.3	800	160	28	200	460	180	GA	Example
37	S	1230	910	380	cold rolling not performed	790	200	17	230	420	190	GI	Example
38	T	1220	880	410	cold rolling not performed	810	240	17	240	410	380	EG	Example
39	U	1230	880	400	5.3	790	160	16	200	400	540	GI	Example
40	V	1240	890	420	cold rolling not performed	800	280	15	190	450	250	HR	Example
41	W	1220	880	400	8.0	780	200	16	180	420	180	EG	Example
42	X	1230	910	350	cold rolling not performed	810	90	22	260	400	200	HR	Example
43	Y	1230	870	380	cold rolling not performed	770	150	20	240	460	180	GI	Example

(continued)

No.	Steel ID	Slab heating temp. (°C)	Hot-rolling conditions		Cold-rolling conditions	Annealing treatment conditions				Reheating treatment conditions		Type*	Remarks
			Finisher delivery temp. (°C)	Mean coiling temp. (°C)	Rolling reduction (%)	Annealing temp. (°C)	Annealing holding time (s)	Mean cooling rate (°C/s)	Cooling stop temp. (°C)	Reheating temp. (°C)	Reheating holding time (s)		
44	Z	1210	860	400	5.3	800	200	20	200	450	190	CR	Example
45	AA	1250	900	450	11.1	790	200	15	200	410	200	CR	Example
46	AB	1220	910	480	9.1	800	180	14	210	430	180	GA	Example
47	AC	1240	870	490	cold rolling not performed	780	250	13	180	410	200	HR	Example
48	AD	1230	880	480	10.0	810	200	16	230	400	150	GI	Example
49	AE	1250	900	400	11.1	820	250	14	200	410	220	CR	Example
50	AF	1240	880	440	cold rolling not performed	790	180	22	240	380	180	HR	Example
51	AG	1210	890	400	cold rolling not performed	800	200	18	220	400	150	HR	Example
52	AH	1200	900	380	12.5	820	200	22	210	460	200	GA	Example
53	AI	1230	910	410	cold rolling not performed	790	250	19	200	450	150	HR	Example
54	AJ	1230	880	400	13.3	830	230	21	200	450	190	EG	Example
55	AK	1240	880	420	6.3	790	160	17	220	390	510	CR	Example
56	AL	1220	890	400	cold rolling not performed	760	300	16	210	400	200	HR	Example
57	AM	1230	880	350	7.7	780	170	17	190	400	450	CR	Example

(continued)

No.	Steel ID	Slab heating temp. (°C)	Hot-rolling conditions		Cold-rolling conditions	Annealing treatment conditions				Reheating treatment conditions		Type*	Remarks
			Finisher delivery temp. (°C)	Mean coiling temp. (°C)	Rolling reduction (%)	Annealing temp. (°C)	Annealing holding time (s)	Mean cooling rate (°C/s)	Cooling stop temp. (°C)	Reheating temp. (°C)	Reheating holding time (s)		
58	AN	1230	910	420	6.7	800	250	16	270	420	510	CR	Example
59	AO	1210	860	380	6.7	820	90	26	190	500	190	CR	Example
60	AP	1230	880	400	cold rolling not performed	810	100	17	220	480	410	HR	Example
61	AQ	1250	900	420	6.7	810	200	18	210	400	350	GI	Example

Underlined if outside of the appropriate range.
* HR: Hot-rolled steel sheets (uncoated), CR: Cold-rolled steel sheets (uncoated),
GI: hot-dip galvanized steel sheets (alloying treatment not performed on galvanized layers), GA: galvannealed steel sheets, EG: electrogalvanized steel sheets

