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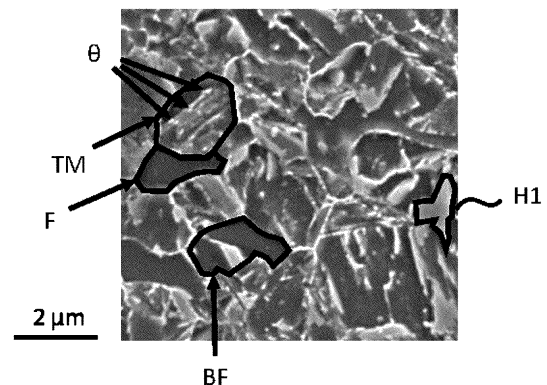
(54) **STEEL SHEET, MEMBER, AND METHOD FOR MANUFACTURING SAME**

(57) To provide a steel sheet and a member with a TS of 1180 MPa or more and high YS, high press formability (ductility, flangeability, and bendability), and fracture resistance characteristics (bending fracture characteristics and axial compression characteristics) at the time of compression, and a method for producing them.

A base steel sheet has a specified chemical composition and has a steel microstructure containing ferrite, bainitic ferrite, tempered martensite, retained austenite, and fresh martensite in predetermined ranges, a V-VDA bending test is performed to a maximum load point, in a V-bending ridge line portion and a VDA bending ridge line portion, the value obtained by dividing the number of voids at a boundary between a hard phase and a soft phase and the number of voids due to fracture of the hard phase among all voids by the total number of voids is 0.60 or less, in a V-bending flat portion and the VDA bending ridge line portion, the value obtained by dividing the number of voids at the boundary between the hard phase and the soft phase and the number of voids due to fracture of the hard phase among all voids by the total number of voids is 0.20 or less, and carbide has a mean

free path of 0.20 μm or more.

FIG. 1



Description

Technical Field

- 5 **[0001]** The present invention relates to a steel sheet, a member made of the steel sheet, and methods for producing them.

Background Art

- 10 **[0002]** In recent years, from the viewpoint of global environmental conservation, improvement of fuel efficiency in automobiles has been an important issue. Thus, there has been an active movement to reduce the weight of automobile bodies by increasing the strength and reducing the thickness of steel sheets used as materials for automotive body parts.

- [0003]** Furthermore, a social demand for improvement of crash safety of automobiles is further increased. Thus, there is a demand for the development of a steel sheet with high strength and enhanced crashworthiness when a vehicle collides while traveling (hereinafter referred to simply as crashworthiness).

- 15 **[0004]** For example, Patent Literature 1 discloses, as such a steel sheet serving as a material of automobile body parts, a high-strength steel sheet with high stretch flangeability and enhanced crashworthiness, which has a chemical composition containing, on a mass percent basis, C: 0.04% to 0.22%, Si: 1.0% or less, Mn: 3.0% or less, P: 0.05% or less, S: 0.01% or less, Al: 0.01% to 0.1%, and N: 0.001% to 0.005%, the remainder being Fe and incidental impurities, and
20 which is composed of a ferrite phase as a main phase and a martensite phase as a second phase, the martensite phase having a maximum grain size of 2 μm or less and an area fraction of 5% or more.

- [0005]** Patent Literature 2 discloses a high-strength hot-dip galvanized steel sheet with high coating adhesion and formability having a hot-dip galvanized layer on the surface of a cold-rolled steel sheet, which has a surface layer ground off with a thickness of 0.1 μm or more and is precoated with 0.2 g/m² or more and 2.0 g/m² or less of Ni, wherein the cold-rolled
25 steel sheet contains, on a mass percent basis, C: 0.05% or more and 0.4% or less, Si: 0.01% or more and 3.0% or less, Mn: 0.1% or more and 3.0% or less, P: 0.04% or less, S: 0.05% or less, N: 0.01% or less, Al: 0.01% or more and 2.0% or less, Si + Al > 0.5%, the remainder being Fe and incidental impurities, has a microstructure containing, on a volume fraction basis, 40% or more ferrite as a main phase, 8% or more retained austenite, two or more of three types of martensite [1], [2], and [3] as specified below including martensite [3], 1% or more bainite, and 0% to 10% pearlite, the three types of martensite [1],
30 [2], and [3] being, on a volume fraction basis, martensite [1]: 0% or more and 50% or less, martensite [2]: 0% or more and less than 20%, and martensite [3]: 1% or more and 30% or less, and having a hot-dip galvanized layer containing less than 7% Fe and the remainder composed of Zn, Al, and incidental impurities, on the surface of a steel sheet, and has TS x EL of 18000 MPa·% or more and TS x λ of 35000 MPa·% or more, wherein TS denotes tensile strength (MPa), EL denotes total elongation percentage (%), and λ denotes hole expansion ratio (%), and a tensile strength of 980 MPa or more (when martensite [1]:C concentration (CM1) is less than 0.8%, hardness Hv1 satisfies $Hv1/(-982.1 \times CM1^2 + 1676 \times CM1 + 189) \leq 0.60$, when martensite [2]:C concentration (CM2) is 0.8% or more, the hardness Hv2 satisfies $Hv2/(-982.1 \times CM2^2 + 1676 \times CM2 + 189) \leq 0.60$, and when martensite [3]:C concentration (CM3) is 0.8% or more, the hardness Hv3 satisfies $Hv3/(-982.1 \times CM3^2 + 1676 \times CM3 + 189) \geq 0.80$).

- [0006]** Patent Literature 3 discloses a high-strength hot-dip galvanized steel sheet that has a chemical composition composed of, on a mass percent basis, C: 0.15% or more and 0.25% or less, Si: 0.50% or more and 2.5% or less, Mn: 2.3% or more and 4.0% or less, P: 0.100% or less, S: 0.02% or less, and Al: 0.01% or more and 2.5% or less, the remainder being Fe and incidental impurities, and that has a steel sheet microstructure having, on an area fraction, a tempered martensite phase: 30% or more and 73% or less, a ferrite phase: 25% or more and 68% or less, a retained austenite phase: 2% or more and 20% or less, and other phases: 10% or less (including 0%), the other phases being a martensite phase: 3% or less
45 (including 0%) and bainitic ferrite phase: less than 5% (including 0%), the tempered martensite phase having an average grain size of 8 μm or less, the retained austenite phase having a C concentration of less than 0.7% by mass.

Citation List

- 50 Patent Literature

[0007]

- 55 PTL 1: Japanese Patent No. 3887235
PTL 2: Japanese Patent No. 5953693
PTL 3: Japanese Patent No. 6052472

Summary of Invention

Technical Problem

[0008] At present, however, only steel sheets with a tensile strength (hereinafter also referred to as TS) up to 590 MPa are used for impact energy absorbing members of automobiles exemplified by front side members and rear side members.

[0009] Thus, to increase absorbed energy at the time of impact (hereinafter also referred to as impact absorbed energy), it is effective to improve yield stress (hereinafter also referred to as YS). However, a steel sheet with higher TS and YS typically has lower press formability and, in particular, lower ductility, flangeability, bendability, and the like. Thus, when such a steel sheet with higher TS and YS is applied to the impact energy absorbing members of automobiles, not only press forming is difficult, but also the member cracks in an axial compression test simulating a collision test. In other words, the actual impact absorbed energy is not increased as expected from the value of YS. Thus, the impact energy absorbing members are currently limited to steel sheets with a TS of 590 MPa.

[0010] Actually, it also cannot be said that the steel sheets disclosed in Patent Literature 1 to Patent Literature 3 have a TS of 1180 MPa or more, high YS, high press formability (ductility, flangeability, and bendability), and fracture resistance characteristics (bending fracture characteristics and axial compression characteristics) at the time of compression.

[0011] The present invention has been developed in view of such circumstances and aims to provide a steel sheet with a tensile strength TS of 1180 MPa or more, high yield stress YS, high press formability (ductility, flangeability, and bendability), and fracture resistance characteristics (bending fracture characteristics and axial compression characteristics) at the time of compression, together with an advantageous method for producing the steel sheet.

[0012] The present invention also aims to provide a member made of the steel sheet and a method for producing the member.

[0013] The term "steel sheet", as used herein, includes a galvanized steel sheet, and the galvanized steel sheet is a hot-dip galvanized steel sheet (hereinafter also referred to as GI) or a hot-dip galvanized steel sheet (hereinafter also referred to as GA).

[0014] The tensile strength TS is measured in the tensile test according to JIS Z 2241 (2011).

[0015] The phrase "with high yield stress YS, high press formability (ductility, flangeability, and bendability), and fracture resistance characteristics (bending fracture characteristics and axial compression characteristics) at the time of compression" refers to satisfying the following.

[0016] The phrase "high yield stress YS" means that YS measured in the tensile test according to JIS Z 2241 (2011) satisfies the following formula (A) or (B) depending on TS measured in the tensile test.

(A) For $1180 \text{ MPa} \leq \text{TS} < 1320 \text{ MPa}$, $750 \text{ MPa} \leq \text{YS}$

(B) For $1320 \text{ MPa} \leq \text{TS}$, $850 \text{ MPa} \leq \text{YS}$

[0017] The phrase "high ductility" means that the total elongation (EI) measured in the tensile test according to JIS Z 2241 (2011) satisfies the following formula (A) or (B) depending on TS measured in the tensile test.

(A) For $1180 \text{ MPa} \leq \text{TS} < 1320 \text{ MPa}$, $12.0\% \leq \text{EI}$

(B) For $1320 \text{ MPa} \leq \text{TS}$, $10.0\% \leq \text{EI}$

[0018] The phrase "high flangeability" refers to a limiting hole expansion ratio (λ) of 30% or more as measured in the hole expansion test according to JIS Z 2256 (2020).

[0019] The phrase "high bendability" refers to a bending angle (α) of 80 degrees or more at the maximum load measured in a bending test according to the VDA standard (VDA 238-100) defined by German Association of the Automotive Industry.

[0020] The phrase "good bending fracture characteristics" refers to a stroke ($S_{F\text{max}}$) of 26.0 mm or more at the maximum load measured in a V-VDA bending test.

[0021] The phrase "good axial compression characteristics" means that, after an axial compression test, fracture (appearance crack) occurs at three or less positions in the regions of $R = 5.0 \text{ mm}$ and 200 mm of lower two bending ridge line portions in Fig. 5-1(b) (see regions Cx in Fig. 5-1).

[0022] EI, λ , and α described above are characteristics indicating formability at the time of press forming of a steel sheet. On the other hand, the V-VDA bending test is a test simulating the deformation and fracture behavior of a bending ridge line portion in a collision test, and the stroke at the maximum load ($S_{F\text{max}}$) measured in the V-VDA bending test is a characteristic indicating the resistance to cracking of a member.

Solution to Problem

[0023] To achieve the above objects, the present inventors have conducted extensive studies.

[0024] As a result, it has been found that a steel sheet with a TS of 1180 MPa or more, high YS, high press formability (ductility, flangeability, and bendability), and fracture resistance characteristics (bending fracture characteristics and axial compression characteristics) at the time of compression can be produced when the steel sheet has a base steel sheet with an appropriately adjusted chemical composition, the base steel sheet of the steel sheet has a steel microstructure in which the area fraction of ferrite: 57.0% or less, the total area fraction of bainitic ferrite and tempered martensite: 40.0% or more and 90.0% or less, the area fraction of retained austenite: 3.0% or more and 10.0% or less, the area fraction of fresh martensite: 10.0% or less, and the value obtained by dividing the area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite is 0.70 or more, a V-VDA bending test is performed to a maximum load point, in a V-bending ridge line portion and a VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with a hard phase (the number of voids at a boundary between the hard phase and a soft phase and the number of voids formed by fracture of the hard phase) among all voids by the total number of voids is 0.60 or less, in a V-bending flat portion and the VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with the hard phase among (the number of voids at the boundary between the hard phase and the soft phase and the number of voids formed by fracture of the hard phase) all voids by the total number of voids is 0.20 or less, and the center of gravity of carbide has a mean free path of 0.20 μm or more.

[0025] The present invention has been accomplished on the basis of these findings after further consideration.

[0026] The gist of the present invention can be summarized as follows:

[1] A steel sheet including a base steel sheet, wherein the base steel sheet has a chemical composition containing, on a mass percent basis,

C: 0.050% or more and 0.400% or less,

Si: more than 0.75% and 3.00% 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,

Al: 0.010% or more and 2.000% or less, and

N: 0.0100% or less,

with the remainder being Fe and incidental impurities,

the base steel sheet has a steel microstructure in which

an area fraction of ferrite: 57.0% or less,

a total area fraction of bainitic ferrite and tempered martensite: 40.0% or more and 90.0% or less,

an area fraction of retained austenite: 3.0% or more and 10.0% or less,

an area fraction of fresh martensite: 10.0% or less, and

a value obtained by dividing an area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite is 0.70 or more,

a V-VDA bending test is performed to a maximum load point,

in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion, a value obtained by dividing the number of voids in contact with a hard phase among all voids by the total number of voids is 0.60 or less,

in an overlap region of a V-bending flat portion and the VDA bending ridge line portion, a value obtained by dividing the number of voids in contact with the hard phase among all voids by the total number of voids is 0.20 or less,

carbide has a mean free path L_M of 0.20 μm or more as represented by the following formula (1), and

the steel sheet has a tensile strength of 1180 MPa or more.

$$L_M = (d_M/2) \times (400\pi/3f)^{1/3} \quad \text{formula (1)}$$

wherein L_M denotes the mean free path (μm) of carbide, d_M denotes an average equivalent circular diameter (μm) of carbide, π denotes a circumference ratio, and f denotes a volume fraction (%) of all carbide particles.

[2] The steel sheet according to [1], wherein the base steel sheet has a chemical composition further containing, on a mass percent basis, at least one selected from

Nb: 0.200% or less,

Ti: 0.200% or less,
V: 0.200% or less,
B: 0.0100% or less,
Cr: 1.000% or less,
Ni: 1.000% or less,
Mo: 1.000% or less,
Sb: 0.200% or less,
Sn: 0.200% or less,
Cu: 1.000% or less,
Ta: 0.100% or less,
W: 0.500% or less,
Mg: 0.0200% or less,
Zn: 0.0200% or less,
Co: 0.0200% or less,
Zr: 0.1000% or less,
Ca: 0.0200% or less,
Se: 0.0200% or less,
Te: 0.0200% or less,
Ge: 0.0200% or less,
As: 0.0500% or less,
Sr: 0.0200% or less,
Cs: 0.0200% or less,
Hf: 0.0200% or less,
Pb: 0.0200% or less,
Bi: 0.0200% or less, and
REM: 0.0200% or less.

[3] The steel sheet according to [1] or [2], including a galvanized layer as an outermost surface layer on one or both surfaces of the steel sheet.

[4] The steel sheet according to any one of [1] to [3], wherein an average value σ_c of a standard deviation of a distance between a carbide particle A selected from all carbide particles in the steel sheet and a remaining carbide particle other than the carbide particle A is 7.50 μm or less.

[5] The steel sheet according to any one of [1] to [4], wherein

when a region of 200 μm or less from a surface of the base steel sheet in the thickness direction is defined as a surface layer,
the base steel sheet has, in the surface layer, a surface soft layer with a Vickers hardness of 85% or less with respect to a Vickers hardness at a quarter thickness position, and
when nanohardness is measured at 300 points or more in a 50 $\mu\text{m} \times 50 \mu\text{m}$ region on a sheet surface at a quarter depth position in the thickness direction and at a half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet,
a ratio of a number of measurements with a nanohardness of 7.0 GPa or more on the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet to a total number of measurements at the quarter depth position in the thickness direction of the surface soft layer is 0.10 or less,
the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet has a standard deviation σ of 1.8 GPa or less, and
the nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet has a standard deviation σ of 2.2 GPa or less.

[6] The steel sheet according to any one of [1] to [5], including a metal coated layer formed on the base steel sheet on one or both surfaces of the steel sheet.

[7] A member including the steel sheet according to any one of [1] to [6].

[8] A method for producing a steel sheet, including:

a hot rolling step of hot-rolling a steel slab with the chemical composition according to [1] or [2] to produce a hot-rolled steel sheet;
a pickling step of pickling the hot-rolled steel sheet;

an annealing step of annealing the steel sheet after the pickling step at an annealing temperature of $(Ac_1 + (Ac_3 - Ac_1) \times 3/4)^{\circ}C$ or more and $900^{\circ}C$ or less for an annealing time of 20 seconds or more;
a first cooling step of cooling the steel sheet after the annealing step to a first cooling stop temperature of $100^{\circ}C$ or more and $300^{\circ}C$ or less;
5 a holding step of holding the steel sheet after the first cooling step in a temperature range of $350^{\circ}C$ or more and $550^{\circ}C$ or less for 3 seconds or more and less than 80 seconds;
a second cooling step of cooling the steel sheet after the holding step to a second cooling stop temperature of $50^{\circ}C$ or less, during the cooling, applying a tension of 2.0 kgf/mm^2 or more to the steel sheet once or more in a temperature range of $300^{\circ}C$ or more and $450^{\circ}C$ or less,
10 then
subjecting the steel sheet to four or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll, and
subjecting the steel sheet to two or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for half a circumference of the roll; and
15 optionally a cold rolling step of cold-rolling the steel sheet after the pickling step and before the annealing step to produce a cold-rolled steel sheet.

[9] The method for producing a steel sheet according to [8], including a galvanizing step of performing a galvanizing treatment on the steel sheet after the holding step and before the second cooling step to form a galvanized layer on the steel sheet.

[10] The production method according to [8] or [9], wherein the annealing in the annealing step is performed in an atmosphere with a dew point of $-30^{\circ}C$ or more.

[11] The method for producing a steel sheet according to any one of [8] to [10], including a metal coating step of performing metal coating on one or both surfaces of the steel sheet to form a metal coated layer after the pickling step and before the annealing step.

[12] A method for producing a member, including a step of subjecting the steel sheet according to any one of [1] to [6] to at least one of forming and joining to produce a member.

Advantageous Effects of Invention

[0027] The present invention provides a steel sheet with a tensile strength TS of 1180 MPa or more, high yield stress YS, high press formability (ductility, flangeability, and bendability), and fracture resistance characteristics (bending fracture characteristics and axial compression characteristics) at the time of compression.

[0028] Furthermore, a member including a steel sheet according to the present invention as a material has high strength and enhanced crashworthiness and can therefore be extremely advantageously applied to an impact energy absorbing member or the like of an automobile.

Brief Description of Drawings

[0029]

[Fig. 1] Fig. 1 is a SEM microstructure image used to identify a microstructure.

[Fig. 2-1] Fig. 2-1(a) is an explanatory view of V-bending (primary bending) in a V-VDA bending test in Examples. Fig. 2-1(b) is an explanatory view of VDA bending (secondary bending) in the V-VDA bending test in Examples.

[Fig. 2-2] Fig. 2-2(c) is a perspective view of a test specimen subjected to V-bending (primary bending) in V-VDA. Fig. 2-2(d) is a perspective view of a test specimen subjected to VDA bending (secondary bending) in V-VDA.

[Fig. 2-3] Fig. 2-3(e) is a cross-sectional view of a measurement point of a change in the grain size of bainitic ferrite in the thickness direction due to processing in an L cross-sectional observation surface of a test specimen subjected to VDA bending (secondary bending) in V-VDA.

[Fig. 3] Fig. 3 is a schematic view of a stroke-load curve obtained in a V-VDA test.

[Fig. 4] Fig. 4(a) is an example of a SEM microstructure image showing a void at a boundary between a hard phase and a soft phase. Fig. 4(b) is an example of a SEM microstructure image showing a void due to fracture of a hard phase. Fig. 4(c) is an example of a SEM microstructure image showing a void due to carbide.

[Fig. 5-1] Fig. 5-1(a) is a front view of a test member composed of a hat-shaped member and a steel sheet spot-welded together for an axial compression test in Examples. Fig. 5-1(b) is a perspective view of the test member illustrated in Fig. 5-1(a).

[Fig. 5-2] Fig. 5-2(c) is a schematic explanatory view of an axial compression test in Examples.

Description of Embodiments

[0030] The present invention is described on the basis of the following embodiments.

5 [1. Steel Sheet]

[0031] A steel sheet according to the present invention is a steel sheet including a base steel sheet, wherein the base steel sheet has a chemical composition containing, on a mass percent basis, C: 0.050% or more and 0.400% or less, Si: more than 0.75% and 3.00% 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, Al: 0.010% or more and 2.000% or less, and N: 0.0100% or less, with the remainder being Fe and incidental impurities, the base steel sheet has a steel microstructure in which an area fraction of ferrite: 57.0% or less, a total area fraction of bainitic ferrite and tempered martensite: 40.0% or more and 90.0% or less, an area fraction of retained austenite: 3.0% or more and 10.0% or less, an area fraction of fresh martensite: 10.0% or less, and a value obtained by dividing an area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite is 0.70 or more, a V-VDA bending test is performed to a maximum load point, in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion, a value obtained by dividing the number of voids in contact with a hard phase among all voids by the total number of voids is 0.60 or less, in a V-bending flat portion and the VDA bending ridge line portion, a value obtained by dividing the number of voids in contact with the hard phase among all voids by the total number of voids is 0.20 or less, carbide has a mean free path L_M of 0.20 μm or more as represented by the following formula (1), and the steel sheet has a tensile strength of 1180 MPa or more.

$$L_M = (d_M/2) \times (400\pi/3f)^{1/3} \quad \text{formula (1)}$$

wherein L_M denotes the mean free path (μm) of carbide, d_M denotes the average equivalent circular diameter (μm) of carbide, π denotes the circumference ratio, and f denotes the volume fraction (%) of all carbide particles.

[0032] The steel sheet may have a galvanized layer as an outermost surface layer on one or both surfaces of the steel sheet. A steel sheet with a galvanized layer may be a galvanized steel sheet.

30 Chemical Composition

[0033] First, the chemical composition of a base steel sheet of a steel sheet according to an embodiment of the present invention is described. The unit in the chemical composition is "% by mass" and is hereinafter expressed simply in "%" unless otherwise specified.

C: 0.050% or more and 0.400% or less

[0034] C is an element effective in forming appropriate amounts of fresh martensite, tempered martensite, bainitic ferrite, and retained austenite and ensuring a tensile strength TS of 1180 MPa or more and high YS. At a C content of less than 0.050%, the area fraction of ferrite increases, and a TS of 1180 MPa or more may not be achieved. This may also reduce YS.

[0035] On the other hand, at a C content of more than 0.400%, the hardness of fresh martensite formed by deformation-induced transformation when a steel sheet is punched in a hole expansion test or is subjected to V-bending in a V-VDA test increases greatly, subsequent void formation and crack growth are promoted, and desired λ and S_{Fmax} cannot be achieved.