[0108] The high-strength hot-rolled steel sheets (HR), high-strength cold-rolled steel sheets (CR), hot-dip galvanizing steel sheets (GI), galvannealed steel sheets (GA), and electrogalvanized steel sheets (EG) thus obtained were subjected to structure observation, tensile test, hole expansion test, and fatigue test.
In this case, tensile test was performed in accordance with JIS Z 2241 (2011) to measure TS (tensile strength) and EL (total elongation), using JIS No. 5 test pieces that were sampled such that the longitudinal direction of each test piece coincides with a direction perpendicular to the rolling direction of the steel sheet (the C direction).
In this case, TS and EL were determined to be good when EL ≥ 34 % for TS 780 MPa grade, EL ≥ 27 % for TS 980 MPa grade, and EL ≥ 23 % for TS 1180 MPa grade, and TS x EL ≥ 27000 MPa·%.
[0109] Further, hole expansion test was performed in accordance with JIS Z 2256 (2010). Each of the steel sheets thus obtained was cut to a sample size of 100 mm x 100 mm, and a hole with a diameter of 10 mm was drilled through each sample with clearance 12 % ± 1 %. Subsequently, each steel sheet was clamped into a die having an inner diameter of 75 mm with a blank holding force of 8 tons (7.845 kN). In this state, a conical punch of 60° was pushed into the hole, and the hole diameter at the time of occurrence of cracking (hole diameter at crack initiation limit) was measured. Based on the hole diameter thus measured, the maximum hole expansion ratio λ (%) was calculated by the following equation to evaluate hole expansion formability:

$$\text{maximum hole expansion ratio } \lambda\ (\%) = \{(D_f - D_0)/D_0\} \times 100$$

[0110] Where D_f is a hole diameter at the time of occurrence of cracking (mm) and Do is an initial hole diameter (mm).
[0111] In this case, TS and EL were determined to be good when λ ≥ 40 % for TS 780 MPa grade, λ ≥ 30 % for TS 980 MPa grade, and λ ≥ 20 % TS 1180 MPa grade.
[0112] Moreover, in fatigue test, sampling was performed such that the longitudinal direction of each fatigue test piece coincides with a direction perpendicular to the rolling direction of the steel sheet, and plane bending fatigue test was conducted under the completely reversed (stress ratio: -1) condition and at the frequency of 20 Hz in accordance with JIS Z 2275 (1978). In the completely reversed plane bending fatigue test, the stress at which no fracture was observed after 10^7 cycles was measured and used as fatigue limit strength.
Fatigue limit strength was divided by tensile strength TS to calculate a fatigue ratio. In this case, the fatigue property was determined to be good when fatigue limit strength ≥ 400 MPa and fatigue ratio ≥ 0.40.
[0113] Additionally, during the manufacture of steel sheets, measurements were made of productivity, sheet passage ability during hot rolling and cold rolling, and surface characteristics of each steel sheet obtained after final annealing (hereinafter also referred to as a "final-annealed sheet").
In this case, productivity was evaluated according to the lead time costs, including:

(1) malformation of a hot-rolled steel sheet occurred;
(2) a hot-rolled steel sheet requires straightening before proceeding to the subsequent steps;
(3) a prolonged annealing treatment holding time; and
(4) a prolonged austemper holding time (a prolonged holding time in a reheating temperature range in annealing treatment).

The productivity was determined to be "high" when none of (1) to (4) applied, "middle" when only (4) applied, and "low" when any of (1) to (3) applied.
[0114] The sheet passage ability during hot rolling was determined to be low when the risk of trouble during rolling increased with increasing rolling load. Similarly, the sheet passage ability during cold rolling was determined to be low when the risk of trouble during rolling increased with increasing rolling load.
[0115] Furthermore, the surface characteristics of each final-annealed sheet were determined to be poor when defects such as blow hole generation and segregation on the surface layer of the slab could not be scaled-off, cracks and irregularities on the steel sheet surface increased, and a smooth steel sheet surface could not be obtained. The surface characteristics were also determined to be poor when the amount of oxides (scales) generated suddenly increased, the interface between the steel substrate and oxides was roughened, and the surface quality after pickling and cold rolling degraded, or when some hot-rolling scales remained after pickling.
Structure observation was performed following the above-described procedure.
The evaluation results are shown in Tables 3 and 4.
[0116] Table 3

Table 3

No.	Steel ID	Steel structure							Remarks
		Sheet thickness (mm)	Area ratio of F+BF (%)	Area ratio of TM (%)	Volume fraction of RA (%)	Mean grain size of RA (μM)	Mean free path of BF (μm)	Balance structure	
1	A	2.3	69.1	9.2	11.9	0.6	1.8	M+P+θ	Example
2	B	2.0	68.4	9.8	10.2	0.7	1.7	M-P+θ	Example
3	C	2.3	67.8	11.1	12.2	0.7	2.0	M-P+θ	Example
4	C	2.9	63.6	10.4	17.1	1.4	2.1	M+P+θ	Comparative example
5	C	2.5	62.2	11.1	16.8	1.3	2.4	M+P+θ	Comparative example
6	C	2.5	59.2	9.7	6.8	0.6	5.6	M+P+θ	Comparative example
7	C	2.3	65.7	10.6	12.5	2.9	2.2	M+P+θ	Comparative example
8	C	1.9	64.9	12.2	15.4	1.4	2.4	M+P+θ	Comparative example
9	C	1.4	70.6	8.9	3.8	0.5	2.5	M-P+θ	Comparative example
10	C	1.4	66.9	8.6	9.1	3.8	5.2	M+P+θ	Comparative example
11	C	2.0	64.2	1.2	5.7	3.0	2.6	M+P+θ	Comparative example
12	C	2.1	66.4	23.4	9.1	3.1	2.7	M+P+θ	Comparative example
13	C	1.8	67.6	5.6	6.7	3.4	2.4	M+P+θ	Comparative example
14	C	1.7	85.6	7.9	3.2	1.6	2.1	M+P+θ	Comparative example
15	C	2.1	54.8	26.0	11.0	1.7	2.2	M+P+θ	Comparative example
16	C	1.7	63.1	31.4	3.3	3.4	2.2	M+P+θ	Comparative example
17	C	2.3	64.6	0.6	2.9	0.5	2.3	M-P+θ	Comparative example
18	C	1.8	46.9	37.8	2.4	0.6	1.8	M-P+θ	Comparative example
19	C	2.1	48.2	10.6	4.2	0.7	2.2	M-P+θ	Comparative example
20	C	2.3	63.7	3.1	3.5	0.6	2.4	M-P+θ	Comparative example
21	C	1.9	66.6	9.6	14.4	0.8	2.5	M+P+θ	Example
22	D	1.6	59.9	12.1	14.5	1.1	1.9	M-P+θ	Example

(continued)

No.	Steel ID	Sheet thickness (mm)	Steel structure						Remarks
			Area ratio of F+BF (%)	Area ratio of TM (%)	Volume fraction of RA (%)	Mean grain size of RA (µM)	Mean free path of BF (µm)	Balance structure	
23	E	1.6	66.6	11.6	11.4	1.2	1.8	M+P+θ	Example
24	F	1.9	67.4	10.8	10.9	0.9	1.7	M+P+θ	Example
25	G	1.5	68.4	9.2	11.4	0.7	1.9	M+P+θ	Example
26	H	1.8	66.5	8.4	12.8	0.9	1.5	M-P+θ	Example
27	I	2.1	58.2	12.8	15.6	0.8	2.0	M+P+θ	Example
28	J	2.3	83.3	5.5	2.1	0.3	2.3	M+P+θ	Comparative example
29	K	2.5	48.4	26.2	3.5	0.6	2.1	M+P+θ	Comparative example
30	L	2.2	81.7	0.5	4.6	0.7	2.4	M+P+θ	Comparative example
31	M	2.5	65.4	11.4	11.1	0.7	1.7	M+P+θ	Example
32	N	1.8	66.5	10.9	11.9	0.9	1.5	M+P+θ	Example
33	O	1.7	64.4	9.7	12.8	1.1	1.2	M+P+θ	Example
34	P	1.7	67.7	9.9	11.4	0.9	1.6	M+P+θ	Example
35	Q	2.4	64.5	10.6	11.4	1.0	1.1	M+P+θ	Example
36	R	1.8	68.2	11.2	9.1	0.7	1.8	M+P+θ	Example
37	S	2.7	71.7	8.9	9.6	0.6	2.0	M+P+θ	Example
38	T	2.5	69.7	9.7	10.1	0.5	1.2	M+P+θ	Example
39	U	1.8	67.6	10.4	11.4	0.7	1.5	M+P+θ	Example
40	V	2.5	65.4	10.1	12.5	0.5	1.8	M+P+θ	Example
41	W	2.3	63.0	11.8	13.6	0.6	1.1	M+P+θ	Example
42	X	1.9	68.4	9.4	11.6	0.7	0.9	M+P+θ	Example
43	Y	2.5	66.1	10.6	12.8	0.9	1.5	M+P+θ	Example
44	Z	1.8	67.4	9.7	12.5	0.9	1.6	M+P+θ	Example
45	AA	1.6	68.3	11.2	11.1	0.8	1.6	M+P+θ	Example
46	AB	2.0	66.9	12.4	13.2	0.9	1.7	M+P+θ	Example
47	AC	2.2	65.1	12.9	14.8	1.1	2.1	M+P+θ	Example
48	AD	1.8	66.2	10.8	12.1	0.7	1.9	M+P+θ	Example
49	AE	1.6	68.9	9.2	10.9	0.6	1.6	M+P+θ	Example
50	AF	2.0	69.2	12.1	12.5	1.3	2.2	M+P+θ	Example
51	AG	1.8	68.9	11.6	11.4	1.4	2.3	M+P+θ	Example
52	AH	1.4	69.1	10.8	10.9	1.0	1.8	M+P+θ	Example
53	AI	1.8	67.5	12.2	11.4	0.9	2.2	M+P+θ	Example
54	AJ	1.3	66.6	11.4	13.8	0.7	2.4	M+P+θ	Example