[0036] Thus, the C content is 0.050% or more and 0.400% or less. The C content is preferably 0.100% or more. The C content is preferably 0.300% or less.

Si: more than 0.75% and 3.00% or less

[0037] Si suppresses the formation of carbide and promotes the formation of retained austenite during cooling and holding after annealing. Thus, Si is an element that affects the volume fraction of retained austenite. A Si content of 0.75% or less results in a decrease in the volume fraction of retained austenite and lower ductility.

[0038] On the other hand, at a Si content of more than 3.00%, the area fraction of ferrite increases excessively, and a TS of 1180 MPa or more may not be achieved. This may also reduce YS. This also excessively increases the C concentration in austenite during annealing and results in undesired λ and S_{Fmax} .

[0039] Thus, the Si content is more than 0.75% and 3.00% or less. The Si content is preferably 2.00% or less.

Mn: 2.00% or more and less than 3.50%

[0040] Mn is an element that adjusts the area fraction of bainitic ferrite, tempered martensite, or the like. A Mn content of less than 2.00% results in an excessive increase in the area fraction of ferrite and makes it difficult to achieve a TS of 1180 MPa or more. This also reduces YS.

[0041] On the other hand, a Mn content of 3.50% or more results in a decrease in martensite start temperature M_s (hereinafter also referred to simply as an M_s temperature or M_s) and a decrease in martensite formed in a first cooling step. This increases martensite formed in a second cooling step, does not sufficiently temper martensite formed at that time, and increases the area fraction of hard fresh martensite. Fresh martensite acts as a starting point of void formation in a hole expansion test, a VDA bending test, or a V-VDA bending test. An area fraction of fresh martensite exceeding 10.0% results in undesired $\lambda_{S_{Fmax}}$. Furthermore, desired α may not be achieved.

[0042] Thus, the Mn content is 2.00% or more and less than 3.50%. The Mn content is preferably 2.50% or more. The Mn content is preferably 3.20% or less.

P: 0.001% or more and 0.100% or less

[0043] P is an element that has a solid-solution strengthening effect and increases TS and YS of a steel sheet. To produce such effects, the P content is 0.001% or more. On the other hand, a P content of more than 0.100% results in segregation of P at a prior-austenite grain boundary and embrittlement of the grain boundary. Thus, after the steel sheet is punched or is subjected to V-bending in a V-VDA bending test, the number of voids formed increases, and desired λ and S_{Fmax} cannot be achieved.

[0044] Thus, the P content is 0.001% or more and 0.100% or less. The P content is preferably 0.030% or less.

S: 0.0001% or more and 0.0200% or less

[0045] S is present as a sulfide in steel. In particular, at a S content of more than 0.0200%, after the steel sheet is punched or is subjected to V-bending in a V-VDA bending test, the number of voids formed increases, and desired λ and S_{Fmax} cannot be achieved.

[0046] Thus, the S content is 0.0200% or less. The S content is preferably 0.0080% or less. Due to constraints on production technology, the S content is 0.0001% or more.

Al: 0.010% or more and 2.000% or less

[0047] Al suppresses the formation of carbide and promotes the formation of retained austenite during cooling and holding after annealing. Thus, Al is an element that affects the volume fraction of retained austenite. To produce such effects, the Al content is preferably 0.010% or more.

[0048] On the other hand, an Al content of more than 2.000% results in an excessive increase in the area fraction of ferrite and makes it difficult to achieve a TS of 1180 MPa or more. This also reduces YS. This also excessively increases the C concentration in austenite during annealing and results in undesired λ and S_{Fmax} .

[0049] Thus, the Al content is 0.010% or more and 2.000% or less. The Al content is preferably 0.015% or more. The Al content is preferably 1.000% or less.

N: 0.0100% or less

[0050] N is present as a nitride in steel. In particular, at a N content of more than 0.0100%, after the steel sheet is punched or is subjected to V-bending in a V-VDA bending test, the number of voids formed increases, and desired λ and S_{Fmax} cannot be achieved.

[0051] Thus, the N content is 0.0100% or less. The N content is preferably 0.0050% or less. The N content may have any lower limit but is preferably 0.0005% or more due to constraints on production technology.

[0052] A base chemical composition of a base steel sheet of a steel sheet according to an embodiment of the present invention has been described above. A base steel sheet of a steel sheet according to an embodiment of the present invention has a chemical composition that contains the base components and the remainder other than the base components including Fe (iron) and incidental impurities. A base steel sheet of a steel sheet according to an embodiment of the present invention preferably has a chemical composition that contains the base components and the remainder composed of Fe and incidental impurities.

[0053] A base steel sheet of a steel sheet according to an embodiment of the present invention may contain, in addition to the base components, at least one selected from the following optional components. As long as the following optional components are contained in an amount equal to or less than their respective upper limits described below, the advantages

of the present invention can be achieved. Thus, there is no particular lower limit. Any of the following optional elements contained in amounts below the following appropriate lower limits is considered to be an incidental impurity.

[0054] At least one selected from Nb: 0.200% or less, Ti: 0.200% or less, V: 0.200% or less, B: 0.0100% or less, Cr: 1.000% or less, Ni: 1.000% or less, Mo: 1.000% or less, Sb: 0.200% or less, Sn: 0.200% or less, Cu: 1.000% or less, Ta: 0.100% or less, W: 0.500% or less, Mg: 0.0200% or less, Zn: 0.0200% or less, Co: 0.0200% or less, Zr: 0.1000% or less, Ca: 0.0200% or less, Se: 0.0200% or less, Te: 0.0200% or less, Ge: 0.0200% or less, As: 0.0500% or less, Sr: 0.0200% or less, Cs: 0.0200% or less, Hf: 0.0200% or less, Pb: 0.0200% or less, Bi: 0.0200% or less, and REM: 0.0200% or less

Nb: 0.200% or less

[0055] Nb forms fine carbide, nitride, or carbonitride during hot rolling or annealing and thereby increases TS and YS. To produce such effects, the Nb content is preferably 0.001% or more. The Nb content is more preferably 0.005% or more. On the other hand, a Nb content of more than 0.200% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Nb is contained, the Nb content is preferably 0.200% or less. The Nb content is more preferably 0.060% or less.

Ti: 0.200% or less

[0056] Like Nb, Ti forms fine carbide, nitride, or carbonitride during hot rolling or annealing and thereby increases TS and YS. To produce such effects, the Ti content is preferably 0.001% or more. The Ti content is more preferably 0.005% or more. On the other hand, a Ti content of more than 0.200% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Ti is contained, the Ti content is preferably 0.200% or less. The Ti content is more preferably 0.060% or less.

V: 0.200% or less

[0057] Like Nb or Ti, V forms fine carbide, nitride, or carbonitride during hot rolling or annealing and thereby increases TS and YS. To produce such effects, the V content is preferably 0.001% or more. The V content is more preferably 0.005% or more. The V content is even more preferably 0.010% or more, even further more preferably 0.030% or more. On the other hand, a V content of more than 0.200% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when V is contained, the V content is preferably 0.200% or less. The V content is more preferably 0.060% or less.

B: 0.0100% or less

[0058] B is an element that segregates at an austenite grain boundary and enhances hardenability. B is also an element that suppresses the formation and grain growth of ferrite during cooling after annealing. To produce such effects, the B content is preferably 0.0001% or more. The B content is more preferably 0.0002% or more.

[0059] The B content is even more preferably 0.0005% or more, even further more preferably 0.0007% or more.

[0060] On the other hand, a B content of more than 0.0100% may result in a crack in a steel sheet during hot rolling. After the steel sheet is punched or is subjected to V-bending in a V-VDA bending test, the number of voids formed increases, and desired λ and S_{Fmax} may not be achieved.

[0061] Thus, when B is contained, the B content is preferably 0.0100% or less. The B content is more preferably 0.0050% or less.

Cr: 1.000% or less

[0062] Cr is an element that enhances hardenability, and the addition of Cr forms a large amount of tempered martensite and ensures a TS of 1180 MPa or more and high YS. To produce such effects, the Cr content is preferably 0.0005% or more. The Cr content is more preferably 0.010% or more.

[0063] Cr is even more preferably 0.030% or more, even further more preferably 0.050% or more.

[0064] On the other hand, at a Cr content of more than 1.000%, the area fraction of hard fresh martensite increases excessively, fresh martensite acts as a starting point of void formation in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Cr is contained, the Cr content is preferably 1.000% or less. The Cr content is more preferably 0.800% or less, even more preferably 0.700% or less.

Ni: 1.000% or less

[0065] Ni is an element that enhances hardenability, and the addition of Ni forms a large amount of tempered martensite and ensures a TS of 1180 MPa or more and high YS. To produce such effects, the Ni content is preferably 0.005% or more. The Ni content is more preferably 0.020% or more. The Ni content is even more preferably 0.040% or more, even further more preferably 0.060% or more.

[0066] On the other hand, at a Ni content of more than 1.000%, the area fraction of fresh martensite increases excessively, fresh martensite acts as a starting point of void formation in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Ni is contained, the Ni content is preferably 1.000% or less. The Ni content is more preferably 0.800% or less.

[0067] The Ni content is even more preferably 0.600% or less, even further more preferably 0.400% or less.

Mo: 1.000% or less

[0068] Mo is an element that enhances hardenability, and the addition of Mo forms a large amount of tempered martensite and ensures a TS of 1180 MPa or more and high YS. To produce such effects, the Mo content is preferably 0.010% or more. The Mo content is more preferably 0.030% or more.

[0069] On the other hand, at a Mo content of more than 1.000%, the area fraction of fresh martensite increases excessively, fresh martensite acts as a starting point of void formation in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Mo is contained, the Mo content is preferably 1.000% or less. The Mo content is more preferably 0.500% or less, even more preferably 0.450% or less, even further more preferably 0.400% or less. The Mo content is even more preferably 0.350% or less, even further more preferably 0.300% or less.

Sb: 0.200% or less

[0070] Sb is an element effective in suppressing the diffusion of C near the surface of a steel sheet during annealing and controlling the formation of a soft layer near the surface of the steel sheet. An excessive increase of a soft layer near the surface of a steel sheet makes it difficult to achieve a TS of 1180 MPa or more. This also reduces YS. Thus, the Sb content is preferably 0.002% or more. The Sb content is more preferably 0.005% or more. On the other hand, an Sb content of more than 0.200% may result in no soft layer near the surface of a steel sheet and lower flangeability and bendability. Thus, when Sb is contained, the Sb content is preferably 0.200% or less. The Sb content is more preferably 0.020% or less.

Sn: 0.200% or less

[0071] Like Sb, Sn is an element effective in suppressing the diffusion of C near the surface of a steel sheet during annealing and controlling the formation of a soft layer near the surface of the steel sheet. An excessive increase of a soft layer near the surface of a steel sheet makes it difficult to achieve a TS of 1180 MPa or more. This also reduces YS. Thus, the Sn content is preferably 0.002% or more. The Sn content is more preferably 0.005% or more.

[0072] On the other hand, a Sn content of more than 0.200% may result in no soft layer near the surface of a steel sheet and lower flangeability and bendability. Thus, when Sn is contained, the Sn content is preferably 0.200% or less. The Sn content is more preferably 0.020% or less.

Cu: 1.000% or less

[0073] Cu is an element that enhances hardenability, and the addition of Cu forms a large amount of tempered martensite and ensures a TS of 1180 MPa or more and high YS. To produce such effects, the Cu content is preferably 0.005% or more. The Cu content is more preferably 0.008% or more, even more preferably 0.010% or more. The Cu content is even more preferably 0.020% or more.

[0074] On the other hand, a Cu content of more than 1.000% may result in an excessive increase in the area fraction of fresh martensite and a large number of coarse precipitates or inclusions. In such a case, fresh martensite and coarse precipitates or inclusions may act as starting points of voids and cracks in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Cu is contained, the Cu content is preferably 1.000% or less. The Cu content is more preferably 0.200% or less.

Ta: 0.100% or less

[0075] Like Ti, Nb, and V, Ta forms fine carbide, nitride, or carbonitride during hot rolling or annealing and increases TS

and YS. Furthermore, Ta partially dissolves in Nb carbide or Nb carbonitride and forms a complex precipitate, such as (Nb, Ta) (C, N). This suppresses coarsening of a precipitate and stabilizes precipitation strengthening. This further improves TS and YS. To produce such effects, the Ta content is preferably 0.001% or more. The Ta content is more preferably 0.002% or more, even more preferably 0.004% or more.

[0076] On the other hand, a Ta content of more than 0.100% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Ta is contained, the Ta content is preferably 0.100% or less.

[0077] The Ta content is more preferably 0.090% or less, even more preferably 0.080% or less.

W: 0.500% or less

[0078] W is an element that enhances hardenability, and the addition of W forms a large amount of tempered martensite and ensures a TS of 1180 MPa or more and high YS. To produce such effects, the W content is preferably 0.001% or more.

The W content is more preferably 0.030% or more.

[0079] On the other hand, at a W content of more than 0.500%, the area fraction of hard fresh martensite increases excessively, fresh martensite acts as a starting point of void formation in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when W is contained, the W content is preferably 0.500% or less. The W content is more preferably 0.450% or less, even more preferably 0.400% or less. The W content is even further more preferably 0.300% or less.

Mg: 0.0200% or less

[0080] Mg is an element effective in spheroidizing the shape of an inclusion of sulfide, oxide, or the like and improving the flangeability of a steel sheet. To produce such effects, the Mg content is preferably 0.0001% or more. The Mg content is more preferably 0.0005% or more, even more preferably 0.0010% or more.

[0081] On the other hand, a Mg content of more than 0.0200% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Mg is contained, the Mg content is preferably 0.0200% or less. The Mg content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

Zn: 0.0200% or less

[0082] Zn is an element effective in spheroidizing the shape of an inclusion and improving the flangeability of a steel sheet. To produce such effects, the Zn content is preferably 0.0010% or more. The Zn content is more preferably 0.0020% or more, even more preferably 0.0030% or more.

[0083] On the other hand, a Zn content of more than 0.0200% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Zn is contained, the Zn content is preferably 0.0200% or less. The Zn content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

Co: 0.0200% or less

[0084] Like Zn, Co is an element effective in spheroidizing the shape of an inclusion and improving the flangeability of a steel sheet. To produce such effects, the Co content is preferably 0.0010% or more. The Co content is more preferably 0.0020% or more, even more preferably 0.0030% or more.

[0085] On the other hand, a Co content of more than 0.0200% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Co is contained, the Co content is preferably 0.0200% or less. The Co content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

Zr: 0.1000% or less

[0086] Like Zn and Co, Zr is an element effective in spheroidizing the shape of an inclusion and improving the flangeability of a steel sheet. To produce such effects, the Zr content is preferably 0.0010% or more. On the other hand,

a Zr content of more than 0.1000% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Zr is contained, the Zr content is preferably 0.1000% or less.

5 **[0087]** The Zr content is more preferably 0.0300% or less, even more preferably 0.0100% or less.

Ca: 0.0200% or less

10 **[0088]** Ca is present as an inclusion in steel. A Ca content of more than 0.0200% may result in a large number of coarse inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when Ca is contained, the Ca content is preferably 0.0200% or less.

[0089] The Ca content is preferably 0.0020% or less. The Ca content may have any lower limit but is preferably 0.0005% or more. Due to constraints on production technology, the Ca content is more preferably 0.0010% or more.

15 **[0090]** Se: 0.0200% or less, Te: 0.0200% or less, Ge: 0.0200% or less, As: 0.0500% or less, Sr: 0.0200% or less, Cs: 0.0200% or less, Hf: 0.0200% or less, Pb: 0.0200% or less, Bi: 0.0200% or less, REM: 0.0200% or less

[0091] Se, Te, Ge, As, Sr, Cs, Hf, Pb, Bi, and REM are elements effective in improving the flangeability of a steel sheet. To produce such effects, each of the Se, Te, Ge, As, Sr, Cs, Hf, Pb, Bi, and REM contents is preferably 0.0001% or more.

20 **[0092]** On the other hand, a Se, Te, Ge, Sr, Cs, Hf, Pb, Bi, or REM content of more than 0.0200% or an As content of more than 0.0500% may result in a large number of coarse precipitates or inclusions. In such a case, a coarse precipitate or inclusion may act as a starting point of a crack in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} may not be achieved. Thus, when at least one of Se, Te, Ge, As, Sr, Cs, Hf, Pb, Bi, and REM is contained, each of the Se, Te, Ge, As, Sr, Cs, Hf, Pb, Bi, and REM contents is preferably 0.0200% or less, and the As content is preferably 0.0500% or less.

25 **[0093]** The Se content is more preferably 0.0005% or more, even more preferably 0.0008% or more. The Se content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

[0094] The Te content is more preferably 0.0005% or more, even more preferably 0.0008% or more. The Te content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

30 **[0095]** The Ge content is more preferably 0.0005% or more, even more preferably 0.0008% or more. The Ge content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

[0096] The As content is more preferably 0.0010% or more, even more preferably 0.0015% or more. The As content is more preferably 0.0400% or less, even more preferably 0.0300% or less.

[0097] The Sr content is more preferably 0.0005% or more, even more preferably 0.0008% or more. The Sr content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

35 **[0098]** The Cs content is more preferably 0.0005% or more, even more preferably 0.0008% or more. The Cs content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

[0099] The Hf content is more preferably 0.0005% or more, even more preferably 0.0008% or more. The Hf content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

40 **[0100]** The Pb content is more preferably 0.0005% or more, even more preferably 0.0008% or more. The Pb content is more preferably 0.0180% or less, even more preferably 0.0150% or less.

[0101] The Bi content is more preferably 0.0005% or more, even more preferably 0.0008% or more. Bi is more preferably 0.0180% or less, even more preferably 0.0150% or less.

[0102] REM is more preferably 0.0005% or more, even more preferably 0.0008% or more. REM is more preferably 0.0180% or less, even more preferably 0.0150% or less.

45 **[0103]** The term "REM", as used herein, refers to scandium (Sc) with atomic number 21, yttrium (Y) with atomic number 39, and lanthanoids from lanthanum (La) with atomic number 57 to lutetium (Lu) with atomic number 71.

[0104] The term "REM concentration", as used herein, refers to the total content of one or two or more elements selected from the REM.

[0105] REM is preferably, but not limited to, Sc, Y, Ce, or La.

50 **[0106]** Thus, a base steel sheet of a steel sheet according to an embodiment of the present invention has a chemical composition containing, on a mass percent basis, C: 0.050% or more and 0.400% or less, Si: more than 0.75% and 3.00% 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, Al: 0.010% or more and 2.000% or less, and N: 0.0100% or less, and optionally containing at least one selected from Nb: 0.200% or less, Ti: 0.200% or less, V: 0.200% or less, B: 0.0100% or less, Cr: 1.000% or less, Ni: 1.000% or less, Mo: 1.000% or less, Sb: 0.200% or less, Sn: 0.200% or less, Cu: 1.000% or less, Ta: 0.100% or less, W: 0.500% or less, Mg: 0.0200% or less, Zn: 0.0200% or less, Co: 0.0200% or less, Zr: 0.1000% or less, Ca: 0.0200% or less, Se: 0.0200% or less, Te: 0.0200% or less, Ge: 0.0200% or less, As: 0.0500% or less, Sr: 0.0200% or less, Cs: 0.0200% or less, Hf: 0.0200% or less, Pb: 0.0200% or less, Bi: 0.0200% or less, and REM: 0.0200% or less, the remainder being Fe and incidental

impurities.

Steel Microstructure

[0107] Next, the steel microstructure of a base steel sheet of a steel sheet according to an embodiment of the present invention is described.

[0108] A base steel sheet of a steel sheet according to an embodiment of the present invention has a steel microstructure in which the area fraction of ferrite: 57.0% or less, the total area fraction of bainitic ferrite and tempered martensite: 40.0% or more and 90.0% or less, the area fraction of retained austenite: 3.0% or more and 10.0% or less, the area fraction of fresh martensite: 10.0% or less, and the value obtained by dividing the area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite is 0.70 or more, a V-VDA bending test is performed to a maximum load point, in a V-bending ridge line portion and a VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with a hard phase among all voids by the total number of voids is 0.60 or less, in a V-bending flat portion and the VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with the hard phase among all voids by the total number of voids is 0.20 or less, and carbide has a mean free path L_M of 0.20 μm or more.

[0109] The reasons for these limitations are described below.

Area fraction of ferrite: 57.0% or less (including 0.0%)

[0110] Soft ferrite is a phase that improves ductility. However, an excessive increase in the area fraction of ferrite makes it difficult to achieve a TS of 1180 MPa or more. This also reduces YS. This also excessively increases the C concentration in austenite during annealing and results in undesired λ and S_{Fmax} . Thus, the area fraction of ferrite is 57.0% or less. The area fraction of ferrite is preferably 30.0% or less, more preferably 20.0% or less. The area fraction of ferrite may have any lower limit and may be 0.0%.

[0111] Total area fraction of bainitic ferrite and tempered martensite (excluding retained austenite): 40.0% or more and 90.0% or less

[0112] Bainitic ferrite and tempered martensite have intermediate hardness as compared with soft ferrite, hard fresh martensite, and the like and is an important phase for ensuring high flangeability and bendability and good bending fracture characteristics and axial compression characteristics. Bainitic ferrite is also a phase useful for utilizing the diffusion of C from bainitic ferrite to non-transformed austenite to form an appropriate amount of retained austenite. Tempered martensite is also effective in improving TS. Thus, the total area fraction of bainitic ferrite and tempered martensite (excluding retained austenite) is 40.0% or more. The total area fraction of bainitic ferrite and tempered martensite (excluding retained austenite) is preferably 60.0% or more. On the other hand, an excessive increase in the total area fraction of bainitic ferrite and tempered martensite (excluding retained austenite) results in lower ductility. Thus, the total area fraction of bainitic ferrite and tempered martensite (excluding retained austenite) is 90.0% or less. The total area fraction of bainitic ferrite and tempered martensite (excluding retained austenite) is preferably 87.0% or less, more preferably 85.0% or less.

[0113] The term "bainitic ferrite" refers to upper bainite that is formed in a relatively high temperature region and has a small amount of carbide.

Area fraction of retained austenite: 3.0% or more and 10.0% or less

[0114] From the perspective of high ductility, the area fraction of retained austenite is 3.0% or more. The area fraction of retained austenite is preferably 5.0% or more.

[0115] On the other hand, an excessive increase in the area fraction of retained austenite results in fresh martensite formed by deformation-induced transformation acting as a starting point of void formation when a steel sheet is punched in a hole expansion test or is subjected to V-bending in a V-VDA test, and desired λ and S_{Fmax} cannot be achieved. Thus, the area fraction of retained austenite is 10.0% or less. The area fraction of retained austenite is preferably 9.0% or less, more preferably 8.0% or less.