(continued)

No.	Steel ID	Sheet thickness (mm)	Steel structure						Remarks
			Area ratio of F+BF (%)	Area ratio of TM (%)	Volume fraction of RA (%)	Mean grain size of RA (μM)	Mean free path of BF (μm)	Balance structure	
55	AK	1.5	62.9	12.8	15.6	0.7	2.5	M+P+θ	Example
56	AL	2.0	61.9	11.9	22.5	0.9	1.9	M+P+θ	Example
57	AM	1.2	56.7	10.8	23.5	0.9	1.8	M+P+θ	Example
58	AN	1.4	64.1	9.2	18.3	0.7	1.7	M+P+θ	Example
59	AO	1.4	61.3	11.6	21.3	0.8	1.9	M+P+θ	Example
60	AP	1.8	59.9	10.7	22.1	1.0	1.9	M+P+θ	Example
61	AQ	1.4	57.7	10.4	24.9	1.1	1.8	M+P+θ	Example

Underlined if outside of the appropriate range.
F: ferrite, BF: bainitic ferrite, RA: retained austenite, M: martensite,
TM: tempered martensite, P: pearlite, θ: cementite

[0117] Table 4

Table 4

No.	Tensile test results			Hole expansion test results	Fatigue test results		Productivity	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Remarks
	TS (MPa)	EL (%)	TS x EL (MPa·%)	λ (%)	Fatigue limit strength (MPa)	Fatigue ratio					
1	794	40.1	31839	68	450	0.57	High	High	-	Good	Example
2	910	37.1	33761	52	460	0.51	High	High	High	Good	Example
3	1008	33.5	33768	42	470	0.47	High	High	-	Good	Example
4	1028	27.8	28578	35	410	0.40	Low	Low	-	Fairly poor	Comparative example
5	1034	27.2	28125	33	410	0.40	Low	Low	-	Fairly poor	Comparative example
6	1235	12.4	15314	26	500	0.40	Low	Low	-	Fairly poor	Comparative example
7	1012	18.9	19127	34	410	0.41	Low	High	Low	Poor	Comparative example
8	942	28.1	26470	42	400	0.42	Low	High	-	Good	Comparative example
9	679	34.1	23154	50	280	0.41	High	High	-	Good	Comparative example
10	1044	15.8	16495	26	290	0.28	High	High	High	Good	Comparative example
11	1189	16.2	19262	16	480	0.40	High	High	High	Good	Comparative example
12	1022	18.4	18805	38	410	0.40	Low	High	-	Good	Comparative example
13	1279	14.8	18929	24	520	0.41	High	High	High	Good	Comparative example

(continued)

No.	Tensile test results			Hole expansion test results	Fatigue test results		Productivity	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Remarks
	TS (MPa)	EL (%)	TS x EL (MPa·%)	λ (%)	Fatigue limit strength (MPa)	Fatigue ratio					
14	682	26.9	18346	45	290	0.43	Low	High	-	Good	Comparative example
15	1289	8.9	11472	24	510	0.40	High	High	High	Good	Comparative example
16	802	20.5	16441	52	340	0.42	High	High	-	Good	Comparative example
17	1030	27.6	28428	24	480	0.47	High	High	-	Good	Comparative example
18	716	24.5	17542	53	300	0.42	High	High	-	Good	Comparative example
19	1199	14.7	17625	21	480	0.40	High	High	-	Good	Comparative example
20	1088	14.2	15450	14	490	0.45	High	High	High	Good	Comparative example
21	1011	28.9	29218	35	430	0.43	Middle	High	-	Good	Example
22	1122	30.1	33772	36	470	0.42	High	High	High	Good	Example
23	1000	33.4	33400	38	430	0.43	High	High	High	Good	Example
24	1041	30.8	32063	35	440	0.42	High	High	-	Good	Example
25	984	34.5	33948	41	420	0.43	High	High	High	Good	Example
26	1008	33.1	33365	37	440	0.44	High	High	-	Good	Example
27	1211	27.8	33666	27	510	0.42	High	High	High	Good	Example
28	678	25.8	17492	68	310	0.46	High	High	High	Good	Comparative example

(continued)

No.	Tensile test results			Hole expansion test results	Fatigue test results		Productivity	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Remarks
	TS (MPa)	EL (%)	TS x EL (MPa·%)	λ (%)	Fatigue limit strength (MPa)	Fatigue ratio					
29	1245	10.9	13571	14	520	0.42	High	High	-	Good	Comparative example
30	679	26.9	18265	40	320	0.47	High	High	High	Good	Comparative example
31	1056	30.1	31786	45	450	0.43	High	High	-	Good	Example
32	1047	29.8	31201	40	440	0.42	High	High	High	Good	Example
33	1070	28.4	30388	36	470	0.44	High	High	-	Good	Example
34	1004	32.9	33032	39	480	0.48	High	High	High	Good	Example
35	1007	32.4	32627	46	450	0.45	High	High	-	Good	Example
36	1004	33.9	34036	41	430	0.43	High	High	High	Good	Example
37	827	39.1	32336	51	410	0.50	High	High	-	Good	Example
38	908	35.5	32234	53	420	0.46	High	High	-	Good	Example
39	1001	33.6	33634	42	430	0.43	High	High	High	Good	Example
40	1033	32.0	33056	39	460	0.45	High	High	-	Good	Example
41	1107	28.9	31992	40	450	0.41	High	High	High	Good	Example
42	1002	33.7	33767	39	480	0.48	High	High	-	Good	Example
43	1039	32.6	33871	38	440	0.42	High	High	-	Good	Example
44	1026	32.8	33653	40	500	0.49	High	High	High	Good	Example
45	989	32.2	31846	56	450	0.46	High	High	High	Good	Example
46	1036	30.8	31909	62	460	0.44	High	High	High	Good	Example
47	1198	29.2	34982	48	510	0.43	High	High	-	Good	Example

(continued)

No.	Tensile test results			Hole expansion test results	Fatigue test results		Productivity	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Remarks
	TS (MPa)	EL (%)	TS x EL (MPa·%)	λ (%)	Fatigue limit strength (MPa)	Fatigue ratio					
48	996	32.1	31972	54	450	0.45	High	High	High	Good	Example
49	810	37.8	30618	61	440	0.54	High	High	High	Good	Example
50	822	34.1	28030	48	430	0.52	High	High	-	Good	Example
51	1014	27.9	28291	39	490	0.48	High	High	-	Good	Example
52	797	34.9	27815	45	400	0.50	High	High	High	Good	Example
53	1002	28.8	28858	38	470	0.47	High	High	-	Good	Example
54	1189	24.4	29012	31	520	0.44	High	High	High	Good	Example
55	1092	30.7	33524	37	490	0.45	High	High	High	Good	Example
56	1111	29.9	33219	33	520	0.47	High	High	-	Good	Example
57	1239	28.2	34940	28	560	0.45	High	High	High	Good	Example
58	985	30.6	30141	41	480	0.49	High	High	High	Good	Example
59	1134	28.7	32546	37	500	0.44	High	High	High	Good	Example
60	1122	28.2	31640	39	520	0.46	High	High	-	Good	Example
61	1086	31.9	34643	45	500	0.46	High	High	High	Good	Example