[0116] For example, tension in a second cooling step in a production method described later can be controlled to suppress the area fraction of retained austenite to 10.0% or less. Applying a tension of 2.0 kgf/mm² or more once or more after a holding step (after a galvanizing treatment when the galvanizing treatment is performed (when necessary, after an alloying treatment)), then subjecting a steel sheet to four or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll, and subjecting the steel sheet to two or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for half the circumference of the roll cause deformation-induced transformation of unstable retained austenite to fresh martensite, temper the fresh martensite during subsequent cooling, and finally form tempered martensite.

Area fraction of fresh martensite: 10.0% or less (including 0.0%)

[0117] An excessive increase in the area fraction of fresh martensite results in fresh martensite acting as a starting point of void formation in a hole expansion test, a VDA bending test, or a V-VDA bending test, and desired λ , α , and S_{Fmax} cannot be achieved. From the perspective of ensuring high flangeability and bendability, the area fraction of fresh martensite is 10.0% or less, preferably 5.0% or less. The area fraction of fresh martensite may have any lower limit and may be 0.0%.
[0118] The term "fresh martensite" refers to as-quenched (untempered) martensite.

Value obtained by dividing area fraction of tempered martensite by total area fraction of bainitic ferrite and tempered martensite: 0.70 or more

[0119] The diffusion of C from bainitic ferrite to non-transformed austenite increases the area fraction of retained austenite. To ensure that the area fraction of retained austenite is 10.0% or less, the value obtained by dividing the area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite is 0.70 or more. The value obtained by dividing the area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite is preferably 0.75 or more. The upper limit is not particularly limited, and the value obtained by dividing the area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite may be 1.00.

[0120] The area fraction of the remaining microstructure other than those described above is preferably 10.0% or less. The area fraction of the remaining microstructure is more preferably 5.0% or less. The area fraction of the remaining microstructure may be 0.0%.

[0121] The remaining microstructure is, for example, but not limited to, lower bainite, pearlite, carbide such as cementite, or the like. The type of the remaining microstructure can be determined, for example, by scanning electron microscope (SEM) observation.

[0122] The area fractions of ferrite, bainitic ferrite, tempered martensite, and a hard phase (a hard second phase (retained austenite + fresh martensite)) are measured at a quarter thickness position of a base steel sheet as described below.

[0123] A sample is cut out from a base steel sheet to form a thickness cross section parallel to the rolling direction of the base steel sheet as an observation surface. The observation surface of the sample is then mirror-polished with a diamond paste. The observation surface of the sample is then subjected to final polishing with colloidal silica and is then etched with 3% by volume nital to expose the microstructure.

[0124] Three visual fields of $25.6 \mu\text{m} \times 17.6 \mu\text{m}$ on the observation surface of the sample are then photographed with a scanning electron microscope (SEM) under the conditions of an acceleration voltage of 15 kV and a magnification of 5000 times.

[0125] From a microstructure image thus photographed (see Fig. 1), ferrite, bainitic ferrite, tempered martensite, and the hard phase (hard second phase (retained austenite + fresh martensite)) are identified as described below.

[0126] In Fig. 1, the symbol BF indicates bainitic ferrite, the symbol F indicates ferrite, and the symbol TM indicates tempered martensite. In Fig. 1, θ denotes carbide, and H1 denotes a hard phase.

[0127] Ferrite: a massive black region. Almost no iron-based carbide is contained. When an iron-based carbide is contained, however, the area of ferrite includes the area of the iron-based carbide. The same applies to bainitic ferrite and tempered martensite described later.

[0128] Bainitic ferrite: a black to dark gray region of a massive form, an indefinite form, or the like. No or a relatively small number of iron-based carbide particles is contained.

[0129] Tempered martensite: a gray region of an indefinite form. A relatively large number of iron-based carbide particles is contained.

[0130] Hard phase (hard second phase (retained austenite + fresh martensite)): a white to light gray region of an indefinite form. No iron-based carbide is contained. One with a relatively large size has a gradually darker color with the distance from the interface with another microstructure and may have a dark gray interior.

[0131] Carbide: a dotted or linear white region. It is contained in tempered martensite, bainitic ferrite, and ferrite.

[0132] Remaining microstructure: the lower bainite, pearlite, and the like of known forms.

[0133] Next, the region of each phase identified in the microstructure image is subjected to calculation by the following method. On the 5000x SEM image, a 20×20 grid spaced at regular intervals is placed on a region with an actual length of $23.1 \mu\text{m} \times 17.6 \mu\text{m}$, and the area fractions of ferrite, bainitic ferrite, tempered martensite, and the hard phase (hard second phase) are calculated by a point counting method of counting the number of points on each phase. Each area fraction is the average value of three area fractions determined from different 5000x SEM images.

[0134] The area fraction of retained austenite is measured as described below.

[0135] A base steel sheet is mechanically ground to a quarter thickness position in the thickness direction (depth direction) and is then chemically polished with oxalic acid to form an observation surface. The observation surface is then observed by X-ray diffractometry. A $\text{MoK}\alpha$ radiation source is used for incident X-rays to determine the ratio of the

diffraction intensity of each of (200), (220), and (311) planes of fcc iron (austenite) to the diffraction intensity of each of (200), (211), and (220) planes of bcc iron. The volume fraction of retained austenite is calculated from the ratio of the diffraction intensity of each plane. On the assumption that retained austenite is three-dimensionally homogeneous, the volume fraction of retained austenite is defined as the area fraction of the retained austenite.

[0136] The area fraction of fresh martensite is determined by subtracting the area fraction of retained austenite from the area fraction of the hard phase (hard second phase) determined as described above.

[Area fraction of fresh martensite (%)] = [area fraction (%) of hard second phase] - [area fraction (%) of retained austenite]

[0137] The area fraction of the remaining microstructure is determined by subtracting the area fraction of ferrite, the area fraction of bainitic ferrite, the area fraction of tempered martensite, and the area fraction of the hard phase (hard second phase), which are determined as described above, from 100.0%.

[Area fraction of remaining microstructure (%)] = 100.0 - [area fraction of ferrite (%)] - [area fraction of --> bainitic ferrite (%)] - [area fraction of tempered martensite (%)] - [area fraction of hard second phase (%)]

Surface Soft Layer

[0138] A base steel sheet of a steel sheet according to an embodiment of the present invention preferably has a surface soft layer on the surface of the base steel sheet. The surface soft layer contributes to the suppression of the development of flex cracking during press forming and in case of a collision of an automobile body and therefore further improves bending fracture resistance characteristics. The term "surface soft layer" means a decarburized layer and refers to a surface layer region with a Vickers hardness of 85% or less with respect to the Vickers hardness of a cross section at a quarter thickness position.

[0139] The surface soft layer is formed in a region of 200 μm or less from the surface of the base steel sheet in the thickness direction. The region where the surface soft layer is formed is preferably 150 μm or less, more preferably 120 μm or less, from the surface of the base steel sheet in the thickness direction. The thickness of the surface soft layer may have any lower limit but is preferably 7 μm or more, more preferably 11 μm or more. The surface soft layer is preferably 30 μm or more, more preferably 40 μm or more.

[0140] The quarter thickness position of the base steel sheet where the Vickers hardness is measured is a non-surface-soft layer (a layer that does not satisfy the condition of the hardness of the surface soft layer defined in the present invention).

[0141] The Vickers hardness is measured at a load of 10 gf in accordance with JIS Z 2244-1 (2020).

Nanohardness of Surface Soft Layer

[0142] When the nanohardness is measured at 300 points or more in a 50 μm x 50 μm region on a sheet surface at each of a quarter depth position in the thickness direction and a half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet, the ratio of the number of measurements in which the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet is 7.0 GPa or more is 0.10 or less with respect to the total number of measurements at the quarter depth position in the thickness direction of the surface soft layer.

[0143] In the present invention, to achieve high bendability during press forming and good bending fracture characteristics in case of a collision, when the nanohardness is measured at 300 points or more in a 50 μm x 50 μm region on a sheet surface at each of a quarter depth position in the thickness direction and a half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet, the ratio of the number of measurements in which the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet is 7.0 GPa or more is preferably 0.10 or less with respect to the total number of measurements at the quarter depth position in the thickness direction of the surface soft layer. When the ratio of the nanohardness of 7.0 GPa or more is 0.10 or less, it means a low ratio of a hard microstructure (martensite or the like), an inclusion, or the like, and this can further suppress the formation and connection of voids and crack growth in the hard microstructure (martensite and the like), inclusion, or the like during press forming and in case of a collision, thus resulting in good R/t, α , and SFmax.

[0144] The nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the steel sheet has a standard deviation σ of 1.8 GPa or less, and the nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the steel sheet has a

standard deviation σ of 2.2 GPa or less.

[0145] In the present invention, to achieve high bendability during press forming and good bending fracture characteristics in case of a collision, the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the steel sheet preferably has a standard deviation σ of 1.8 GPa or less, and the nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the steel sheet preferably has a standard deviation σ of 2.2 GPa or less. When the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the steel sheet has a standard deviation σ of 1.8 GPa or less, and the nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the steel sheet has a standard deviation σ of 2.2 GPa or less, this means a small difference in microstructure hardness in a micro region and can further suppress the formation and connection of voids and crack growth during press forming and in case of a collision, thus resulting in good R/t, α , and SFmax.

[0146] The nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet preferably has a standard deviation σ of 1.7 GPa or less.

[0147] The nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet more preferably has a standard deviation σ of 1.3 GPa or less. The standard deviation σ of the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet may have any lower limit and may be 0.5 GPa or more.

[0148] The nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet more preferably has a standard deviation σ of 2.1 GPa or less. The nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet more preferably has a standard deviation σ of 1.7 GPa or less. The standard deviation σ of the nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet may have any lower limit and may be 0.6 GPa or more.

[0149] The phrase "nanohardness of a sheet surface at a quarter depth position and at a half depth position in the thickness direction" refers to a hardness measured by the following method.

[0150] When a coated layer is formed, after the coated layer is peeled off, mechanical polishing is performed to the quarter depth position - 5 μm in the thickness direction of the surface soft layer from the surface of the base steel sheet, and buffing with diamond and alumina and colloidal silica polishing are performed to the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet. The coated layer to be peeled off is a galvanized layer when the galvanized layer is formed, is a metal coated layer when the metal coated layer is formed, or is a galvanized layer and a metal coated layer when the galvanized layer and the metal coated layer are formed.

[0151] The nanohardness is measured with Hysitron tribo-950 and a Berkovich diamond indenter under the conditions of a load of 500 μN , a measurement area of 50 μm x 50 μm , and a dot-to-dot distance of 2 μm .

[0152] Mechanical polishing, buffing with diamond and alumina, and colloidal silica polishing were then performed to the half depth position in the thickness direction of the surface soft layer. The nanohardness is measured with Hysitron tribo-950 and a Berkovich diamond indenter under the conditions of a load of 500 μN , a measurement area of 50 μm x 50 μm , and a dot-to-dot distance of 2 μm .

[0153] The nanohardness is measured at 300 points or more at the quarter depth position in the thickness direction, and the nanohardness is measured at 300 points or more at the half depth position in the thickness direction.

[0154] For example, when the surface soft layer has a thickness of 100 μm , the quarter position is a position of 25 μm from the surface of the surface soft layer, and the half position is a position of 50 μm from the surface of the surface soft layer. The nanohardness is measured at 300 points or more at the position of 25 μm , and the nanohardness is also measured at 300 points or more at the position of 50 μm .

Metal Coated Layer (First Coated Layer)

[0155] A steel sheet according to an embodiment of the present invention preferably has a metal coated layer (first coated layer, precoated layer) on one or both surfaces of a base steel sheet (the metal coated layer (first coated layer) excludes a hot-dip galvanized layer and a galvanized layer of a hot-dip galvanized layer). The metal coated layer is preferably a metal electroplated layer, and the metal electroplated layer is described below as an example.

[0156] When the metal electroplated layer is formed on the surface of a steel sheet, the metal electroplated layer as the outermost surface layer contributes to the suppression of the occurrence of flex cracking during press forming and in case of a collision of an automobile body and therefore further improves the bending fracture resistance characteristics.

[0157] In the present invention, the dew point can be more than -5°C to further increase the thickness of the soft layer and significantly improve axial compression characteristics. In this regard, in the present invention, due to a metal coated layer, even when the dew point is -5°C or less and the soft layer has a small thickness, axial compression characteristics equivalent to those in the case where the soft layer has a large thickness can be achieved.

[0158] The metal species of the metal electroplated layer may be any of Cr, Mn, Fe, Co, Ni, Cu, Ga, Ge, As, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Os, Ir, Rt, Au, Hg, Ti, Pb, and Bi and is preferably Fe. Although an Fe-based electroplated layer is described below as an example, the following conditions for Fe can also be applied to other metal species.

[0159] The coating weight of the Fe-based electroplated layer is more than 0 g/m², preferably 2.0 g/m² or more. The upper limit of the coating weight per side of the Fe-based electroplated layer is not particularly limited, and from the perspective of cost, the coating weight per side of the Fe-based electroplated layer is preferably 60 g/m² or less. The coating weight of the Fe-based electroplated layer is preferably 50 g/m² or less, more preferably 40 g/m² or less, even more preferably 30 g/m² or less.

[0160] The coating weight of the Fe-based electroplated layer is measured as described below. A sample with a size of 10 x 15 mm is taken from the Fe-based electroplated steel sheet and is embedded in a resin to prepare a cross-section embedded sample. Three arbitrary places on the cross section are observed with a scanning electron microscope (SEM) at an acceleration voltage of 15 kV and at a magnification of 2,000 to 10,000 times depending on the thickness of the Fe-based coated layer. The average thickness of the three visual fields is multiplied by the specific gravity of iron to convert it into the coating weight per side of the Fe-based electroplated layer.

[0161] The Fe-based electroplated layer may be, in addition to pure Fe, an alloy coated layer, such as an Fe-B alloy, an Fe-C alloy, an Fe-P alloy, an Fe-N alloy, an Fe-O alloy, an Fe-Ni alloy, an Fe-Mn alloy, an Fe-Mo alloy, or an Fe-W alloy. The Fe-based electroplated layer may have any chemical composition and preferably has a chemical composition containing 10% by mass or less in total of one or two or more elements selected from the group consisting of B, C, P, N, O, Ni, Mn, Mo, Zn, W, Pb, Sn, Cr, V, and Co, with the remainder being Fe and incidental impurities. When the total amount of elements other than Fe is 10% by mass or less, this can prevent a decrease in electrolysis efficiency and can form an Fe-based electroplated layer at low cost. For an Fe-C alloy, the C content is preferably 0.08% by mass or less.

[0162] A surface soft layer is more preferably provided under an Fe-based electroplated layer, and this can significantly improve bending fracture resistance characteristics. In the presence of an Fe-based electroplated layer, the Vickers hardness distribution is measured by the method described above from the interface between the Fe-based electroplated layer and the base steel sheet in the thickness direction, and the depth of the surface soft layer in the thickness direction is evaluated.

[0163] In a V-VDA bending test performed to a maximum load point, in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with a hard phase (the number of voids at a boundary between the hard phase and a soft phase and the number of voids formed by fracture of the hard phase) among all voids by the total number of voids: 0.60 or less

[0164] In an overlap region of a V-bending flat portion and a VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with a hard phase (the number of voids at the boundary between the hard phase and a soft phase and the number of voids formed by fracture of the hard phase) among all voids by the total number of voids: 0.20 or less

[0165] In the present invention, high bending fracture characteristics in a V-VDA bending test can be achieved by void control as described above. When a void in a steel sheet microstructure is formed adjacent to a hard phase, the void is likely to develop along a boundary between the hard phase and a soft phase and finally causes a crack. For a void not adjacent to a hard phase, for example, for a void formed adjacent to carbide, it is thought that the connection and development of the void are less likely to occur.

[0166] In a V-bending ridge line portion and a VDA bending ridge line portion, fresh martensite formed by deformation-induced transformation during V-bending increases the area fraction of a hard phase. In the present invention, in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with a hard phase (the number of voids at a boundary between the hard phase and a soft phase and the number of voids formed by fracture of the hard phase) among all voids by the total number of voids is 0.60 or less. This value is preferably 0.59 or less, more preferably 0.58 or less. The lower limit is not particularly limited, and the value may be 0.00.

[0167] On the other hand, in a V-bending flat portion and a VDA bending ridge line portion, the area fraction of a hard phase is relatively low. In the present invention, in an overlap region of a V-bending flat portion and a VDA bending ridge line portion, the value obtained by dividing the number of voids in contact with a hard phase among all voids by the total number of voids is 0.20 or less. This value is preferably 0.19 or less, more preferably 0.18 or less. The lower limit is not particularly limited, and the value may be 0.00.

[0168] The term "soft phase", as used herein, refers to a phase other than the hard phase.

[0169] The V-VDA bending test is performed as described below.

[0170] A 60 mm x 65 mm test specimen is taken from the steel sheet by shearing. The sides of 60 mm are parallel to the rolling (L) direction. 90-degree bending (primary bending) is performed at a radius of curvature/thickness ratio of 4.2 in the rolling (L) direction with respect to an axis extending in the width (C) direction to prepare a test specimen. In the 90-degree bending (primary bending), as illustrated in Fig. 2-1(a), a punch B1 is pressed against a steel sheet on a die A1 with a V-groove to prepare a test specimen T1. Next, as illustrated in Fig. 2-1(b), the test specimen T1 on support rolls A2 is

subjected to orthogonal bending (secondary bending) by pressing a punch B2 against the test specimen T1 in the direction perpendicular to the rolling direction. In Figs. 2-1(a) and 2-1(b), the symbol D1 indicates the width (C) direction, and the symbol D2 indicates the rolling (L) direction.

[0171] Fig. 3 is a schematic view of a stroke-load curve obtained in a V-VDA test. A sample obtained by performing the V-VDA test to the maximum load point P and then removing the load when the load reaches 94.9% to 99.9% of the maximum load (see the symbol R in Fig. 3) is used as an evaluation sample in the V-VDA bending test.

[0172] Fig. 2-2(c) illustrates the test specimen T1 prepared by subjecting the steel sheet to V-bending (primary bending) in the V-VDA bending test. Fig. 2-2(d) illustrates a test specimen T2 obtained by subjecting the test specimen T1 to VDA bending (secondary bending). The position indicated by the broken line in the test specimen T2 in Fig. 2-2(d) is the V-bending ridge line portion and corresponds to the position indicated by the broken line in the test specimen T1 in Fig. 2-2(c) before the VDA bending is performed. A V-bending ridge line portion and a VDA bending ridge line portion "a" (an overlap region "a" of the V-bending ridge line portion and the VDA bending ridge line portion), and a V-bending flat portion (unprocessed portion) and the VDA bending ridge line portion "b" are shown in Fig. 2-2(d).

[0173] The term "V-bending ridge line portion", as used herein, refers to the region within 5 mm on both sides of a V-bending corner portion (peak) that is subjected to V-bending and extends in the width direction.

[0174] The term "V-bending flat portion" refers to a region other than the V-bending ridge line portion in a steel sheet.

[0175] The term "VDA bending ridge line portion" refers to the region within 5 mm on both sides of a VDA bending corner portion (peak) that is subjected to VDA bending and extends in the rolling direction.

[0176] Fig. 2-3(e) shows the L cross section AL with the D2 direction being perpendicular to the drawing and the D1 direction being parallel to the drawing.

[0177] A void in the V-bending ridge line portion and the VDA bending ridge line portion and a void in the V-bending flat portion and the VDA bending ridge line portion are measured as described below. A thickness cross section obtained by cutting a steel sheet after a V-VDA bending test in a V-bending ridge line portion and a VDA bending ridge line portion "a" and in a V-bending flat portion and the VDA bending ridge line portion "b" in a direction perpendicular to the rolling direction is polished, and three visual fields in a C cross section in a region of 0 to 100 μm from the surface of the steel sheet at a bending peak portion on the outside of a VDA bend (an AB region indicated by the dotted line in Fig. 2-3(e)) are then photographed with a scanning electron microscope (SEM) at a magnification of 3000 times. In an image thus taken, microstructures around a void are identified as described above, and the void is darker black than ferrite and can be clearly distinguished from the microstructures. Of all voids, the number of voids in which more than 0% of the circumferential length is in contact with a hard phase (a hard second phase (retained austenite + fresh martensite)) is the sum of the number of voids at a boundary between the hard phase and a soft phase and the number of voids formed by fracture of the hard phase.

[0178] The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids specified in the present invention is calculated by averaging in three visual fields the values obtained by dividing the number of voids in which more than 0% of the circumferential length is in contact with the hard phase (the sum of the number of voids at a boundary between the hard phase and the soft phase and the number of voids formed by fracture of the hard phase) by the total number of voids. This measurement is performed on a test specimen prepared by performing the V-VDA bending test to the maximum load and then removing the load when the load reaches 94.9% to 99.9% (for example, 95%) of the maximum load (see Fig. 3 again).

[0179] For one void, in a SEM image, an island-like region with the outer periphery surrounded by a microstructure and integrally formed without interruption is regarded as one to be measured.

Mean free path L_M of carbide: 0.20 μm or more

[0180] Figs. 4(a) to 4(c) show examples of a microstructure image for explaining a void. In Fig. 4, the symbol H1 indicates a hard phase, and the symbol S1 indicates a soft phase. The symbol V1 in Fig. 4(a) indicates a void at a boundary between a hard phase and a soft phase, the symbol V2 in Fig. 4(b) indicates a void formed by fracture of a hard phase, the symbol V3 in Fig. 4(c) indicates a void due to carbide, and the symbol θ indicates carbide.

[0181] In the present invention, as shown in Fig. 4 (in particular, see Fig. 4(c)), after V-VDA bending performed to the maximum load, void formation in a steel sheet microstructure may be caused by carbide (see the symbols V3 and θ). When carbide has a mean free path of less than 0.20 μm , the distance between voids due to the carbide increases, stress is concentrated on a portion where a void is formed, and voids are easily connected. Consequently, desired $S_{F\text{max}}$ cannot be achieved. Thus, in a steel sheet (a steel sheet not subjected to a V-VDA bending test), carbide has a mean free path L_M of 0.20 μm or more. L_M is preferably 0.25 μm or more, more preferably 0.30 μm or more. L_M is preferably 0.50 μm or less, more preferably 0.45 μm or less.

[0182] An average value σ_C of a standard deviation of a distance between a carbide particle A selected from all carbide particles in a steel sheet and a remaining carbide particle other than the carbide particle A: 7.50 μm or less

[0183] Variations in carbide distribution affect the formation and connection of voids. When the average value σ_C of the

standard deviation of the distance between carbide particles is more than 7.50 μm , variations in the distribution of voids due to carbide increase, stress is concentrated on a portion where many voids are formed, and voids are easily connected. Consequently, desired $S_{F\text{max}}$ cannot be achieved. Thus, in a steel sheet (a steel sheet not subjected to a V-VDA bending test), the average value σ_C of the standard deviation of the distance between carbide particles is 7.50 μm or less. σ_C is preferably 7.30 μm or less, more preferably 7.00 μm or less. σ_C is preferably 5.00 μm or more, more preferably 6.00 μm or more.

[0184] The mean free path L_M and the standard deviation of carbide are measured as described below. In a 25.6 μm x 17.6 μm region of a steel sheet (a steel sheet not subjected to a V-VDA bending test), carbide is extracted by manual color-coding from the SEM microstructure image used for the microstructure fraction measurement to obtain an image of only the carbide. The area fraction of all carbide particles and the coordinate of the center of gravity and the equivalent circular diameter of each carbide particle are determined using ImageJ from an open source. Assuming that carbide is three-dimensionally homogeneous, the area fraction of the carbide is defined as the volume fraction of the carbide.

[0185] The mean free path L_M of carbide is calculated using the following formula:

$$L_M = (d_M/2) \times ((400\pi/3f)^{1/3}) \quad \text{formula (1)}$$

wherein L_M denotes the mean free path of carbide (the mean free path of the center of gravity of carbide), d_M denotes the average (number average) equivalent circular diameter (μm) of carbide, π denotes the circumference ratio, and f denotes the volume fraction (%) of all carbide particles.

[0186] The average value σ_C of the standard deviation of the distance between carbide particles is calculated using the following formula (2):

[Math. 1]

$$\sigma_C = \frac{1}{n} \sum_{i=1}^n \sqrt{\frac{1}{n-1} \sum_{j=1}^{n-1} (d_{ij} - d_{iave})^2} \quad \text{Formula (2)}$$

[0187] In the formula (2), n , i , j , d_{ij} , and d_{iave} are as follows:

n : the number of all carbide particles in the visual field (25.6 μm x 17.6 μm).

i : the number of a carbide particle (one carbide particle A arbitrarily selected from all carbide particles) to measure the distance from another carbide particle, and i is an integer in the range of 1 to n .

j : the number of a carbide particle other than the carbide particle A, and j is an integer in the range of 1 to n other than i .

d_{ij} : the distance (μm) between the i -th carbide particle (the carbide particle A) and the j -th carbide particle.

d_{iave} : the average distance (μm) between all carbide particles (excluding the i -th carbide particle) and the i -th carbide particle in the visual field.

[0188] Next, mechanical characteristics of a steel sheet according to an embodiment of the present invention are described.

Tensile strength (TS): 1180 MPa or more

[0189] A steel sheet according to an embodiment of the present invention has a tensile strength TS of 1180 MPa or more. The tensile strength TS may have any upper limit but is preferably less than 1470 MPa.

[0190] The yield stress (YS), the total elongation (EI), the limiting hole expansion ratio (λ), the critical bending angle (α) in the VDA bending test, the stroke at the maximum load ($S_{F\text{max}}$) in the V-VDA bending test, and the presence or absence of axial compression fracture of a steel sheet according to an embodiment of the present invention are as described above.

[0191] The tensile strength (TS), the yield stress (YS), and the total elongation (EI) are measured in the tensile test according to JIS Z 2241 (2011) described later in Examples. The limiting hole expansion ratio (λ) is measured in the hole expansion test according to JIS Z 2256 (2020) described later in Examples. The critical bending angle (α) in the VDA bending test is measured in the VDA bending test according to VDA 238-100 described later in Examples. The stroke at the maximum load ($S_{F\text{max}}$) in the V-VDA bending test is measured in a V-VDA bending test described later in Examples. The presence or absence of axial compression fracture is measured in an axial compression test described later in Examples.

Galvanized Layer (Second Coated Layer)

[0192] A steel sheet according to an embodiment of the present invention may have a galvanized layer formed on a base steel sheet (on the surface of the base steel sheet or on the surface of a metal coated layer when the metal coated layer is formed) as the outermost surface layer, and the galvanized layer may be provided on only one surface or both surfaces of the base steel sheet.

[0193] Thus, a steel sheet according to the present invention may have a base steel sheet and a second coated layer (a galvanized layer) formed on the base steel sheet or may have a base steel sheet and a metal coated layer (a first coated layer (excluding a second coated layer of a galvanized layer) and a second coated layer (a galvanized layer) sequentially formed on the base steel sheet.

[0194] A steel sheet with a galvanized layer may be a galvanized steel sheet.

[0195] The term "galvanized layer", as used herein, refers to a coated layer containing Zn as a main component (Zn content: 50.0% or more), for example, a hot-dip galvanized layer or a hot-dip galvanized annealed layer.

[0196] The hot-dip galvanized layer is preferably composed of, for example, Zn, 20.0% by mass or less of Fe, and 0.001% by mass or more and 1.0% by mass or less of Al. The hot-dip galvanized layer may optionally contain one or two or more elements selected from the group consisting of Pb, Sb, Si, Sn, Mg, Mn, Ni, Cr, Co, Ca, Cu, Li, Ti, Be, Bi, and REM in a total amount of 0.0% by mass or more and 3.5% by mass or less. The hot-dip galvanized layer more preferably has an Fe content of less than 7.0% by mass. The remainder other than these elements is incidental impurities.

[0197] The hot-dip galvanized annealed layer is preferably composed of, for example, Zn, 20.0% by mass or less of Fe, and 0.001% by mass or more and 1.0% by mass or less of Al. The hot-dip galvanized annealed layer may optionally contain one or two or more elements selected from the group consisting of Pb, Sb, Si, Sn, Mg, Mn, Ni, Cr, Co, Ca, Cu, Li, Ti, Be, Bi, and REM in a total amount of 0.0% by mass or more and 3.5% by mass or less. The hot-dip galvanized annealed layer more preferably has an Fe content of 7.0% by mass or more, even more preferably 8.0% by mass or more. The hot-dip galvanized annealed layer more preferably has an Fe content of 15.0% by mass or less, even more preferably 12.0% by mass or less. The remainder other than these elements is incidental impurities.

[0198] Furthermore, the coating weight per side of the galvanized layer is preferably, but not limited to, 20 g/m² or more. The coating weight per side of the galvanized layer is preferably 80 g/m² or less.

[0199] The coating weight of the galvanized layer is measured as described below.

[0200] A treatment liquid is prepared by adding 0.6 g of a corrosion inhibitor for Fe ("IBIT 700BK" (registered trademark) manufactured by Asahi Chemical Co., Ltd.) to 1 L of 10% by mass aqueous hydrochloric acid. A steel sheet as a sample is immersed in the treatment liquid to dissolve a galvanized layer. The mass loss of the sample due to the dissolution is measured and is divided by the surface area of a base steel sheet (the surface area of a coated portion) to calculate the coating weight (g/m²).

[0201] The thickness of a steel sheet according to an embodiment of the present invention is preferably, but not limited to, 0.5 mm or more, more preferably 0.6 mm or more.

[0202] The thickness is more preferably more than 0.8 mm. The thickness is even more preferably 0.9 mm or more. The thickness is more preferably 1.0 mm or more. The thickness is even more preferably 1.2 mm or more.

[0203] The steel sheet preferably has a thickness of 3.5 mm or less. The thickness is more preferably 2.3 mm or less.

[0204] The width of a steel sheet according to the present invention is preferably, but not limited to, 500 mm or more, more preferably 750 mm or more. The steel sheet preferably has a width of 1600 mm or less, more preferably 1450 mm or less.

[2. Method for Producing Steel Sheet]

[0205] Next, a method for producing a steel sheet according to an embodiment of the present invention is described.

[0206] A method for producing a steel sheet according to an embodiment of the present invention includes: a hot rolling step of hot-rolling a steel slab with the chemical composition described above to produce a hot-rolled steel sheet; a pickling step of pickling the hot-rolled steel sheet; an annealing step of annealing the steel sheet after the pickling step at an annealing temperature of $(Ac_1 + (Ac_3 - Ac_1) \times 3/4)^\circ\text{C}$ or more and 900°C or less for an annealing time of 20 seconds or more; a first cooling step of cooling the steel sheet after the annealing step to a first cooling stop temperature of 100°C or more and 300°C or less; a holding step of holding the steel sheet after the first cooling step in a temperature range of 350°C or more and 550°C or less for 3 seconds or more and less than 80 seconds; a second cooling step of cooling the steel sheet after the holding step to a second cooling stop temperature of 50°C or less, during the cooling, applying a tension of 2.0 kgf/mm² or more to the steel sheet once or more in a temperature range of 300°C or more and 450°C or less, then subjecting the steel sheet to four or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll, and subjecting the steel sheet to two or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for half a circumference of the roll; and optionally a cold rolling step of cold-rolling the steel sheet after the pickling step and before the annealing step to produce a cold-rolled

steel sheet.

[0207] Unless otherwise specified, the temperatures described above mean the surface temperatures of a steel slab and a steel sheet.

[0208] First, a steel slab with the chemical composition described above is prepared. For example, a steel material is melted to produce a molten steel with the chemical composition described above. The melting method may be, but is not limited to, any known melting method using a converter, an electric arc furnace, or the like. The resulting molten steel is then solidified into a steel slab. The steel slab may be produced from the molten steel by any method, for example, a continuous casting method, an ingot casting method, a thin slab casting method, or the like. From the perspective of preventing macrosegregation, a continuous casting method is preferred.

[Hot Rolling Step]

[0209] Next, in the hot rolling step, the steel slab is hot-rolled to produce a hot-rolled steel sheet.

[0210] The hot-rolling may be performed in an energy-saving process. The energy-saving process may be hot charge rolling (a method of charging a furnace with the steel slab as a hot piece not cooled to room temperature and hot-rolling the steel slab), hot direct rolling (a method of keeping the steel slab slightly warm and then immediately rolling the steel slab), or the like.

[0211] The hot rolling may be performed under any conditions, for example, under the following conditions.

[0212] The steel slab is temporarily cooled to room temperature and is then reheated and rolled. The slab heating temperature (reheating temperature) is preferably 1100°C or more from the perspective of melting carbide and reducing rolling force. The slab heating temperature is preferably 1300°C or less to prevent an increase in scale loss. The slab heating temperature is based on the temperature of the steel slab surface.

[0213] The steel slab is then rough-rolled in the usual manner to form a rough-rolled sheet (hereinafter also referred to as a sheet bar). The sheet bar is then finish-rolled to form a hot-rolled steel sheet. When the slab is heated at a slightly lower temperature, the sheet bar is preferably heated with a bar heater or the like before finish rolling to prevent trouble in the finish rolling. The finish rolling temperature is preferably 800°C or more to reduce the rolling load. Furthermore, when the rolling reduction of austenite in an unrecrystallized state is increased, an abnormal microstructure elongated in the rolling direction may be developed and impair the workability of an annealed sheet. Furthermore, at a finish rolling temperature of 800°C or more, not only the steel microstructure of the hot-rolled steel sheet but also the steel microstructure of the final product is likely to be uniform. A nonuniform steel microstructure tends to result in lower bendability.

[0214] On the other hand, at a finish rolling temperature of more than 950°C, the amount of oxide (scale) formed increases. This may roughen the interface between a steel substrate and the oxide and impair the surface quality of the steel sheet after pickling and cold rolling. This may also coarsen crystal grains and reduce the strength and bendability of the steel sheet. Thus, the finish rolling temperature is preferably 950°C or more. Thus, the finish rolling temperature is preferably 800°C or more and 950°C or more.

[0215] After the finish rolling, the hot-rolled steel sheet is coiled. The coiling temperature is preferably 450°C or more. The coiling temperature is preferably 750°C or less.

[0216] Sheet bars may be joined together during hot rolling to continuously perform the finish rolling. The sheet bar may be temporarily coiled before the finish rolling. Furthermore, to reduce the rolling force during hot rolling, the finish rolling may be partly or entirely rolling with lubrication. The rolling with lubrication is also effective in making the shape and the material quality of a steel sheet uniform. The friction coefficient in the rolling with lubrication is preferably 0.10 or more and 0.25 or less.

[0217] In the hot rolling step including rough rolling and finish rolling (hot rolling step), the steel slab is typically formed into a sheet bar by the rough rolling and then into a hot-rolled steel sheet by the finish rolling. Depending on the mill capacity or the like, however, such classification is not concerned, provided that a predetermined size is obtained.

[Pickling Step]

[0218] The hot-rolled steel sheet after the hot rolling step is pickled. The pickling can remove an oxide from the surface of the steel sheet and ensure high chemical convertibility and coating quality. The pickling may be performed once or multiple times. The pickling may be performed under any conditions and may be performed in the usual manner.

[Cold Rolling Step]

[0219] Next, when necessary, the hot-rolled steel sheet is cold-rolled to produce a cold-rolled steel sheet. The cold rolling is, for example, multi-pass rolling requiring two or more passes, such as tandem multi-stand rolling or reverse rolling.

[0220] The rolling reduction (cumulative rolling reduction ratio) in the cold rolling is preferably, but not limited to, 20% or more. The rolling reduction in the cold rolling is preferably 80% or less. A rolling reduction of less than 20% in the cold rolling

tends to result in coarsening or a lack of uniformity of the steel microstructure in the annealing step and may result in the final product with lower TS or bendability. On the other hand, a rolling reduction of more than 80% in the cold rolling tends to result in a steel sheet with a poor shape and may result in an uneven galvanizing coating weight.

[0221] Optionally, a cold-rolled steel sheet after the cold rolling may be pickled.

[Metal Coating (Metal Electroplating, First Coating) Step]

[0222] An embodiment of the present invention may include a first coating step of performing metal coating on one or both surfaces of the steel sheet after the hot rolling step (after the pickling step or after the cold rolling step after the pickling step when cold rolling is performed) and before the annealing step to form a metal coated layer (first coated layer).

[0223] For example, a metal electroplating treatment may be performed on the surface of the hot-rolled steel sheet or the cold-rolled steel sheet thus formed to produce a metal electroplated steel sheet before annealing in which a metal electroplated layer before annealing is formed on at least one surface thereof. The term "metal coating", as used herein, excludes galvanizing (second coating).

[0224] Although the metal electroplating treatment method is not particularly limited, as described above, the metal coated layer formed on the base steel sheet is preferably a metal electroplated layer, and the metal electroplating treatment is therefore preferably performed.

[0225] For example, a sulfuric acid bath, a hydrochloric acid bath, a mixture of both, or the like can be used as an Fe-based electroplating bath. The coating weight of the metal electroplated layer before annealing can be adjusted by the energization time or the like. The phrase "metal electroplated steel sheet before annealing" means that the metal electroplated layer is not subjected to an annealing step, and does not exclude a hot-rolled steel sheet, a pickled sheet after hot rolling, or a cold-rolled steel sheet each annealed in advance before a metal electroplating treatment.

[0226] The metal species of the electroplated layer may be any of Cr, Mn, Fe, Co, Ni, Cu, Ga, Ge, As, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Os, Ir, Rt, Au, Hg, Ti, Pb, and Bi and is preferably Fe. Although a method for producing Fe-based electroplating is described below as an example, the following conditions for the Fe-based electroplating can also be applied to another metal electroplating.

[0227] The Fe ion content of an Fe-based electroplating bath before the start of energization is preferably 0.5 mol/L or more in terms of Fe^{2+} . When the Fe ion content of an Fe-based electroplating bath is 0.5 mol/L or more in terms of Fe^{2+} , a sufficient Fe coating weight can be obtained. To obtain a sufficient Fe coating weight, the Fe ion content of the Fe-based electroplating bath before the start of energization is preferably 2.0 mol/L or less.

[0228] The Fe-based electroplating bath may contain an Fe ion and at least one element selected from the group consisting of B, C, P, N, O, Ni, Mn, Mo, Zn, W, Pb, Sn, Cr, V, and Co. The total content of these elements in the Fe-based electroplating bath is preferably such that the total content of these elements in an Fe-based electroplated layer before annealing is 10% by mass or less. A metal element may be contained as a metal ion, and a non-metal element can be contained as part of boric acid, phosphoric acid, nitric acid, an organic acid, or the like. An iron sulfate coating solution may contain a conductive aid, such as sodium sulfate or potassium sulfate, a chelating agent, or a pH buffer.

[0229] Other conditions of the Fe-based electroplating bath are also not particularly limited. The temperature of an Fe-based electroplating solution is preferably 30°C or more and 85°C or less in view of constant temperature retention ability. The pH of the Fe-based electroplating bath is also not particularly limited, is preferably 1.0 or more from the perspective of preventing a decrease in current efficiency due to hydrogen generation, and is preferably 3.0 or less in consideration of the electrical conductivity of the Fe-based electroplating bath. The electric current density is preferably 10 A/dm² or more from the perspective of productivity and is preferably 150 A/dm² or less from the perspective of facilitating the control of the coating weight of an Fe-based electroplated layer. The line speed is preferably 5 mpm or more from the perspective of productivity and is preferably 150 mpm or less from the perspective of stably controlling the coating weight.

[0230] A degreasing treatment and water washing for cleaning the surface of a steel sheet and also a pickling treatment and water washing for activating the surface of a steel sheet can be performed as a treatment before Fe-based electroplating treatment. These pretreatments are followed by an Fe-based electroplating treatment. The degreasing treatment and water washing may be performed by any method, for example, by a usual method. In the pickling treatment, various acids, such as sulfuric acid, hydrochloric acid, nitric acid, and mixtures thereof can be used. Among them, sulfuric acid, hydrochloric acid, or a mixture thereof is preferred. The acid concentration is not particularly limited and preferably ranges from approximately 1% to 20% by mass in consideration of the capability of removing an oxide film, prevention of a rough surface (surface defect) due to overpickling, and the like. A pickling treatment liquid may contain an antifoaming agent, a pickling accelerator, a pickling inhibitor, or the like.

[Annealing Step]

[0231] In an embodiment of the present invention, after the pickling step (after the cold rolling step when cold rolling is performed, after a metal coating (first coating) step when metal coating is performed to form a metal coated layer (first

coated layer), or after the metal coating (first coating) step when cold rolling and metal coating are performed), the steel sheet thus produced is annealed at an annealing temperature of $(Ac_1 + (Ac_3 - Ac_1) \times 3/4)^\circ\text{C}$ or more and 900°C or less for an annealing time of 20 seconds or more. The number of annealing processes may be two or more but is preferably one from the perspective of energy efficiency.

Annealing temperature: $(Ac_1 + (Ac_3 - Ac_1) \times 3/4)^\circ\text{C}$ or more and 900°C or less

[0232] An annealing temperature lower than $(Ac_1 + (Ac_3 - Ac_1) \times 3/4)^\circ\text{C}$ results in an insufficient proportion of austenite formed during heating in a two-phase region of ferrite and austenite. This results in an excessive increase in the area fraction of ferrite after annealing and lower YS. This also excessively increases the C concentration in austenite during annealing and results in undesired λ and S_{Fmax} . This also makes it difficult to achieve a TS of 1180 MPa or more.

[0233] On the other hand, an annealing temperature of more than 900°C results in excessive grain growth of austenite, a higher MS temperature, and a large amount of tempered martensite containing carbide, makes it difficult to form 3.0% or more of retained austenite, and results in lower ductility. Thus, the annealing temperature is $(Ac_1 + (Ac_3 - Ac_1) \times 3/4)^\circ\text{C}$ or more and 900°C or less. The annealing temperature is preferably 880°C or less. The annealing temperature is more preferably 870°C or less. The annealing temperature is preferably $(Ac_1 + (Ac_3 - Ac_1) \times 4/5)^\circ\text{C}$ or more, more preferably $(Ac_1 + (Ac_3 - Ac_1) \times 5/6)^\circ\text{C}$ or more.

[0234] The annealing temperature is the highest temperature reached in the annealing step.

[0235] The Ac_1 point ($^\circ\text{C}$) and the Ac_3 point ($^\circ\text{C}$) are calculated using the following formula:

$$Ac_1 \text{ point } (^\circ\text{C}) = 727.0 - 32.7 \times [\%C] + 14.9 \times [\%Si] + 2.0 \times [\%Mn]$$

$$Ac_3 \text{ point } (^\circ\text{C}) = 912.0 - 230 \times [\%C] + 31.6 \times [\%Si] - 20.4 \times [\%Mn]$$

wherein $[\%C]$ denotes the C content (% by mass), $[\%Si]$ denotes the Si content (% by mass), and $[\%Mn]$ denotes the Mn content (% by mass).

Annealing time: 20 seconds or more

[0236] An annealing time of less than 20 seconds results in an insufficient proportion of austenite formed during heating in a two-phase region of ferrite and austenite. This results in an excessive increase in the area fraction of ferrite after annealing and lower YS. This also excessively increases the C concentration in austenite during annealing and results in undesired λ and S_{Fmax} . This also makes it difficult to achieve a TS of 1180 MPa or more. Thus, the annealing time is 20 seconds or more. The annealing time is preferably 30 seconds or more, more preferably 50 seconds or more. The annealing time may have any upper limit and is preferably 900 seconds or less, more preferably 800 seconds or less. The annealing time is even more preferably 300 seconds or less, even further more preferably 220 seconds or less.

[0237] The term "annealing time" refers to the holding time in the temperature range of (annealing temperature - 40°C) or more and the annealing temperature or less. Thus, the annealing time includes, in addition to the holding time at the annealing temperature, the residence time in the temperature range of (annealing temperature - 40°C) or more and the annealing temperature or less in heating and cooling before and after reaching the annealing temperature.

Dew point of annealing atmosphere in annealing step: -30°C or more

[0238] In an embodiment of the present invention, the dew point of the atmosphere in the annealing step (annealing atmosphere) is preferably -30°C . Annealing at a dew point of -30°C or more in the annealing atmosphere in the annealing step can promote a decarburization reaction and more deeply form a surface soft layer. The dew point of the annealing atmosphere in the annealing step is more preferably -25°C or more, even more preferably -15°C or more, most preferably more than -5°C .

[0239] The dew point of the annealing atmosphere in the annealing step may have any upper limit and is preferably 30°C or less in order to suitably prevent oxidation of the surface of an Fe-based electroplated layer and to improve the coating adhesion when a galvanized layer is provided.

[First Cooling Step]

[0240] The steel sheet annealed as described above is then cooled to a first cooling stop temperature of 100°C or more and 300°C or less.