[0118] It can be seen that each of our examples has TS of 780 MPa or more, and the present disclosure enables manufacture of high-strength steel sheets with high productivity that are excellent not only in ductility but also in hole expansion formability (stretch flangeability) and fatigue properties. It can also be appreciated that each of our examples exhibits excellent sheet passage ability during hot rolling and cold rolling, as well as excellent surface characteristics of the final-annealed sheet.
In contrast, comparative examples are inferior in terms of one or more of tensile strength, ductility, balance between strength and ductility, hole expansion formability (stretch flangeability), fatigue properties, and productivity.

Claims

1. A method for manufacturing a high-strength steel sheet, the method comprising:

preparing a steel slab containing, in mass%, C: 0.10 % or more and 0.35 % or less, Si: 0.50 % or more and 2.50 % or less, Mn: 2.00 % or more and less than 3.50 %, P: 0.001 % or more and 0.100 % or less, S: 0.0001 % or more and 0.0200 % or less, and N: 0.0005 % or more and 0.0100 % or less, and the balance consisting of Fe and incidental impurities;
subjecting the steel slab to hot rolling by heating the steel slab to a temperature of 1100 °C or higher and 1300 °C or lower, hot rolling the steel slab with a finisher delivery temperature of 800 °C or higher and 1000 °C or lower to form a hot-rolled steel sheet, and coiling the hot-rolled steel sheet at a mean coiling temperature of 200 °C or higher and 500 °C or lower;
subjecting the hot-rolled steel sheet to pickling treatment;
subjecting the hot-rolled steel sheet to annealing by retaining the hot-rolled steel sheet at a temperature of 740 °C or higher and 840 °C or lower for 10 s or more and 900 s or less, and then cooling the hot-rolled steel sheet at a mean cooling rate of 5 °C/s or higher and 30 °C/s or lower to a cooling stop temperature of 150 °C or higher and 350 °C or lower; and
subjecting the hot-rolled steel sheet to reheating treatment by reheating the hot-rolled steel sheet to a reheating temperature of higher than 350 °C and 550 °C or lower, and retaining the hot-rolled steel sheet at the reheating temperature for 10 s or more.

2. The method for manufacturing a high-strength steel sheet according to claim 1, the method further comprising prior to the annealing, cold rolling the hot-rolled steel sheet at a rolling reduction of less than 30 % to form a cold-rolled steel sheet, wherein
in the annealing, the cold-rolled steel sheet is retained at a temperature of 740 °C or higher and 840 °C or lower for 10 s or more and 900 s or less, and cooled at a mean cooling rate of 5 °C/s or higher and 30 °C/s or lower to a cooling stop temperature of 150 °C or higher and 350 °C or lower, and
in the reheating treatment, the cold-rolled steel sheet is reheated to a reheating temperature of higher than 350 °C and 550 °C or lower and retained at the reheating temperature for 10 s or more.

3. The method for manufacturing a high-strength steel sheet according to claim 1 or 2, the method further comprising after the reheating treatment, subjecting the hot-rolled steel sheet or the cold-rolled steel sheet to galvanizing treatment.

4. The method for manufacturing a high-strength steel sheet according to any of claims 1 to 3, wherein the steel slab further contains, in mass%, at least one element selected from the group consisting of Ti: 0.005 % or more and 0.100 % or less and B: 0.0001 % or more and 0.0050 % or less.