First cooling stop temperature: 100°C or more and 300°C or less

[0241] The first cooling step is a step necessary to control the area fraction of tempered martensite and the volume fraction of retained austenite formed in the subsequent reheating step within predetermined ranges. At a first cooling stop temperature of less than 100°C, almost all the non-transformed austenite present in the steel is transformed into martensite in the first cooling step. This finally results in an excessive increase in the area fraction of tempered martensite, makes it difficult to form 3.0% or more by area of retained austenite, and results in lower ductility. On the other hand, a second cooling stop temperature of more than 300°C results in a decrease in the area fraction of tempered martensite and an increase in the area fraction of fresh martensite. This results in fresh martensite acting as a starting point of void formation in a hole expansion test, a VDA bending test, and a V-VDA bending test, and desired λ , α , and S_{Fmax} cannot be achieved. Thus, the first cooling stop temperature is 100°C or more and 300°C or less. The first cooling stop temperature is preferably 120°C or more. The first cooling stop temperature is preferably 280°C or less.

[Holding Step]

[0242] After the first cooling step, the steel sheet is held in the temperature range of 350°C or more and 550°C or less (hereinafter also referred to as a holding temperature range) for 3 seconds or more and less than 80 seconds.

[0243]

Holding temperature range: 350°C or more and 550°C or less

Holding time in holding temperature range: 3 seconds or more and less than 80 seconds

[0244] In the holding step, bainitic ferrite is formed, and C diffuses from the formed bainitic ferrite to non-transformed austenite adjacent to the bainitic ferrite. This ensures a predetermined area fraction of retained austenite.

[0245] At a holding temperature of less than 350°C, the value obtained by dividing the area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite cannot be in the desired range, and the desired α and S_{Fmax} cannot be achieved. Good axial compression characteristics also cannot be achieved.

[0246] On the other hand, at a holding temperature of more than 550°C, the area fraction of retained austenite is less than 3.0%, the area fraction of fresh martensite is more than 10.0%, desired ductility cannot be achieved, and desired α and S_{Fmax} also cannot be achieved. Good axial compression characteristics also cannot be achieved.

[0247] Thus, the holding temperature range is 350°C or more and 550°C or less. The holding temperature range is preferably 360°C or more, more preferably 370°C or more. The holding temperature range is preferably 530°C or less, more preferably 510°C or less.

[0248] A holding time of less than 3 seconds in the holding temperature range makes it difficult to form 3.0% or more of retained austenite and results in lower ductility.

[0249] On the other hand, a holding time of 80 seconds or more in the holding temperature range results in an excessive increase in the area fraction of bainitic ferrite and lower YS. This also results in excessive diffusion of C from bainitic ferrite to non-transformed austenite, retained austenite with an area fraction of more than 10.0%, and undesired S_{Fmax} . Furthermore, desired λ may not be achieved.

[0250] Thus, the holding time in the holding temperature range is preferably 3 seconds or more and less than 80 seconds. The holding time in the holding temperature range is preferably 5 seconds or more. The holding time in the holding temperature range is preferably less than 60 seconds. The holding time in the holding temperature range does not include the residence time in the temperature range after the hot-dip galvanizing treatment in the coating step.

[Galvanizing Step (Second Coating Step)]

[0251] After the holding step, the steel sheet may be subjected to a galvanizing treatment. A galvanized steel sheet can be produced by the galvanizing treatment. The galvanizing treatment is, for example, a hot-dip galvanizing treatment or a galvannealing treatment.

[0252] In the hot-dip galvanizing treatment, preferably, the steel sheet is immersed in a galvanizing bath at 440°C or more and 500°C or less, and the coating weight is then adjusted by gas wiping or the like. The hot-dip galvanizing bath is not particularly limited as long as the galvanized layer has the composition described above. For example, the galvanizing bath preferably has a composition with an Al content of 0.10% by mass or more, the remainder being Zn and incidental impurities. The Al content is preferably 0.23% by mass or less.

[0253] In the galvannealing treatment, after the hot-dip galvanizing treatment performed in the manner described above, the galvanized steel sheet is preferably heated to an alloying temperature of 450°C or more to perform an alloying treatment. The alloying temperature is preferably 600°C or less.

[0254] An alloying temperature of less than 450°C may result in a low Zn-Fe alloying speed and make alloying difficult. At

an alloying temperature of less than 450°C, martensite formed in the first cooling step is not sufficiently tempered, the area fraction of fresh martensite increases excessively, and desired λ , α , and S_{Fmax} may not be achieved. On the other hand, an alloying temperature of more than 600°C results in transformation of non-transformed austenite into pearlite, makes it difficult to achieve a TS of 1180 MPa or more, and results in lower ductility. The alloying temperature is more preferably 510°C or more. The alloying temperature is more preferably 570°C or less.

[0255] The coating weight of each of the hot-dip galvanized steel sheet (GI) and the hot-dip galvanized steel sheet (GA) is preferably 20 g/m² or more per side. The coating weight per side of the galvanized layer is preferably 80 g/m² or less. The coating weight can be adjusted by gas wiping or the like.

10 [Second Cooling Step]

[0256] The steel sheet after the holding step is then cooled to a second cooling stop temperature of 50°C or less.

[0257] When a steel sheet is cooled to the second cooling stop temperature of 50°C or less, a tension of 2.0 kgf/mm² or more is applied once or more in the temperature range of 300°C or more and 450°C or less. The steel sheet to which the tension has been applied is subjected to four or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll, and is subjected to two or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for half a circumference of the roll.

[0258] As described above, applying a tension of 2.0 kgf/mm² or more to the steel sheet once or more and subjecting the steel sheet to a specified number of passes cause deformation-induced transformation of retained austenite excessively formed in the steel sheet microstructure into martensite and then into tempered martensite during subsequent cooling. Consequently, desired λ and S_{Fmax} can be achieved.

[0259] The number of passes to which the steel sheet is subjected during contact with the roll for a quarter circumference of the roll is preferably five or more passes, more preferably six or more passes.

[0260] The upper limit is not particularly limited, but the number of passes to which the steel sheet is subjected during contact with the roll for a quarter circumference of the roll is preferably 12 or less passes, more preferably 10 or less passes.

[0261] The number of passes to which the steel sheet is subjected during contact with the roll for half a circumference of the roll is preferably three or more passes, more preferably four or more passes.

[0262] The upper limit is not particularly limited, but the number of passes to which the steel sheet is subjected during contact with the roll for half a circumference of the roll is preferably six or less passes, more preferably five or less passes.

[0263] The tension is calculated by dividing the total load (kgf) of a load cell on the left and right of the roll by the cross-sectional area of the steel sheet (= sheet thickness (mm) x sheet width (mm)) (mm²). The load cells should be arranged parallel to the direction of the tension.

[0264] The load cells are preferably disposed at a position of 200 mm from both ends of the roll. The length of the roll to be used is preferably 1500 mm or more. The length of the roll to be used is preferably 2500 mm or less.

[0265] The tension is preferably 2.2 kgf/mm² or more, more preferably 2.4 kgf/mm² or more.

[0266] The tension is preferably 15.0 kgf/mm² or less, more preferably 10.0 kgf/mm² or less. The tension is even more preferably 7.0 kgf/mm² or less, even further more preferably 4.0 kgf/mm² or less.

[0267] With respect to the tension applied once or more, for example, the application of the tension twice means that a first tension of 2.0 kgf/mm² or more is applied once, and after the tension becomes less than 2.0 kgf/mm² a second tension of 2.0 kgf/mm² or more is applied. The application of the tension three times means that a first tension of 2.0 kgf/mm² or more is applied once, after the tension becomes less than 2.0 kgf/mm² a second tension of 2.0 kgf/mm² or more is applied, and after the tension becomes less than 2.0 kgf/mm² a third tension of 2.0 kgf/mm² or more is applied.

Second cooling stop temperature: 50°C or less

[0268] The cooling conditions in the second cooling step are not particularly limited and may be based on a usual method. The cooling method is, for example, gas jet cooling, mist cooling, roll cooling, water cooling, natural cooling, or the like.

[0269] From the perspective of preventing surface oxidation, cooling to 50°C or less is preferred, and cooling to room temperature is more preferred. The average cooling rate is preferably, for example, 1°C/s or more and 50°C/s or less. The average cooling rate can be calculated by "(cooling start temperature (°C) - second cooling stop temperature (°C))/cooling time (s)".

[0270] The steel sheet thus produced may be further subjected to temper rolling. A rolling reduction of more than 2.00% in the temper rolling may result in an increase in yield stress and a decrease in dimensional accuracy when the steel sheet is formed into a member. Thus, the rolling reduction in the temper rolling is preferably 2.00% or less. The lower limit of the rolling reduction in the temper rolling is preferably, but not limited to, 0.05% or more from the perspective of productivity. The temper rolling may be performed with an apparatus coupled to an annealing apparatus for each step (on-line) or with an apparatus separated from the annealing apparatus for each step (offline). The number of temper rolling processes may

be one or two or more. The rolling may be performed with a leveler or the like, provided that the elongation can be equivalent to that in the temper rolling.

[0271] Conditions other than those described above are not particularly limited and may be based on a usual method.

[3. Member]

[0272] Next, a member according to an embodiment of the present invention is described.

[0273] A member according to an embodiment of the present invention is a member produced by using the steel sheet described above (as a material). For example, the steel sheet as a material is subjected to at least one of forming and joining to produce a member.

[0274] The steel sheet has a TS of 1180 MPa or more, high YS, high press formability (ductility, flangeability, and bendability), and fracture resistance characteristics (bending fracture characteristics and axial compression characteristics) at the time of compression. Thus, a member according to an embodiment of the present invention has high strength and enhanced crashworthiness. Thus, a member according to an embodiment of the present invention is suitable for an impact energy absorbing member used in the automotive field.

[4. Method for Producing Member]

[0275] Next, a method for producing a member according to an embodiment of the present invention is described.

[0276] A method for producing a member according to an embodiment of the present invention includes a step of subjecting the steel sheet (for example, a steel sheet produced by the method for producing a steel sheet) to at least one of forming and joining to produce a member.

[0277] The forming method is, for example, but not limited to, a typical processing method, such as press working. The joining method is also, for example, but not limited to, typical welding, such as spot welding, laser welding, or arc welding, riveting, caulking, or the like. The forming conditions and the joining conditions are not particularly limited and may be based on a usual method.

EXAMPLES

[0278] A steel material with the chemical composition (the remainder being Fe and incidental impurities) listed in Table 1 was produced by steelmaking in a converter and was formed into a steel slab in a continuous casting method. In Table 1, "-" indicates the content at the level of incidental impurities.

[0279] The calculated transformation points Ac_1 (°C) and Ac_3 (°C) in Table 1 are calculated using the following formula:

$$Ac_1 \text{ point (}^\circ\text{C)} = 727.0 - 32.7 \times [\%C] + 14.9 \times [\%Si] + 2.0 \times [\%Mn]$$

$$Ac_3 \text{ point (}^\circ\text{C)} = 912.0 - 230 \times [\%C] + 31.6 \times [\%Si] - 20.4 \times [\%Mn]$$

wherein [%C] denotes the C content (% by mass), [%Si] denotes the Si content (% by mass), and [%Mn] denotes the Mn content (% by mass).

[0280] The steel slab was heated to 1200°C and, after the heating, was subjected to hot rolling composed of rough rolling and finish rolling at a finish rolling temperature of 900°C to form a hot-rolled steel sheet. Hot-rolled steel sheets No. 1 to No. 57, No. 60 to No. 74, No. 80 to 93, and No. 100 to No. 105 thus produced were pickled and cold-rolled (rolling reduction: 50%) to produce cold-rolled steel sheets with thicknesses shown in Tables 3, 6, and 9. Hot-rolled steel sheets No. 58 and No. 59, No. 75 to No. 79, and No. 95 to 99 were pickled to produce hot-rolled steel sheets (pickled) with thicknesses shown in Tables 3, 6, and 9. The cold-rolled steel sheets or hot-rolled steel sheets (pickled) were subjected to the annealing step, the first cooling step, the holding step, the coating step, the second cooling step, and the reheating step under the conditions shown in Table 2 and were subjected to treatments in the first coating step (metal coating step), the annealing step, the first cooling step, the holding step, the second coating step (galvanizing step), the second cooling step, and the reheating step under the conditions shown in Tables 5 and 8 to produce steel sheets (galvanized steel sheets).

[0281] Tables 5 and 8 show the presence or absence of the first coating step (metal coating step) and the coating type in the treatment in the metal coating step for the steel sheets No. 60 to No. 105. Tables 6 and 9 show the thickness of the surface soft layer, the metal coating weight, and the hardness distribution of the surface soft layer for the steel sheets No. 60 to No. 105.

[0282] In the galvanizing step, the hot-dip galvanizing treatment or the galvannealing treatment was performed to produce a hot-dip galvanized steel sheet (hereinafter also referred to as GI) or a galvannealed steel sheet (hereinafter also referred to as GA). In Tables 2, 5, and 8, the type in the coating step is also denoted by "GI" and "GA". In the GI steel sheets

in Tables 2 and 5, no alloying treatment was performed, and the alloying temperature is indicated by "-". In Table 8, a cold-rolled steel sheet formed without the galvanizing treatment in the galvanizing step is denoted by "CR", and a hot-rolled steel sheet formed without the galvanizing treatment in the galvanizing step is denoted by "HR". These cold-rolled steel sheets and the hot-rolled steel sheets were also not subjected to the alloying treatment, and the alloying temperature is indicated by "-".

[0283] The galvanizing bath temperature was 470°C in the production of GI and GA.

[0284] The galvanizing coating weight ranged from 45 to 72 g/m² per side to produce GI and was 45 g/m² per side to produce GA.

[0285] The composition of the galvanized layer of the final galvanized steel sheet in GI contained Fe: 0.1% to 1.0% by mass and Al: 0.2% to 0.33% by mass, the remainder being Zn and incidental impurities. GA contained Fe: 8.0% to 12.0% by mass and Al: 0.1% to 0.23% by mass, the remainder being Zn and incidental impurities.

[0286] In both cases, the galvanized layer was formed on both surfaces of the base steel sheet.

[0287] In Tables 2, 5, and 8, the term "pass 1" refers to the number of passes to which the steel sheet is subjected, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll, after an average tension of 2.0 kgf/mm² or more is applied once or more in the temperature range of 300°C or more and 450°C or less in the second cooling step, and the phrase "the number of passes 2" refers to the number of passes to which the steel sheet is subsequently subjected, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for half a circumference of the roll.

[0288] In the steel sheet thus produced, the steel microstructure of the base steel sheet was identified in the manner described above. Tables 3, 6, and 9 show the measurement results. In Tables 3, 6, and 9, F denotes ferrite, BF denotes bainitic ferrite, TM denotes tempered martensite, RA denotes retained austenite, FM denotes fresh martensite, LB denotes lower bainite, P denotes pearlite, and θ denotes carbide. L_M denotes the mean free path of the center of gravity of carbide, and σ_C denotes the average value of the standard deviation of the distance between carbide particles.

[0289] In Tables 4, 7, and 10, *1 is the value obtained by dividing the number of voids in contact with a hard phase (the number of voids at a boundary between the hard phase and a soft phase and the number of voids formed by fracture of the hard phase) among all voids by the total number of voids in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion, and *2 is the value obtained by dividing the number of voids in contact with a hard phase (the number of voids at a boundary between the hard phase and a soft phase and the number of voids formed by fracture of the hard phase) among all voids by the total number of voids in an overlap region of a V-bending flat portion and the VDA bending ridge line portion.

[0290] Measurement is performed on the surface soft layer as described below. After smoothing a thickness cross section (L cross section) parallel to the rolling direction of the steel sheet by wet grinding, measurement was performed in accordance with JIS Z 2244-1 (2020) using a Vickers hardness tester at a load of 10 gf from a 1- μ m position to a 100- μ m position in the thickness direction from the surface of the steel sheet at intervals of 1 μ m. Measurement was then performed at intervals of 20 μ m to the central portion in the thickness direction. A region with hardness corresponding to 85% or less of the hardness at the quarter thickness position is defined as a soft layer (surface soft layer), and the thickness of the region in the thickness direction is defined as the thickness of the soft layer.

[0291] A tensile test, a hole expansion test, a VDA bending test, a V-VDA bending test, and an axial compression test were performed in the manner described below. The tensile strength (TS), the yield stress (YS), the total elongation (EI), the limiting hole expansion ratio (λ), the critical bending angle (α) in the VDA bending test, the stroke at the maximum load (S_{Fmax}) in the V-VDA bending test, and the presence or absence of axial compression fracture were evaluated in accordance with the following criteria.

- TS

[0292]

Good (pass): 1180 MPa or more

Poor (fail): less than 1180 MPa

- YS

[0293]

Good (pass):

(A) For 1180 MPa $\leq$ TS < 1320 MPa, 750 MPa $\leq$ YS

(B) For 1320 MPa $\leq$ TS, 850 MPa $\leq$ YS

Poor (fail):

- (A) For $1180 \text{ MPa} \leq \text{TS} < 1320 \text{ MPa}$, $750 \text{ MPa} > \text{YS}$
- (B) For $1320 \text{ MPa} \leq \text{TS}$, $850 \text{ MPa} > \text{YS}$

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- EI

[0294]

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Good (pass):

- (A) For $1180 \text{ MPa} \leq \text{TS} < 1320 \text{ MPa}$, $12.0\% \leq \text{EI}$
- (B) For $1320 \text{ MPa} \leq \text{TS}$, $10.0\% \leq \text{EI}$

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Poor (fail):

- (A) For $1180 \text{ MPa} \leq \text{TS} < 1320 \text{ MPa}$, $12.0\% > \text{EI}$
- (B) For $1320 \text{ MPa} \leq \text{TS}$, $10.0\% > \text{EI}$

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- λ

[0295]

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Good (pass): 30% or more

Poor (fail): less than 30%

- α

[0296]

30

Good (pass): 80 degrees or more

Poor (fail): less than 80 degrees

- S_{Fmax}

35

[0297]

Good (pass): 26.0 mm or more

Poor (fail): less than 26.0 mm

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- Presence or absence of axial compression fracture

[0298]

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A (pass): No crack was observed in a sample after the axial compression test

B (pass): Two or less cracks were observed in a sample after the axial compression test

C (pass): Three or less cracks were observed in a sample after the axial compression test

D (fail): Four or more cracks were observed in a sample after the axial compression test, or a sample after the axial compression test was broken

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(1) Tensile Test

[0299] The tensile test was performed in accordance with JIS Z 2241 (2011). A JIS No. 5 test specimen was taken from the steel sheet such that the longitudinal direction was perpendicular to the rolling direction of the base steel sheet. TS, YS, and EI of the test specimen were measured at a crosshead speed of 10 mm/min in the tensile test. Tables 4, 7, and 10 show the results.

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(2) Hole Expansion Test

[0300] The hole expansion test was performed in accordance with JIS Z 2256 (2020). A 100 mm x 100 mm test specimen was taken from the steel sheet by shearing. A hole with a diameter of 10 mm was punched in the test specimen with a clearance of 12.5%. Using a die with an inner diameter of 75 mm, a blank holding force of 9 ton (88.26 kN) was then applied to the periphery of the hole, a conical punch with a vertex angle of 60 degrees was pushed into the hole, and the hole diameter of the test specimen at the crack initiation limit (in crack initiation) was measured. The limiting hole expansion ratio λ (%) was determined using the following formula. λ is a measure for evaluating stretch flangeability. Tables 4, 7, and 10 show the results.

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

D_f : diameter (mm) of hole of test specimen in crack initiation

D_0 : hole diameter (mm) of initial test specimen

(3) VDA Bending Test

[0301] The VDA bending test was performed in a bending test according to the VDA standard (VDA 238-100) defined by German Association of the Automotive Industry.

[0302] More specifically, a 70 mm x 60 mm test specimen was taken from the steel sheet by shearing. The sides of 60 mm are parallel to the rolling (L) direction.

[0303] The test specimen was subjected to the VDA bending test under the following conditions.

Test method: roll support, punch pressing

Roll diameter: $\phi 30$ mm

Punch tip R: 0.4 mm

Distance between rolls: (sheet thickness x 2) + 0.5 mm

Stroke speed: 20 mm/min

Bending direction: direction (C) perpendicular to rolling direction

[0304] When the load F applied with a press bending jig from above reaches the maximum, the angle on the outside of a bend at the central portion of a plate-like test specimen is measured as the critical bending angle (degree). The average value of the critical bending angle at the maximum load in the VDA bending test performed three times is defined as α (degree). Tables 4, 7, and 10 show the results.

(4) V-VDA Bending Test (V-Bending + Orthogonal VDA Bending Test)

[0305] The V-VDA bending test was performed as described below.

[0306] A 60 mm x 65 mm test specimen was taken from the steel sheet by shearing. The sides of 60 mm are parallel to the rolling (L) direction. 90-degree bending (primary bending) was performed at a radius of curvature/thickness ratio of 4.2 in the rolling (L) direction with respect to an axis extending in the width (C) direction to prepare a test specimen. In the 90-degree bending (primary bending), as illustrated in Fig. 2-1(a), a punch B1 was pressed against a steel sheet on a die A1 with a V-groove to prepare a test specimen T1. Next, as illustrated in Fig. 2-1(b), the test specimen T1 on support rolls A2 was subjected to orthogonal bending (secondary bending) by pressing a punch B2 against the test specimen T1 in the direction perpendicular to the rolling direction. In Figs. 2-1(a) and 2-1(b), the symbol D1 indicates the width (C) direction, and the symbol D2 indicates the rolling (L) direction.

[0307] The V-bending conditions in the V-VDA bending test (V-bending + orthogonal VDA bending test) are as follows:

Test method: die support, punch pressing

Forming load: 10 t

Test speed: 30 mm/min

Holding time: 5 s

Bending direction: rolling (L) direction

[0308] The conditions for VDA bending in the V-VDA bending test are as follows:

Test method: roll support, punch pressing

Roll diameter: $\phi 30$ mm
 Punch tip R: 0.4 mm
 Distance between rolls: (sheet thickness x 2) + 0.5 mm
 Stroke speed: 20 mm/min
 Test specimen size: 60 mm x 60 mm
 Bending direction: direction (C) perpendicular to rolling direction

[0309] The stroke at the maximum load is determined in a stroke-load curve of the VDA bending. The average value of the stroke at the maximum load in the V-VDA bending test performed three times is defined as S_{Fmax} (mm). Tables 4, 7, and 10 show the results.