5. The method for manufacturing a high-strength steel sheet according to any of claims 1 to 4, wherein the steel slab further contains, in mass%, at least one element selected from the group consisting of Al: 0.01 % or more and 1.00 % or less, Nb: 0.005 % or more and 0.100 % or less, Cr: 0.05 % or more and 1.00 % or less, Cu: 0.05 % or more and 1.00 % or less, Sb: 0.002 % or more and 0.200 % or less, Sn: 0.002 % or more and 0.200 % or less, Ta: 0.001 % or more and 0.100 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0005 % or more and 0.0050 % or less.

6. A high-strength steel sheet comprising:

a steel chemical composition containing, in mass%, C: 0.10 % or more and 0.35 % or less, Si: 0.50 % or more and 2.50 % or less, Mn: 2.00 % or more and less than 3.50 %, P: 0.001 % or more and 0.100 % or less, S:

0.0001 % or more and 0.0200 % or less, and N: 0.0005 % or more and 0.0100 % or less, and the balance consisting of Fe and incidental impurities; and
a steel structure that contains a total of 30 % or more and 75 % or less by area of ferrite and bainitic ferrite, 5 % or more and 15 % or less by area of tempered martensite, and 8 % or more by volume of retained austenite, wherein the retained austenite has a mean grain size of 2 μm or less and the bainitic ferrite has a mean free path of 3 μm or less.

7. The high-strength steel sheet according to claim 6, wherein the steel chemical composition further contains, in mass%, at least one element selected from the group consisting of Ti: 0.005 % or more and 0.100 % or less and B: 0.0001 % or more and 0.0050 % or less.

8. The high-strength steel sheet according to claim 6 or 7, wherein the steel chemical composition further contains, in mass%, at least one element selected from the group consisting of Al: 0.01 % or more and 1.00 % or less, Nb: 0.005 % or more and 0.100 % or less, Cr: 0.05 % or more and 1.00 % or less, Cu: 0.05 % or more and 1.00 % or less, Sb: 0.002 % or more and 0.200 % or less, Sn: 0.002 % or more and 0.200 % or less, Ta: 0.001 % or more and 0.100 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0005 % or more and 0.0050 % or less.

INTERNATIONAL SEARCH REPORT

International application No. PCT/JP2015/003947

A. CLASSIFICATION OF SUBJECT MATTER
C21D9/46(2006.01)i, *C21D8/02*(2006.01)i, *C22C38/04*(2006.01)i, *C22C38/60*(2006.01)i

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)
C21D9/46-9/48, C21D8/02-8/04, C22C38/00-38/60

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

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2015
Kokai Jitsuyo Shinan Koho	1971-2015	Toroku Jitsuyo Shinan Koho	1994-2015

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 2012/147898 A1 (JFE Steel Corp.), 01 November 2012 (01.11.2012), claims; paragraphs [0054], [0055], [0065]; tables 1 to 3 & EP 2703512 A1 claims; paragraphs [0045], [0046], [0065]; tables 1 to 3 & US 2014/0050941 A1 & JP 2012-237054 A & CN 103502496 A	1-8

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

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Name and mailing address of the ISA/
Japan Patent Office
3-4-3,Kasumigaseki,Chiyoda-ku,
Tokyo 100-8915,Japan

Authorized officer

Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2015/003947

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2013/005714 A1 (Nippon Steel & Sumitomo Metal Corp.), 10 January 2013 (10.01.2013), claims; tables 7 to 9 & EP 2730666 A1 claims; tables 7 to 9 & US 2014/0238557 A1 & JP 2013-32581 A & CN 103797135 A	1-8
A	JP 2011-214081 A (Sumitomo Metal Industries, Ltd.), 27 October 2011 (27.10.2011), claims; tables 1 to 4 (Family: none)	1-8
A	JP 2013-72101 A (JFE Steel Corp.), 22 April 2013 (22.04.2013), claims; paragraphs [0058], [0060], [0071]; tables 1 to 3 (Family: none)	1-8
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P,A	WO 2015/019557 A1 (JFE Steel Corp.), 12 February 2015 (12.02.2015), claims; paragraphs [0059], [0061], [0072]; tables 1 to 3 & JP 2015-34326 A	1-8

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REFERENCES CITED IN THE DESCRIPTION

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- *JIS Z 2275,* 1978 **[0112]**