(5) Axial Compression Test

[0310] A 160 mm x 200 mm test specimen was taken from the steel sheet by shearing. The sides of 160 mm are parallel to the rolling (L) direction. A hat-shaped member 10 with a depth of 40 mm illustrated in Figs. 5-1(a) and 5-1(b) was produced by forming (bending) with a die having a punch corner radius of 5.0 mm and a die corner radius of 5.0 mm. The steel sheet used as the material of the hat-shaped member was separately cut into a size of 80 mm x 200 mm. Next, the cut-out steel sheet 20 and the hat-shaped member 10 were spot-welded together to produce a test member 30 as illustrated in Figs. 5-1(a) and 5-1(b). Fig. 5-1(a) is a front view of the test member 30 produced by spot-welding the hat-shaped member 10 and the steel sheet 20. Fig. 5-1(b) is a perspective view of the test member 30. As illustrated in Fig. 5-1(b), spot welds 40 were positioned such that the distance between an end portion of the steel sheet and a weld was 10 mm and the distance between the welds was 45 mm. Next, as illustrated in Fig. 5-2(c), the test member 30 was joined to a base plate 50 by TIG welding to prepare an axial compression test sample. Next, the axial compression test sample was collided with an impactor 60 at a constant collision speed of 10 mm/min to compress the axial compression test sample by 70 mm. As illustrated in Fig. 5-2(c), the compression direction D3 was a direction parallel to the longitudinal direction of the test member 30.

[0311] The compressed sample was evaluated as described above, and the results are shown in Tables 4, 7, and 10.

[0312] The VDA bending test, the V-VDA bending test, and the axial compression test of a steel sheet with a thickness of more than 1.2 mm were all performed on a steel sheet with a thickness of 1.2 mm in consideration of the influence of the sheet thickness. A steel sheet with a thickness of more than 1.2 mm was ground on one side to have a thickness of 1.2 mm. Since grinding may affect the bendability of the surface of a steel sheet, the ground surface in the VDA bending test was the inside of the bend (the side in contact with the punch), and the ground surface in the V-VDA bending test was the outside of the bend (the side in contact with the die) in the V-bending test and was the inside of the bend (the side in contact with the punch) in the subsequent VDA bending test.

[0313] On the other hand, in the VDA bending test, the V-VDA bending test, and the axial compression test of a steel sheet with a thickness of 1.2 mm or less, the sheet thickness has a small influence, and the test was performed without the grinding treatment.

<Nanohardness Measurement>

[0314] To achieve high bendability during press forming and good bending fracture characteristics in case of a collision, when the nanohardness is measured at 300 points or more in a $50\ \mu\text{m} \times 50\ \mu\text{m}$ region on the sheet surface at each of a quarter depth position in the thickness direction and a half depth position in the thickness direction of the surface soft layer from a base surface layer, the ratio of the number of measurements in which the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet is 7.0 GPa or more is more preferably 0.10 or less with respect to the total number of measurements at the quarter depth position in the thickness direction. When the ratio of the nanohardness of 7.0 GPa or more is 0.10 or less, it means a low ratio of a hard microstructure (martensite or the like), an inclusion, or the like, and this could further suppress the formation and connection of voids and crack growth in the hard microstructure (martensite and the like), inclusion, or the like during press forming and in case of a collision, thus resulting in good R/t and SFmax.

[0315] When galvanizing was performed, peeling the coated layer was followed by mechanical polishing to the quarter depth position - $5\ \mu\text{m}$ in the thickness direction of the surface soft layer from the surface of the base steel sheet, by buffing with diamond and alumina to the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet, and then by colloidal silica polishing. The nanohardness was measured at 512 points in total with Hysitron tribo-950 and a Berkovich diamond indenter under the conditions of

Load: 500 μN ,
 Measurement area: $50\ \mu\text{m} \times 50\ \mu\text{m}$, and

Dot-to-dot distance: 2 μm .

[0316] The coated layer to be peeled off is a galvanized layer when the galvanized layer is formed, is a metal coated layer when the metal coated layer is formed, or is a galvanized layer and a metal coated layer when the galvanized layer and the metal coated layer are formed.

[0317] Mechanical polishing, buffing with diamond and alumina, and colloidal silica polishing were then performed to the half depth position in the thickness direction of the surface soft layer. The nanohardness was measured at 512 points in total with Hysitron tribo-950 and a Berkovich diamond indenter under the conditions of

Load: 500 μN ,
Measurement area: 50 μm x 50 μm , and
Dot-to-dot distance: 2 μm .

[Table 1-1]

Steel grade	Chemical composition (mass%)										Calculated transformation point (°C)		Note
	C	Si	Mn	P	S	Al	N	Others	Ac ₁	Ac ₃			
A	0.090	0.88	3.15	0.007	0.0011	0.035	0.0034	-	743	855			Conforming steel
B	0.208	1.52	2.83	0.010	0.0009	0.026	0.0030	-	749	854			Conforming steel
C	0.322	1.13	2.56	0.007	0.0008	0.037	0.0027	-	738	821			Conforming steel
D	0.283	2.05	2.71	0.006	0.0007	0.036	0.0031	-	754	856			Conforming steel
E	0.207	0.89	2.17	0.006	0.0005	0.037	0.0035	-	738	848			Conforming steel
F	0.351	0.96	3.34	0.006	0.0007	0.035	0.0035	-	737	793			Conforming steel
G	0.192	0.76	2.93	0.007	0.0008	0.751	0.0028	-	738	832			Conforming steel
H	0.047	1.71	2.67	0.008	0.0010	0.049	0.0043	-	756	901			Comparative steel
I	0.450	1.83	2.61	0.008	0.0016	0.027	0.0020	-	745	813			Comparative steel
J	0.260	0.45	2.86	0.003	0.0004	0.015	0.0027	-	731	808			Comparative steel
K	0.175	3.12	2.85	0.006	0.0016	0.040	0.0049	-	773	912			Comparative steel
L	0.167	1.58	1.33	0.005	0.0012	0.035	0.0024	-	748	896			Comparative steel
M	0.256	0.76	3.81	0.006	0.0005	0.012	0.0027	-	738	799			Comparative steel
N	0.132	1.82	2.87	0.016	0.0019	0.028	0.0030	Ti:0.028	756	881			Conforming steel
O	0.198	0.98	2.55	0.021	0.0013	0.030	0.0040	Nb:0.025	740	845			Conforming steel
P	0.161	1.52	2.91	0.019	0.0019	0.031	0.0030	V:0.032	750	864			Conforming steel
Q	0.187	1.51	2.83	0.009	0.0023	0.034	0.0033	Ti:0.019, B:0.0012	749	859			Conforming steel
R	0.210	0.87	2.78	0.006	0.0005	0.037	0.0035	Ti:0.015, Nb:0.020, B:0.0018	739	835			Conforming steel
S	0.207	1.57	2.65	0.004	0.0015	0.030	0.0019	Cu:0.146	749	860			Conforming steel
T	0.173	1.43	2.72	0.021	0.0020	0.027	0.0039	Cr:0.051	748	862			Conforming steel
U	0.238	0.80	2.41	0.009	0.0006	0.036	0.0030	Ni:0.109	736	833			Conforming steel
V	0.116	1.43	2.95	0.005	0.0015	0.032	0.0038	Mo:0.037	750	870			Conforming steel
W	0.104	1.60	3.05	0.011	0.0019	0.038	0.0033	Sb:0.008	754	876			Conforming steel
X	0.186	1.36	2.74	0.008	0.0014	0.014	0.0029	Sn:0.015	747	856			Conforming steel
Y	0.267	1.08	2.76	0.007	0.0011	0.035	0.0034	Nb:0.020, Ta:0.007	740	828			Conforming steel

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Steel grade	Chemical composition (mass%)							Calculated transformation point (°C)		Note	
	C	Si	Mn	P	S	Al	N	Others	Ac ₁		Ac ₃
Z	0.190	1.99	2.53	0.009	0.0025	0.032	0.0037	Ta:0.007	755	880	Conforming steel
- The remainder other than these is Fe and incidental impurities.											

[Table 1-2]

Steel grade	Chemical composition (mass%)									Calculated transformation point (°C)		Note
	C	Si	Mn	P	S	Al	N	Others		Ac ₁	Ac ₃	
AA	0.189	1.72	2.63	0.008	0.0023	0.028	0.0043	W:0.031		752	869	Conforming steel
AB	0.170	2.08	2.40	0.014	0.0021	0.023	0.0031	Mg:0.0040		757	890	Conforming steel
AC	0.212	1.19	2.58	0.012	0.0015	0.029	0.0037	Zn:0.0060		743	848	Conforming steel
AD	0.162	1.62	2.92	0.005	0.0029	0.024	0.0042	Co:0.0090		752	866	Conforming steel
AE	0.158	1.68	2.49	0.016	0.0018	0.032	0.0026	Zr:0.0020		752	878	Conforming steel
AF	0.201	1.35	2.59	0.010	0.0019	0.034	0.0038	Ca:0.0020		746	856	Conforming steel
AG	0.173	0.79	2.58	0.013	0.0021	0.028	0.0036	Se:0.0090		738	845	Conforming steel
AH	0.210	1.51	2.64	0.003	0.0007	0.027	0.0038	Te:0.0140		748	858	Conforming steel
AI	0.177	1.53	2.81	0.008	0.0016	0.028	0.0040	Ge:0.0120		750	862	Conforming steel
AJ	0.298	1.01	2.11	0.010	0.0018	0.027	0.0031	As:0.0257		737	832	Conforming steel
AK	0.165	1.57	2.93	0.019	0.0020	0.027	0.0034	Sr:0.0080		751	864	Conforming steel
AL	0.172	1.28	2.97	0.013	0.0025	0.026	0.0035	Cs:0.0100		746	852	Conforming steel
AM	0.157	1.38	3.05	0.027	0.0022	0.026	0.0038	Hf:0.0050		749	857	Conforming steel
AN	0.191	1.40	2.72	0.007	0.0020	0.026	0.0040	Pb:0.0130		747	857	Conforming steel

(continued)

Steel grade	Chemical composition (mass%)								Calculated transformation point (°C)		Note
	C	Si	Mn	P	S	Al	N	Others	Ac ₁	Ac ₃	
AO	0.158	0.78	3.23	0.006	0.0022	0.030	0.0023	Bi:0.0030	740	834	Conforming steel
AP	0.136	1.48	3.18	0.020	0.0014	0.024	0.0050	REM:0.0030	751	863	Conforming steel
AQ	0.208	1.23	3.08	0.011	0.0025	0.031	0.0027	Ti:0.017, Nb:0.021, B:0.0016	745	840	Conforming steel
AR	0.188	1.56	2.79	0.010	0.0022	0.025	0.0030	Nb:0.195, Ti:0.185, V:0.190, B:0.0098, Cr:0.970, Ni:0.950, Mo:0.980, Sb:0.180, Sn:0.190, Cu:0.920, Ta:0.091, W:0.480, Mg:0.0190, Zn:0.0180, Co:0.0180, Zr:0.0930, Ca:0.0180, Se:0.0180, Te:0.0195, Ge:0.0185, As:0.0450, Sr:0.0195, Cs:0.0180, Hf:0.0185, Pb:0.0194, Bi:0.0189, REM:0.0185	750	861	Conforming steel
- The remainder other than these is Fe and incidental impurities.											

[Table 2-1]

No.	Steel grade	Annealing step		First cooling step	Holding step		Coating step		Second cooling step				Note
		Annealing temperature (°C)	Annealing time (s)		First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	
1	A	850	30	200	500	40	GA	550	3.9	1	4	10	Inventive ex-ample
2	B	840	110	250	450	50	GA	540	2.2	2	10	9	Inventive ex-ample
3	C	820	40	100	490	30	GA	510	3.6	2	4	9	Inventive ex-ample
4	D	840	60	170	360	50	GI	-	2.4	3	6	3	Inventive ex-ample
5	E	870	220	220	530	70	GA	530	2.2	2	10	8	Inventive ex-ample
6	F	890	50	150	370	60	GI	-	2.3	3	5	8	Inventive ex-ample
7	G	830	120	200	400	40	GA	550	2.8	2	5	8	Inventive ex-ample
8	H	900	60	280	500	10	GA	510	2.1	1	8	7	Comparative example
9	I	820	280	130	420	40	GA	550	3.5	3	6	6	Comparative example
10	J	810	30	110	480	60	GA	520	3.0	2	9	5	Comparative example
11	K	890	80	200	410	75	GI	-	2.3	1	9	7	Comparative example
12	L	860	120	230	480	50	GA	600	2.1	2	5	2	Comparative example
13	M	800	250	160	400	65	GA	550	3.9	2	9	5	Comparative example

(continued)

No.	Steel grade	Annealing step		First cooling step	Holding step		Coating step		Second cooling step				Note
		Annealing temperature (°C)	Annealing time (s)		Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	Number of passes 2 *3 (-)	
14	B	<u>780</u>	50	120	380	30	GA	550	3.6	2	6	9	Comparative example
15	B	<u>950</u>	160	230	400	60	GI	-	3.0	2	6	5	Comparative example
16	B	850	<u>10</u>	190	360	65	GA	540	2.2	2	5	2	Comparative example
17	B	850	30	<u>50</u>	380	20	GA	560	2.0	3	8	6	Comparative example
18	B	900	50	<u>350</u>	470	40	GI	-	3.4	3	8	6	Comparative example
19	B	840	190	230	<u>300</u>	20	GA	550	3.5	1	9	8	Comparative example
20	B	860	40	210	<u>600</u>	70	GI	-	2.3	2	4	2	Comparative example
21	B	860	70	220	460	<u>1</u>	GA	550	2.9	1	6	2	Comparative example
22	B	830	170	200	370	<u>100</u>	GA	550	3.4	1	8	9	Comparative example
23	C	810	20	190	370	60	GI	-	<u>1.0</u>	1	7	8	Comparative example
24	C	820	50	240	400	75	GA	510	<u>0.0</u>	<u>0</u>	7	9	Comparative example
25	C	810	30	170	410	20	GA	500	3.1	1	<u>2</u>	8	Comparative example
26	C	840	150	260	380	70	GA	520	3.7	3	10	<u>1</u>	Comparative example

(continued)

No.	Steel grade	Annealing step		First cooling step	Holding step		Coating step		Second cooling step				Note
		Annealing temperature (°C)	Annealing time (s)	First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	Number of passes 2 *3 (-)	
27	N	880	180	190	460	10	GA	520	3.2	2	5	9	Inventive example
28	O	860	100	210	440	40	GA	500	3.5	2	6	10	Inventive example
29	P	880	80	230	420	40	GA	550	2.7	1	4	7	Inventive example

*1: Tension applied in the temperature range of 300°C or more and 450°C or less

*2: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll

*3: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for half the circumference of the roll

[Table 2-2]

No.	Steel grade	Annealing step		First cooling step	Holding step		Coating step		Second cooling step				Note
		Annealing temperature (°C)	Annealing time (s)		First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	
30	Q	840	100	200	400	55	GA	530	2.5	1	9	4	Inventive example
31	R	820	150	190	410	30	GI	-	2.4	3	6	10	Inventive example
32	S	850	170	200	480	70	GI	-	3.8	2	10	7	Inventive example
33	T	850	90	280	480	45	GI	-	2.5	2	8	10	Inventive example
34	U	820	150	150	350	15	GA	500	3.2	2	10	7	Inventive example
35	v	880	40	230	440	70	GI	-	2.0	1	4	7	Inventive example
36	W	850	190	180	440	40	GI	-	3.4	1	7	7	Inventive example
37	X	840	70	200	480	75	GA	600	2.6	2	8	8	Inventive example
38	Y	860	120	220	390	50	GA	530	3.7	3	4	8	Inventive example
39	Z	870	110	240	420	30	GA	570	2.7	1	6	2	Inventive example
40	AA	850	80	160	470	70	GA	540	3.4	1	6	8	Inventive example
41	AB	890	50	160	400	75	GA	550	3.6	3	4	5	Inventive example
42	AC	830	90	220	400	30	GA	530	4.0	3	5	7	Inventive example

(continued)

No.	Steel grade	Annealing step		First cooling step	Holding step		Coating step		Second cooling step				Note
		Annealing temperature (°C)	Annealing time (s)		First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	
44	AD	840	120	250	370	15	GA	520	2.9	3	8	2	Inventive example
45	AE	850	90	200	410	5	GA	530	3.9	2	6	9	Inventive example
46	AF	860	130	170	540	10	GA	510	2.7	3	5	8	Inventive example
47	AG	830	90	150	480	40	GA	550	3.4	3	9	5	Inventive example
48	AH	850	90	240	500	70	GA	520	2.1	3	8	3	Inventive example
49	AI	870	100	200	490	25	GI	-	2.1	2	7	10	Inventive example
50	AJ	850	50	140	420	30	GI	-	3.9	3	6	2	Inventive example
51	AK	870	30	260	440	20	GA	560	4.0	2	5	9	Inventive example
52	AL	830	110	210	450	60	GA	530	2.7	3	6	6	Inventive example
53	AM	850	100	200	460	40	GA	540	3.7	3	8	4	Inventive example
54	AN	870	80	200	400	60	GA	550	2.7	2	9	2	Inventive example
55	AO	820	60	140	430	25	GA	510	3.0	3	8	3	Inventive example
56	AP	860	40	200	430	60	GA	520	2.5	2	8	7	Inventive example

(continued)

No.	Steel grade	Annealing step		First cooling step	Holding step		Coating step		Second cooling step				Note	
		Annealing temperature (°C)	Annealing time (s)	First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	Number of passes 2 *3 (-)		
57	AQ	850	70	210	400	70	GA	500	2.8	1	9	6	Inventive example	
58	Q	840	150	230	410	75	GA	510	2.7	3	6	4	Inventive example	
59	Q	840	300	220	460	70	GA	530	3.0	3	8	4	Inventive example	
*1: Tension applied in the temperature range of 300°C or more and 450°C or less														
*2: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll														
*3: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for half the circumference of the roll														

[Table 3-1]

No.	Steel grade	Sheet thickness (mm)	Steel microstructure											Note
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1 (-)	L _M *2 (μm)	σ _c *3 (μm)		
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)						
1	A	1.6	14.3	8.4	60.0	68.4	9.2	7.9	θ	0.88	0.33	7.31	Inventive example	
2	B	1.8	8.5	20.7	57.2	77.9	7.4	6.0	θ	0.73	0.37	6.76	Inventive example	
3	C	1.4	10.1	2.3	76.3	78.6	3.5	7.5	θ	0.97	0.46	7.12	Inventive example	
4	D	1.2	10.2	8.1	62.2	70.3	6.3	9.6	LB, θ	0.88	0.42	6.98	Inventive example	
5	E	1.2	3.5	12.3	70.2	82.5	5.1	8.4	θ	0.85	0.46	6.23	Inventive example	
6	F	1.4	1.6	12.2	70.9	83.1	5.5	6.8	LB, θ	0.85	0.36	6.15	Inventive example	
7	G	1.4	9.1	12.6	61.3	73.9	7.9	6.4	LB, θ	0.83	0.40	7.45	Inventive example	
8	H	1.6	6.9	15.9	63.5	79.4	2.9	9.6	θ	0.80	0.42	7.83	Comparative example	
9	I	1.4	1.5	9.9	68.6	78.5	3.5	9.5	LB, θ	0.87	0.38	7.22	Comparative example	
10	J	1.4	9.6	5.2	72.1	77.3	2.4	10.4	θ	0.93	0.49	6.72	Comparative example	
11	K	1.2	13.7	9.7	55.3	65.0	6.8	7.6	LB, θ	0.85	0.42	6.14	Comparative example	
12	L	1.6	16.8	12.6	53.1	65.7	7.5	8.3	θ	0.81	0.35	6.09	Comparative example	
13	M	1.2	0.0	18.1	56.2	74.3	9.2	13.8	θ	0.76	0.47	5.92	Comparative example	
14	B	1.2	38.7	2.5	33.6	36.1	9.8	11.1	LB, θ	0.93	0.42	8.91	Comparative example	
15	B	1.4	0.0	5.6	82.8	88.4	1.8	7.8	LB, θ	0.94	0.34	6.54	Comparative example	
16	B	1.4	27.2	4.6	43.0	47.6	9.5	12.7	LB, θ	0.90	0.39	8.11	Comparative example	
17	B	1.2	12.1	0.0	83.1	83.1	1.2	3.2	θ	1.00	0.15	7.87	Comparative example	
18	B	1.2	0.0	34.9	38.3	73.2	8.3	18.0	θ	0.52	0.33	7.95	Comparative example	
19	B	1.4	3.4	20.4	45.0	65.4	7.4	6.9	LB, θ	0.69	0.21	7.62	Comparative example	
20	B	1.6	0.2	4.4	76.5	80.9	1.6	15.3	P, θ	0.95	0.39	7.23	Comparative example	
21	B	1.2	0.0	1.1	89.0	90.1	1.2	8.2	θ	0.99	0.50	6.96	Comparative example	
22	B	1.6	1.7	32.3	51.8	84.1	10.9	2.2	LB, θ	0.62	0.35	7.38	Comparative example	
23	C	1.2	20.2	9.8	40.6	50.4	14.4	9.9	LB, θ	0.81	0.46	7.85	Comparative example	
24	C	1.4	2.3	23.6	51.5	75.1	10.8	7.9	LB, θ	0.69	0.21	6.90	Comparative example	

(continued)

No.	Steel grade	Sheet thickness (mm)	Steel microstructure									Note		
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1 (-)	L _M *2 (μm)		σ _c *3 (μm)	
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)						
25	C	1.4	16.7	9.2	50.3	59.5	<u>12.9</u>	9.5	LB, θ	0.85	0.22	7.64	Comparative example	
26	C	1.2	0.0	23.7	56.2	79.9	<u>10.2</u>	9.5	LB, θ	0.70	0.41	7.48	Comparative example	
27	N	1.2	0.0	12.1	75.7	87.8	6.3	5.6	θ	0.86	0.24	6.76	Inventive example	
28	O	2.0	0.0	15.8	74.1	89.9	5.7	4.0	θ	0.82	0.34	6.55	Inventive example	
29	P	1.6	0.4	22.7	65.4	88.1	6.1	4.9	θ	0.74	0.25	7.00	Inventive example	
*1: BF; bainitic ferrite, TM; tempered martensite, RA; retained austenite, FM; fresh martensite, F; ferrite, LB; lower bainite, P; pearlite, θ; carbide														
*2: L _M ; the mean free path of the center of gravity of carbide														
*3: σ _c ; the average value of the standard deviation of the distance between carbide particles														

[Table 3-2]

No.	Steel grade	Sheet thickness (mm)	Steel microstructure											Note
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1 (-)	L _M *2 (μm)	σ _c *3 (μm)		
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)						
30	Q	1.4	7.7	9.5	70.1	79.6	5.9	5.5	LB, θ	0.88	0.31	6.93	Inventive example	
31	R	1.2	0.6	15.8	68.4	84.2	6.5	6.3	θ	0.81	0.36	6.99	Inventive example	
32	S	1.6	11.5	14.6	63.5	78.1	6.4	3.4	θ	0.81	0.42	7.27	Inventive example	
33	T	1.8	12.4	11.1	59.3	70.4	9.1	6.3	θ	0.84	0.40	7.45	Inventive example	
34	U	1.4	3.5	6.5	76.3	82.8	5.4	4.0	LB, θ	0.92	0.40	6.95	Inventive example	
35	V	1.2	0.0	16.1	69.6	85.7	9.3	4.8	θ	0.81	0.41	6.87	Inventive example	
36	W	1.2	2.2	20.4	65.9	86.3	7.2	4.1	θ	0.76	0.23	6.75	Inventive example	
37	X	1.4	17.4	10.8	61.4	72.2	6.5	3.5	θ	0.85	0.29	7.01	Inventive example	
38	Y	1.4	0.0	18.2	63.5	81.7	6.7	3.8	LB, θ	0.78	0.39	7.27	Inventive example	
39	Z	1.6	6.8	16.6	64.4	81.0	7.6	4.4	θ	0.80	0.42	7.14	Inventive example	
40	AA	1.4	13.7	12.7	59.9	72.6	8.2	4.3	θ	0.83	0.47	7.02	Inventive example	
41	AB	1.4	8.5	16.6	60.9	77.5	7.3	5.3	LB, θ	0.79	0.29	7.32	Inventive example	
42	AC	1.2	17.4	10.2	55.7	65.9	5.9	4.9	LB, θ	0.85	0.22	7.47	Inventive example	
44	AD	1.6	7.6	11.5	59.5	71.0	6.9	4.7	LB, θ	0.84	0.38	7.44	Inventive example	
45	AE	1.2	14.6	14.4	62.6	77.0	4.8	3.5	θ	0.81	0.30	7.31	Inventive example	
46	AF	1.2	3.6	8.5	79.7	88.2	3.3	4.3	θ	0.90	0.32	6.59	Inventive example	
47	AG	0.8	13.4	6.2	67.8	74.0	8.4	3.5	θ	0.92	0.48	6.98	Inventive example	
48	AH	1.0	12.3	8.0	68.1	76.1	6.6	4.7	θ	0.89	0.40	6.86	Inventive example	
49	AI	1.4	1.3	5.9	79.4	85.3	7.5	5.6	θ	0.93	0.23	6.45	Inventive example	
50	AJ	1.4	0.5	14.2	73.2	87.4	8.1	3.5	θ	0.84	0.21	6.90	Inventive example	
51	AK	1.6	0.7	18.6	65.5	84.1	7.5	7.2	θ	0.78	0.33	7.11	Inventive example	
52	AL	1.2	14.6	10.7	61.4	72.1	8.6	4.3	θ	0.85	0.47	7.30	Inventive example	
53	AM	1.2	2.1	19.4	63.8	83.2	9.1	5.3	θ	0.77	0.21	7.32	Inventive example	
54	AN	1.2	0.1	17.1	63.5	80.6	7.2	6.4	LB, θ	0.79	0.39	7.13	Inventive example	

(continued)

No.	Steel grade	Sheet thickness (mm)	Steel microstructure									Note	
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1 (-)	L _M *2 (μm)		σ _c *3 (μm)
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)					
55	AO	1.4	9.5	13.4	65.0	78.4	8.0	3.7	θ	0.83	0.46	7.21	Inventive example
56	AP	1.2	1.3	16.2	69.3	85.5	6.2	6.4	θ	0.81	0.26	6.92	Inventive example
57	AQ	1.6	0.0	6.5	78.9	85.4	6.8	5.9	θ	0.92	0.31	6.98	Inventive example
58	Q	2.6	5.5	15.5	63.2	78.7	7.7	6.2	θ	0.80	0.41	7.05	Inventive example
59	Q	3.2	3.9	12.9	68.4	81.3	6.1	7.1	θ	0.84	0.45	6.90	Inventive example
*1: BF; bainitic ferrite, TM; tempered martensite, RA; retained austenite, FM; fresh martensite, F; ferrite, LB; lower bainite, P; pearlite, θ; carbide													
*2: L _M ; the mean free path of the center of gravity of carbide													
*3: σ _c ; the average value of the standard deviation of the distance between carbide particles													

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[Table 4-1]

	No.	Steel grade	YS (MPa)	TS (MPa)	EI (%)	λ (%)	α (°)	SFmax (mm)	*1 (-)	*2 (-)	Axial compression	Note
5	1	A	759	1186	19.1	37	100	26.1	0.53	0.17	B	Inventive example
	2	B	932	1197	14.8	46	85	26.7	0.41	0.14	B	Inventive example
10	3	C	1020	1312	12.4	52	86	27.1	0.33	0.11	A	Inventive example
	4	D	896	1280	14.1	41	84	26.5	0.50	0.17	B	Inventive example
15	5	E	854	1263	12.9	58	87	27.4	0.43	0.13	A	Inventive example
	6	F	959	1365	12.1	56	85	27.4	0.51	0.12	A	Inventive example
20	7	G	815	1206	14.8	45	80	26.0	0.33	0.11	B	Inventive example
	8	<u>H</u>	<u>731</u>	<u>1173</u>	<u>10.7</u>	45	85	<u>25.9</u>	0.55	0.11	C	Comparative example
25	9	<u>I</u>	955	1291	<u>10.9</u>	<u>29</u>	<u>78</u>	<u>25.7</u>	0.43	0.13	<u>D</u>	Comparative example
	10	<u>J</u>	860	1274	<u>11.5</u>	36	<u>79</u>	26.0	0.50	0.00	B	Comparative example
30	11	<u>K</u>	799	1219	15.2	<u>25</u>	89	<u>25.4</u>	0.33	0.17	C	Comparative example
	12	<u>L</u>	<u>743</u>	<u>1108</u>	14.4	38	80	26.1	0.57	0.00	B	Comparative example
35	13	<u>M</u>	878	1235	14.3	<u>27</u>	88	<u>25.6</u>	<u>0.67</u>	0.11	C	Comparative example
	14	B	<u>678</u>	<u>954</u>	21.9	<u>29</u>	101	<u>24.5</u>	<u>0.88</u>	0.11	<u>D</u>	Comparative example
40	15	B	844	1270	<u>7.9</u>	71	87	28.5	0.50	0.00	A	Comparative example
	16	B	<u>725</u>	<u>1087</u>	20.7	28	99	<u>24.2</u>	<u>0.89</u>	<u>0.33</u>	<u>D</u>	Comparative example
45	17	B	802	1232	<u>10.8</u>	65	83	26.5	0.33	0.00	B	Comparative example
	18	B	790	1205	16.6	<u>25</u>	<u>70</u>	<u>25.8</u>	<u>0.86</u>	<u>0.50</u>	<u>D</u>	Comparative example
50	19	B	819	1228	15.3	31	<u>78</u>	<u>25.1</u>	0.60	<u>0.25</u>	<u>D</u>	Comparative example
	20	B	805	1243	<u>7.5</u>	30	<u>76</u>	<u>25.6</u>	<u>0.88</u>	<u>0.50</u>	<u>D</u>	Comparative example
55	21	B	877	1296	<u>7.3</u>	50	81	27.1	0.38	0.11	A	Comparative example
	22	B	835	1289	14.8	35	82	<u>25.9</u>	0.56	0.00	B	Comparative example

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(continued)

No.	Steel grade	YS (MPa)	TS (MPa)	EI (%)	λ (%)	α (°)	SFmax (mm)	*1 (-)	*2 (-)	Axial compression	Note
23	C	<u>741</u>	<u>1023</u>	23.2	36	105	<u>24.6</u>	<u>0.80</u>	0.13	<u>D</u>	Comparative example
24	C	882	1284	14.9	52	83	<u>25.6</u>	<u>0.89</u>	0.14	<u>D</u>	Comparative example
25	C	767	1256	18.9	41	102	<u>25.3</u>	<u>0.88</u>	0.11	<u>D</u>	Comparative example
26	C	898	1317	14.0	56	84	<u>25.8</u>	<u>0.86</u>	0.00	<u>D</u>	Comparative example
27	N	771	1189	12.0	44	81	26.6	0.57	0.00	C	Inventive example
28	O	821	1193	15.0	63	91	28.5	0.43	0.13	A	Inventive example
29	P	1025	1247	14.2	48	82	26.9	0.50	0.17	B	Inventive example
*1: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion *2: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending flat portion and a VDA bending ridge line portion											

[Table 4-2]

No.	Steel grade	YS (MPa)	TS (MPa)	EI (%)	λ (%)	α (°)	SFmax (mm)	*1 (-)	*2 (-)	Axial compression	Note
30	Q	987	1199	13.7	57	92	27.8	0.20	0.00	A	Inventive example
31	R	998	1225	12.7	48	82	26.5	0.40	0.11	B	Inventive example
32	S	906	1201	16.0	43	80	26.5	0.40	0.00	B	Inventive example
33	T	783	1209	16.4	49	88	26.7	0.57	0.17	B	Inventive example
34	U	903	1213	13.5	55	85	27.6	0.33	0.00	B	Inventive example
35	v	1025	1215	14.8	52	84	27.3	0.50	0.11	B	Inventive example
36	W	1064	1254	13.7	47	82	26.7	0.43	0.11	B	Inventive example
37	X	803	1199	15.4	43	80	26.3	0.33	0.00	C	Inventive example
38	Y	1080	1257	13.3	49	86	26.7	0.33	0.00	B	Inventive example
39	Z	1010	1236	15.6	45	83	26.2	0.40	0.11	C	Inventive example
40	AA	1078	1283	14.0	41	81	26.5	0.50	0.00	C	Inventive example

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(continued)

No.	Steel grade	YS (MPa)	TS (MPa)	EI (%)	λ (%)	α (°)	SFmax (mm)	*1 (-)	*2 (-)	Axial compression	Note
41	AB	969	1241	15.0	53	85	27.4	0.50	0.13	B	Inventive example
42	AC	906	1242	16.1	44	87	26.5	0.40	0.14	C	Inventive example
44	AD	964	1237	14.3	53	83	27.6	0.43	0.00	B	Inventive example
45	AE	867	1195	15.9	45	80	26.8	0.33	0.00	C	Inventive example
46	AF	836	1209	15.2	60	91	28.4	0.25	0.11	A	Inventive example
47	AG	755	1192	14.0	40	80	26.1	0.40	0.17	C	Inventive example
48	AH	762	1205	14.8	42	81	26.3	0.40	0.00	C	Inventive example
49	AI	1140	1293	12.7	66	93	28.9	0.50	0.00	A	Inventive example
50	AJ	1028	1301	12.9	58	85	28.1	0.50	0.00	A	Inventive example
51	AK	1060	1239	16.2	61	98	28.4	0.43	0.17	A	Inventive example
52	AL	837	1211	14.6	49	82	27.3	0.50	0.11	B	Inventive example
53	AM	1016	1280	14.0	58	89	28.5	0.56	0.11	A	Inventive example
54	AN	998	1290	13.9	55	84	28.1	0.50	0.14	B	Inventive example
55	AO	857	1250	14.4	39	80	26.0	0.38	0.00	C	Inventive example
56	AP	1124	1277	13.4	64	95	28.5	0.40	0.17	A	Inventive example
57	AQ	1253	1391	12.9	44	83	26.6	0.25	0.13	C	Inventive example
58	Q	969	1203	13.9	56	82	26.6	0.50	0.11	B	Inventive example
59	Q	992	1219	13.5	58	84	26.3	0.43	0.17	C	Inventive example
*1: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion *2: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending flat portion and a VDA bending ridge line portion											

[Table 5]

No.	Steel grade	First Coating step	Annealing step			First cooling step	Holding step		Second coating step		Second cooling step				Note
			Annealing temperature (°C)	Annealing time (s)	Dew point (°C)		First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	
60	B	Absent	840	90	-15	260	440	50	GA	580	2.6	1	5	9	Inventive example
61	B	Absent	860	90	10	260	450	25	GI	-	2.6	2	7	10	Inventive example
62	B	Present (Fe)	850	110	-15	240	440	50	GA	560	2.5	1	10	8	Inventive example
63	B	Present (Fe)	860	110	10	270	430	45	GA	540	2.4	1	7	7	Inventive example
64	B	Present (Ni)	840	100	10	250	470	35	GA	530	2.3	3	4	8	Inventive example
65	F	Absent	890	30	-10	160	350	45	GA	500	2.3	4	6	10	Inventive example
66	F	Absent	880	70	15	150	350	55	GA	510	2.1	4	4	8	Inventive example
67	F	Present (Fe)	900	40	-10	160	360	70	GI	-	2.2	3	9	10	Inventive example
68	F	Present (Fe)	900	60	15	170	370	40	GI	-	2.2	4	5	10	Inventive example
69	F	Present (Ni)	870	70	15	170	370	65	GA	560	2.3	2	7	10	Inventive example
70	Q	Absent	840	90	-15	200	380	55	GA	550	2.3	2	5	3	Inventive example
71	Q	Absent	840	120	10	210	380	70	GA	520	2.7	2	6	3	Inventive example

(continued)

No.	Steel grade	First Coating step	Annealing step			First cooling step	Holding step		Second coating step		Second cooling step				Note
			Annealing temperature (°C)	Annealing time (s)	Dew point (°C)		First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	
72	Q	Present (Fe)	850	80	-15	220	390	65	GI	-	2.3	1	6	6	Inventive example
73	Q	Present (Fe)	840	120	10	180	380	45	GA	510	2.6	3	6	5	Inventive example
74	Q	Present (Ni)	850	90	10	200	400	75	GI	-	2.5	1	7	2	Inventive example
75	Q	Absent	840	300	-15	230	390	65	GA	530	2.9	3	4	6	Inventive example
76	Q	Absent	850	280	10	210	410	70	GA	500	2.7	2	10	5	Inventive example
77	Q	Present (Fe)	840	320	-15	210	400	75	GA	550	2.7	2	4	5	Inventive example
78	Q	Present (Fe)	840	280	10	220	400	70	GI	-	2.5	3	8	4	Inventive example
79	Q	Present (Ni)	840	290	10	250	430	75	GA	560	2.7	2	6	3	Inventive example

*1: Tension applied in the temperature range of 300°C or more and 450°C or less

*2: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll

*3: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for half the circumference of the roll

[Table 6]

No.	Steel grade	Sheet thickness (mm)	Steel microstructure (quarter thickness position)										Surface layer		Metal coating (g/m ²)	Nanohardness of sheet surface			Note
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1 (-)	LM *2 (μm)	σ _c *3 (μm)	Soft layer thickness (μm)	Ratio of Hn of 7.0 GPa or more *4		Standard deviation of Hn at quarter position (GPa)*5	Standard deviation of Hn at half position (GPa)*6		
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)											
60	B	1.8	9.6	18.7	59.2	77.9	6.1	6.0	θ	0.76	0.35	6.52	8	-	0.20	2.0	2.3	Inventive example	
61	B	1.8	3.9	16.4	63.2	79.6	5.9	7.2	θ	0.79	0.37	6.50	32	-	0.08	1.6	1.8	Inventive example	
62	B	1.8	5.5	15.9	66.7	82.6	6.6	5.1	θ	0.81	0.42	6.99	9	10	0.21	1.7	2.0	Inventive example	
63	B	1.8	2.2	22.6	57.0	79.6	7.2	7.1	θ	0.72	0.35	6.87	35	10	0.03	0.8	1.0	Inventive example	
64	B	1.8	7.8	17.1	58.8	75.9	6.4	7.2	θ	0.77	0.35	7.03	33	10	0.04	0.9	1.2	Inventive example	
65	F	1.4	3.5	15.3	67.4	82.7	6.9	5.4	LB, θ	0.81	0.36	6.39	7	-	0.24	2.2	2.5	Inventive example	
66	F	1.4	1.9	14.6	69.8	84.4	6.0	6.5	LB, θ	0.83	0.36	6.11	24	-	0.12	1.7	2.0	Inventive example	
67	F	1.4	0.0	19.2	65.3	84.5	7.1	7.3	LB, θ	0.77	0.40	6.19	8	15	0.25	1.8	2.1	Inventive example	
68	F	1.4	0.0	17.4	61.8	79.2	6.5	9.7	LB, θ	0.78	0.36	6.07	23	15	0.05	1.0	1.3	Inventive example	
69	F	1.4	4.6	19.9	60.2	80.1	7.6	6.9	LB, θ	0.75	0.37	6.41	25	15	0.06	1.1	1.4	Inventive example	
70	Q	1.4	9.6	14.9	65.2	80.1	6.0	4.2	LB, θ	0.81	0.23	5.82	10	-	0.18	1.9	2.3	Inventive example	
71	Q	1.4	4.5	13.7	67.3	81.0	6.5	6.2	LB, θ	0.83	0.26	6.35	42	-	0.07	1.4	1.6	Inventive example	

(continued)

No.	Steel grade	Sheet thickness (mm)	Steel microstructure (quarter thickness position)										Surface layer		Metal coating (g/m ²)	Nanohardness of sheet surface			Note
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1 (-)	LM *2 (μm)	σ _c *3 (μm)	Soft layer thickness (μm)	Ratio of Hn of 7.0 GPa or more *4		Standard deviation of Hn at quarter position (GPa)*5	Standard deviation of Hn at half position (GPa)*6		
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)											
72	Q	1.4	2.5	16.8	63.1	79.9	7.2	7.8	LB, θ	0.79	0.26	5.93	9	10	0.19	1.6	1.9	Inventive example	
73	Q	1.4	6.1	12.9	69.7	82.6	6.1	4.4	LB, θ	0.84	0.27	6.37	43	10	0.04	0.6	0.8	Inventive example	
74	Q	1.4	2.1	15.3	66.0	81.3	6.3	7.9	LB, θ	0.81	0.28	6.08	40	10	0.05	0.8	1.1	Inventive example	
75	Q	3.2	5.2	16.8	62.3	79.1	7.7	6.4	θ	0.79	0.40	7.29	10	-	0.17	1.9	2.3	Inventive example	
76	Q	3.2	3.1	14.4	64.8	79.2	6.6	8.2	θ	0.82	0.45	6.81	48	-	0.06	1.5	1.8	Inventive example	
77	Q	3.2	5.3	15.2	66.7	81.9	7.5	5.2	θ	0.81	0.38	6.85	10	10	0.18	1.7	1.9	Inventive example	
78	Q	3.2	5.9	13.9	62.4	76.3	7.5	7.8	θ	0.82	0.38	6.95	47	10	0.04	0.7	1.0	Inventive example	
79	Q	3.2	3.6	9.5	69.2	78.7	6.7	7.4	θ	0.88	0.46	7.29	50	10	0.05	0.8	1.1	Inventive example	

*1: BF; bainitic ferrite, TM; tempered martensite, RA; retained austenite, FM; fresh martensite, F; ferrite, LB; lower bainite, P; pearlite, θ; carbide

*2: L_M; the mean free path of the center of gravity of carbide

*3: σ_c; the average value of the standard deviation of the distance between carbide particles

*4: The ratio of the number of measurements with a nanohardness of 7.0 GPa or more to the total number of measurements of nanohardness at a quarter depth position in the thickness direction of a surface soft layer from the surface of a base steel sheet

*5: The standard deviation σ of the nanohardness of a sheet surface at a quarter position in the thickness direction of a surface soft layer from the surface of a base steel sheet

*6: The standard deviation σ of the nanohardness of a sheet surface at a half position in the thickness direction of a surface soft layer from the surface of a base steel sheet

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[Table 7]

No.	Steel grade	YS (MPa)	TS (MPa)	EI (%)	λ (%)	α (°)	SFmax (mm)	*1 (-)	*2 (-)	Axial compression	Note
60	B	944	1187	14.0	51	86	26.7	0.40	0.14	B	Inventive example
61	B	926	1183	12.7	44	98	27.9	0.33	0.11	A	Inventive example
62	B	981	1232	13.8	46	92	27.1	0.38	0.13	A	Inventive example
63	B	931	1185	13.3	49	110	29.1	0.25	0.00	A	Inventive example
64	B	937	1180	14.6	43	107	28.7	0.29	0.00	A	Inventive example
65	F	986	1344	13.3	57	81	26.1	0.51	0.15	B	Inventive example
66	F	969	1332	11.9	61	89	27.0	0.40	0.20	A	Inventive example
67	F	1034	1397	13.0	53	84	26.6	0.44	0.12	A	Inventive example
68	F	957	1324	11.9	58	93	28.2	0.29	0.11	A	Inventive example
69	F	982	1325	14.2	54	91	28.0	0.33	0.13	A	Inventive example
70	Q	941	1184	14.7	55	93	27.8	0.23	0.00	B	Inventive example
71	Q	926	1183	14.1	52	100	28.9	0.17	0.00	A	Inventive example
72	Q	988	1235	14.4	61	95	28.2	0.20	0.00	A	Inventive example
73	Q	919	1181	14.2	60	113	30.1	0.11	0.00	A	Inventive example
74	Q	1003	1199	12.5	57	110	29.7	0.13	0.00	A	Inventive example
75	Q	960	1205	14.6	63	85	26.9	0.43	0.17	B	Inventive example
76	Q	933	1189	13.6	53	97	28.2	0.38	0.13	A	Inventive example
77	Q	974	1222	14.3	58	91	27.2	0.40	0.14	A	Inventive example
78	Q	896	1185	14.6	57	110	29.3	0.25	0.00	A	Inventive example
79	Q	963	1187	14.0	57	107	29.0	0.29	0.00	A	Inventive example

*1: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion

*2: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending flat portion and a VDA bending ridge line portion

[Table 8]

No.	Steel grade	First Coating step	Annealing step			First cooling step	Holding step		Second coating step		Second cooling step				Note
		Presence or absence (Coating type)	Annealing temperature (°C)	Annealing time (s)	Dew point (°C)	First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension *1 (kgf/mm ²)	Applica- tion frequency (-)	Number of passes 1 *2 (-)	Number of passes 2 *3 (-)	
80	B	Absent	850	90	-15	250	440	45	CR	-	2.9	4	9	5	Inventive example
81	B	Absent	850	90	10	270	440	45	CR	-	2.8	1	6	3	Inventive example
82	B	Present (Fe)	850	90	-15	250	440	25	CR	-	2.9	3	9	3	Inventive example
83	B	Present (Fe)	860	100	10	260	440	30	CR	-	2.2	3	9	6	Inventive example
84	B	Present (Ni)	840	110	10	250	450	35	CR	-	2.8	4	9	9	Inventive example
85	F	Absent	880	60	-10	150	360	45	CR	-	2.1	4	4	7	Inventive example
86	F	Absent	870	60	15	170	360	65	CR	-	2.8	3	5	10	Inventive example
87	F	Present (Fe)	870	40	-10	150	370	50	CR	-	2.4	1	9	3	Inventive example
88	F	Present (Fe)	870	30	15	160	350	60	CR	-	2.4	4	10	5	Inventive example
89	F	Present (Ni)	890	60	15	150	350	50	CR	-	2.6	1	5	6	Inventive example
90	Q	Absent	835	100	-15	210	430	45	CR	-	2.7	3	9	10	Inventive example
91	Q	Absent	835	100	10	220	430	70	CR	-	2.4	2	9	6	Inventive example

(continued)

No.	Steel grade	First Coating step Presence or absence (Coating type)	Annealing step			First cooling step	Holding step		Second coating step		Second cooling step				Note
			Annealing temperature (°C)	Annealing time (s)	Dew point (°C)		Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension ^{*1} (kgf/mm ²)	Application frequency (-)	Number of passes 1 * 2 (-)	Number of passes 2 * 3 (-)	
92	Q	Present (Fe)	850	110	-15	200	430	45	CR	-	2.4	1	6	10	Inventive example
93	Q	Present (Fe)	840	100	10	210	410	55	CR	-	2.5	3	6	4	Inventive example
94	Q	Present (Ni)	840	120	10	190	380	65	CR	-	2.3	3	6	5	Inventive example
95	Q	Absent	840	300	-15	240	390	70	HR	-	2.8	2	10	3	Inventive example
96	Q	Absent	845	280	10	200	430	55	HR	-	2.6	2	6	3	Inventive example
97	Q	Present (Fe)	850	300	-15	200	410	60	HR	-	2.6	2	9	6	Inventive example
98	Q	Present (Fe)	840	310	10	190	410	60	HR	-	2.5	4	7	10	Inventive example
99	Q	Present (Ni)	835	310	10	250	430	75	HR	-	2.6	4	10	10	Inventive example
100	AG	Absent	830	90	-15	150	480	40	GA	550	3.4	3	9	5	Inventive example
101	AR	Absent	840	90	-15	170	410	50	CR	-	2.4	2	7	5	Inventive example
102	AR	Absent	840	100	10	170	410	50	CR	-	2.5	3	6	6	Inventive example
103	AR	Present (Fe)	850	80	-15	180	410	50	CR	-	2.1	5	9	6	Inventive example

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No.	Steel grade	First Coating step Presence or absence (Coating type)	Annealing step			First cooling step		Holding step		Second coating step		Second cooling step				Note
			Annealing temperature (°C)	Annealing time (s)	Dew point (°C)	First cooling stop temperature (°C)	First cooling stop temperature (°C)	Holding temperature (°C)	Holding time (s)	Type	Alloying temperature (°C)	Tension ^{*1} (kgf/mm ²)	Application frequency (-)	Number of passes 1 *2 (-)	Number of passes 2 *3 (-)	
104	AR	Present (Fe)	850	100	10	180	400	400	60	CR	-	2.0	4	8	5	Inventive example
105	AR	Present (Ni)	840	110	10	170	400	400	60	CR	-	2.0	5	8	4	Inventive example

*1: Tension applied in the temperature range of 300°C or more and 450°C or less
 *2: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll
 *3: The number of passes, each pass involving contact between a steel sheet and a roll with a diameter of 500 mm or more and 1500 mm or less for half the circumference of the roll

[Table 9]

No.	Steel grade	Sheet thickness (mm)	Steel microstructure (quarter thickness position)										Surface layer		Metal coating (g/m ²)	Nanohardness of sheet surface			Note
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1	L _M *2 (μm)	σ _c *3 (μm)	Soft layer thickness (μm)	Ratio of Hn of 7.0 GPa or more *4		Standard deviation of Hn at quarter position (GPa)*5	Standard deviation of Hn at half position (GPa)*6		
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)											
80	B	1.8	2.4	23.2	58.9	82.1	6.7	7.3	θ	0.72	0.39	6.54	5	-	0.22	2.0	2.5	Inventive example	
81	B	1.8	6.9	20.8	59.4	80.2	6.2	5.7	θ	0.74	0.42	6.46	38	-	0.10	1.4	1.8	Inventive example	
82	B	1.8	5.7	18.4	61.3	79.7	6.7	7.0	θ	0.77	0.42	5.98	6	10	0.20	1.7	2.0	Inventive example	
83	B	1.8	10.0	16.5	57.4	73.9	7.3	6.3	θ	0.78	0.39	6.06	42	10	0.06	0.6	1.2	Inventive example	
84	B	1.8	7.8	17.8	59.5	77.3	6.5	6.9	θ	0.77	0.42	6.48	40	10	0.05	0.8	0.8	Inventive example	
85	F	1.4	4.7	19.2	62.3	81.5	6.8	6.1	LB, θ	0.76	0.37	6.45	6	-	0.24	2.2	2.3	Inventive example	
86	F	1.4	4.7	17.9	60.7	78.6	7.7	7.6	LB, θ	0.77	0.35	6.89	26	-	0.12	1.5	2.1	Inventive example	
87	F	1.4	0.4	17.4	65.7	83.1	7.5	7.3	LB, θ	0.79	0.35	6.21	7	15	0.23	1.8	2.2	Inventive example	
88	F	1.4	3.3	18.3	63.5	81.8	7.4	6.1	LB, θ	0.78	0.36	5.99	27	15	0.05	1.1	1.3	Inventive example	
89	F	1.4	5.0	18.9	58.7	77.6	7.4	8.0	LB, θ	0.76	0.40	6.61	30	15	0.03	0.7	1.4	Inventive example	
90	Q	1.4	5.4	16.1	63.4	79.5	7.1	6.3	LB, θ	0.80	0.24	6.84	9	-	0.24	2.1	2.4	Inventive example	
91	Q	1.4	2.5	20.0	63.6	83.6	6.8	6.6	LB, θ	0.76	0.23	6.56	40	-	0.07	1.5	1.6	Inventive example	

(continued)

No.	Steel grade	Sheet thickness (mm)	Steel microstructure (quarter thickness position)										Surface layer		Metal coating (g/m ²)	Nanohardness of sheet surface			Note
			Area fraction of each phase *1							Microstructure of the remainder *1	TM / (TM+BF) *1	L _M *2 (μm)	σ _c *3 (μm)	Soft layer thickness (μm)		Ratio of Hn of 7.0 GPa or more *4	Standard deviation of Hn at quarter position (GPa)*5	Standard deviation of Hn at half position (GPa)*6	
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)											
92	Q	1.4	6.5	15.4	62.9	78.3	7.6	6.6	LB, θ	0.80	0.26	6.41	7	10	0.20	1.8	2.1	Inventive example	
93	Q	1.4	5.6	17.8	60.3	78.1	6.5	7.5	LB, θ	0.77	0.28	7.10	42	10	0.03	0.7	1.2	Inventive example	
94	Q	1.4	4.4	12.2	66.1	78.3	8.0	7.0	LB, θ	0.84	0.29	6.63	38	10	0.05	0.6	1.1	Inventive example	
95	Q	3.2	3.5	13.1	69.0	82.1	6.2	6.2	θ	0.84	0.41	5.97	8	-	0.25	2.0	2.4	Inventive example	
96	Q	3.2	6.5	12.3	66.4	78.7	6.9	7.0	θ	0.84	0.38	5.87	39	-	0.11	1.5	1.8	Inventive example	
97	Q	3.2	9.6	12.9	61.3	74.2	6.8	7.4	θ	0.83	0.45	6.51	7	10	0.24	1.7	2.2	Inventive example	
98	Q	3.2	2.6	12.2	71.9	84.1	6.4	6.1	θ	0.85	0.38	6.07	40	10	0.05	0.9	1.2	Inventive example	
99	Q	3.2	3.3	13.4	68.5	81.9	6.0	6.8	θ	0.84	0.43	6.48	45	10	0.03	1.0	1.0	Inventive example	
100	AG	0.9	14.5	9.9	60.4	70.3	7.4	6.5	θ	0.86	0.48	6.98	8	-	0.20	2.0	2.3	Inventive example	
101	AR	1.4	6.6	15.9	59.1	75.0	7.3	5.0	LB, θ	0.79	0.20	6.34	6	-	0.17	1.9	2.5	Inventive example	
102	AR	1.4	48	14.1	63.2	77.3	5.4	3.2	LB, θ	0.82	0.23	6.11	38	-	0.06	1.5	2.2	Inventive example	
103	AR	1.4	4.6	20.0	58.5	78.5	6.0	4.9	LB, θ	0.75	0.21	5.18	10	10	0.10	1.5	1.6	Inventive example	

(continued)

No.	Steel grade	Sheet thickness (mm)	Steel microstructure (quarter thickness position)										Surface layer		Metal coating (g/m ²)	Nanohardness of sheet surface			Note
			Area fraction of each phase *1						Microstructure of the remainder *1	TM / (TM+BF) *1	L _M *2 (μm)	σ _c *3 (μm)	Soft layer thickness (μm)	Ratio of Hn of 7.0 GPa or more *4		Standard deviation of Hn at quarter position (GPa)*5	Standard deviation of Hn at half position (GPa)*6		
			F (%)	BF (%)	TM (%)	BF+TM (%)	RA (%)	FM (%)											
104	AR	1.4	3.4	17.9	58.9	76.8	5.5	4.0	LB, θ	0.77	0.31	5.76	41	10	0.04	0.9	1.2	Inventive example	
105	AR	1.4	4.3	10.8	65.0	75.8	5.5	5.0	LB, θ	0.86	0.26	6.53	39	10	0.04	0.8	0.9	Inventive example	
*1: BF; bainitic ferrite, TM; tempered martensite, RA; retained austenite, FM; fresh martensite, F; ferrite, LB; lower bainite, P; pearlite, θ; carbide																			
*2: L _M : the mean free path of the center of gravity of carbide																			
*3: σ _c : the average value of the standard deviation of the distance between carbide particles																			
*4: The ratio of the number of measurements with a nanohardness of 7.0 GPa or more to the total number of measurements of nanohardness at a quarter depth position in the thickness direction of a surface soft layer from the surface of a base steel sheet																			
*5: The standard deviation σ of the nanohardness of a sheet surface at a quarter position in the thickness direction of a surface soft layer from the surface of a base steel sheet																			
*6: The standard deviation a of the nanohardness of a sheet surface at a half position in the thickness direction of a surface soft layer from the surface of a base steel sheet																			

*1: BF; bainitic ferrite, TM; tempered martensite, RA; retained austenite, FM; fresh martensite, F; ferrite, LB; lower bainite, P; pearlite, θ; carbide

*2: L_M; the mean free path of the center of gravity of carbide*3: σ_c; the average value of the standard deviation of the distance between carbide particles

*4: The ratio of the number of measurements with a nanohardness of 7.0 GPa or more to the total number of measurements of nanohardness at a quarter depth position in the thickness direction of a surface soft layer from the surface of a base steel sheet

*5: The standard deviation σ of the nanohardness of a sheet surface at a quarter position in the thickness direction of a surface soft layer from the surface of a base steel sheet

*6: The standard deviation a of the nanohardness of a sheet surface at a half position in the thickness direction of a surface soft layer from the surface of a base steel sheet

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[Table 10]

	No.	Steel grade	YS (MPa)	TS (MPa)	EI (%)	λ (%)	α (°)	SFmax (mm)	*1 (-)	*2 (-)	Axial compression	Note
5	80	B	929	1190	13.6	50	82	27.4	0.37	0.12	B	Inventive example
	81	B	958	1191	14.2	49	95	28.0	0.29	0.13	A	Inventive example
10	82	B	971	1180	14.1	47	90	26.4	0.37	0.15	A	Inventive example
	83	B	977	1200	13.2	48	107	29.6	0.15	0.00	A	Inventive example
15	84	B	949	1183	14.4	43	107	30.5	0.18	0.00	A	Inventive example
	85	F	972	1334	13.9	61	91	26.5	0.35	0.18	B	Inventive example
20	86	F	1014	1320	13.6	58	83	27.7	0.23	0.14	A	Inventive example
	87	F	960	1323	13.0	54	87	26.7	0.35	0.15	A	Inventive example
25	88	F	992	1330	14.2	57	98	29.6	0.13	0.15	A	Inventive example
	89	F	1006	1333	13.2	54	96	29.4	0.15	0.14	A	Inventive example
30	90	Q	933	1194	14.6	58	93	28.0	0.31	0.00	B	Inventive example
	91	Q	970	1188	14.0	55	94	26.4	0.29	0.00	A	Inventive example
35	92	Q	918	1196	14.4	53	82	27.7	0.48	0.00	A	Inventive example
	93	Q	954	1190	13.9	58	99	29.8	0.16	0.00	A	Inventive example
40	94	Q	910	1187	14.4	56	103	28.3	0.10	0.00	A	Inventive example
	95	Q	981	1196	14.3	62	92	26.6	0.24	0.19	B	Inventive example
45	96	Q	980	1187	12.8	63	89	27.2	0.25	0.17	A	Inventive example
	97	Q	912	1191	12.5	60	95	27.1	0.35	0.18	A	Inventive example
50	98	Q	897	1189	13.2	60	107	30.0	0.17	0.00	A	Inventive example
	99	Q	968	1192	13.5	54	113	28.4	0.20	0.00	A	Inventive example
55	100	AG	750	1189	14.5	45	82	26.5	0.45	0.19	B	Inventive example
	101	AR	1010	1233	13.4	69	89	27.6	0.30	0.09	B	Inventive example

(continued)

No.	Steel grade	YS (MPa)	TS (MPa)	EI (%)	λ (%)	α (°)	SFmax (mm)	*1 (-)	*2 (-)	Axial compression	Note
102	AR	1022	1192	12.5	56	110	28.5	0.36	0.05	A	Inventive example
103	AR	1047	1225	12.5	62	106	29.7	0.35	0.00	A	Inventive example
104	AR	1035	1186	12.8	66	98	29.8	0.22	0.00	A	Inventive example
105	AR	994	1197	12.7	68	100	29.8	0.24	0.00	A	Inventive example
*1: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion *2: The value obtained by dividing the number of voids in contact with a hard phase by the total number of voids in an overlap region of a V-bending flat portion and a VDA bending ridge line portion											

[0318] In Tables 1 to 10, the underlined portions indicate values outside the appropriate range of the present invention.

[0319] As shown in Tables 4, 7, and 10, all the inventive examples passed all the tensile strength (TS), the yield stress (YS), the total elongation (EI), the limiting hole expansion ratio (λ), the critical bending angle (α) in the VDA bending test, and the stroke at the maximum load (S_{Fmax}) in the V-VDA bending test, and had no fracture in the axial compression test.

[0320] In contrast, the comparative examples were not satisfactory in at least one of the tensile strength (TS), the yield stress (YS), the total elongation (EI), the limiting hole expansion ratio (λ), the critical bending angle (α) in the VDA bending test, the stroke at the maximum load (S_{Fmax}) in the V-VDA bending test, and the presence or absence of fracture in the axial compression test.

[0321] In Tables 5 to 10, at a dew point of -30°C or more and -5°C or less, although there were some cases where the soft layer had a thickness of less than 11 μ m and the fracture (appearance crack) in the axial compression test was rated as "B", even when the soft layer had a thickness of less than 11 μ m, in the presence of the metal coated layer, the fracture (appearance crack) in the axial compression test was rated as "A".

[0322] It was also found that the members produced by forming or joining the steel sheets of the inventive examples had good characteristics of the present invention in all of the tensile strength (TS), the yield stress (YS), the total elongation (EI), the limiting hole expansion ratio (λ), the critical bending angle (α) in the VDA bending test, and the stroke at the maximum load (S_{Fmax}) in the V-VDA bending test, had no fracture in the axial compression test, and had good characteristics of the present invention.

Reference Signs List

[0323]

10 hat-shaped member

20 steel sheet

30 test member

40 spot weld

50 base plate

60 impactor

A1 die

A2 support roll

B1 punch

B2 punch

D1 width (C) direction

D2 rolling (L) direction

D3 compression direction

T1 test specimen

T2 test specimen

P maximum load point

R a region with the load being 94.9% to 99.9% of the maximum load when the stroke is increased from the maximum

load point

AB a region of 0 to 100 μm from the surface of a steel sheet at a bending peak portion on the outside of a VDA bend

AL an L cross section in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion

F ferrite

BF bainitic ferrite

TM tempered martensite

θ carbide

H1 hard phase (hard second phase)

S1 soft layer

V1 a void at a boundary between a hard phase and a soft phase

V2 a void due to fracture of a hard phase

V3 a void due to carbide

Claims

1. A steel sheet comprising a base steel sheet, wherein the base steel sheet has a chemical composition containing, on a mass percent basis,

C: 0.050% or more and 0.400% or less,

Si: more than 0.75% and 3.00% 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,

Al: 0.010% or more and 2.000% or less, and

N: 0.0100% or less,

with the remainder being Fe and incidental impurities,

the base steel sheet has a steel microstructure in which

an area fraction of ferrite: 57.0% or less,

a total area fraction of bainitic ferrite and tempered martensite: 40.0% or more and 90.0% or less,

an area fraction of retained austenite: 3.0% or more and 10.0% or less,

an area fraction of fresh martensite: 10.0% or less, and

a value obtained by dividing an area fraction of tempered martensite by the total area fraction of bainitic ferrite and tempered martensite is 0.70 or more,

a V-VDA bending test is performed to a maximum load point,

in an overlap region of a V-bending ridge line portion and a VDA bending ridge line portion, a value obtained by dividing the number of voids in contact with a hard phase among all voids by the total number of voids is 0.60 or less,

in an overlap region of a V-bending flat portion and the VDA bending ridge line portion, a value obtained by dividing the number of voids in contact with the hard phase among all voids by the total number of voids is 0.20 or less,

carbide has a mean free path L_M of 0.20 μm or more as represented by the following formula (1), and

the steel sheet has a tensile strength of 1180 MPa or more,

$$L_M = (d_M/2) \times (400\pi/3f)^{1/3} \quad \text{formula (1)}$$

wherein L_M denotes the mean free path (μm) of carbide, d_M denotes an average equivalent circular diameter (μm) of carbide, π denotes a circumference ratio, and f denotes a volume fraction (%) of all carbide particles.

2. The steel sheet according to Claim 1, wherein the base steel sheet has a chemical composition further containing, on a mass percent basis, at least one selected from

Nb: 0.200% or less,

Ti: 0.200% or less,

V: 0.200% or less,

B: 0.0100% or less,

Cr: 1.000% or less,

Ni: 1.000% or less,

Mo: 1.000% or less,

Sb: 0.200% or less,
 Sn: 0.200% or less,
 Cu: 1.000% or less,
 Ta: 0.100% or less,
 W: 0.500% or less,
 Mg: 0.0200% or less,
 Zn: 0.0200% or less,
 Co: 0.0200% or less,
 Zr: 0.1000% or less,
 Ca: 0.0200% or less,
 Se: 0.0200% or less,
 Te: 0.0200% or less,
 Ge: 0.0200% or less,
 As: 0.0500% or less,
 Sr: 0.0200% or less,
 Cs: 0.0200% or less,
 Hf: 0.0200% or less,
 Pb: 0.0200% or less,
 Bi: 0.0200% or less, and
 REM: 0.0200% or less.

3. The steel sheet according to claim 1 or 2, comprising a galvanized layer as an outermost surface layer on one or both surfaces of the steel sheet.

4. The steel sheet according to any one of Claims 1 to 3, wherein an average value σ_C of a standard deviation of a distance between a carbide particle A selected from all carbide particles in the steel sheet and a remaining carbide particle other than the carbide particle A is 7.50 μm or less.

5. The steel sheet according to any one of Claims 1 to 4, wherein

when a region of 200 μm or less from a surface of the base steel sheet in the thickness direction is defined as a surface layer, the base steel sheet has, in the surface layer, a surface soft layer with a Vickers hardness of 85% or less with respect to a Vickers hardness at a quarter thickness position, and
 when nanohardness is measured at 300 points or more in a 50 μm x 50 μm region on a sheet surface at a quarter depth position in the thickness direction and at a half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet,
 a ratio of a number of measurements with a nanohardness of 7.0 GPa or more on the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet to a total number of measurements at the quarter depth position in the thickness direction of the surface soft layer is 0.10 or less,
 the nanohardness of the sheet surface at the quarter depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet has a standard deviation σ of 1.8 GPa or less, and
 the nanohardness of the sheet surface at the half depth position in the thickness direction of the surface soft layer from the surface of the base steel sheet has a standard deviation σ of 2.2 GPa or less.

6. The steel sheet according to any one of Claims 1 to 5, comprising a metal coated layer formed on the base steel sheet on one or both surfaces of the steel sheet.

7. A member comprising the steel sheet according to any one of Claims 1 to 6.

8. A method for producing a steel sheet, comprising:

a hot rolling step of hot-rolling a steel slab with the chemical composition according to Claim 1 or 2 to produce a hot-rolled steel sheet;
 a pickling step of pickling the hot-rolled steel sheet;
 an annealing step of annealing the steel sheet after the pickling step at an annealing temperature of $(Ac_1 + (Ac_3 - Ac_1) \times 3/4)^\circ\text{C}$ or more and 900°C or less for an annealing time of 20 seconds or more;
 a first cooling step of cooling the steel sheet after the annealing step to a first cooling stop temperature of 100°C or

more and 300°C or less;

a holding step of holding the steel sheet after the first cooling step in a temperature range of 350°C or more and 550°C or less for 3 seconds or more and less than 80 seconds;

a second cooling step of cooling the steel sheet after the holding step to a second cooling stop temperature of 50°C or less, during the cooling, applying a tension of 2.0 kgf/mm² or more to the steel sheet once or more in a temperature range of 300°C or more and 450°C or less,

then

subjecting the steel sheet to four or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for a quarter circumference of the roll, and

subjecting the steel sheet to two or more passes, each pass involving contact with a roll with a diameter of 500 mm or more and 1500 mm or less for half a circumference of the roll; and

optionally a cold rolling step of cold-rolling the steel sheet after the pickling step and before the annealing step to produce a cold-rolled steel sheet.

9. The method for producing a steel sheet according to Claim 8, comprising a galvanizing step of performing a galvanizing treatment on the steel sheet after the holding step and before the second cooling step to form a galvanized layer on the steel sheet.

10. The method for producing a steel sheet according to Claim 8 or 9, wherein the annealing in the annealing step is performed in an atmosphere with a dew point of -30°C or more.

11. The method for producing a steel sheet according to any one of Claims 8 to 10, comprising a metal coating step of performing metal coating on one or both surfaces of the steel sheet to form a metal coated layer after the pickling step and before the annealing step.

12. A method for producing a member, comprising a step of subjecting the steel sheet according to any one of Claims 1 to 6 to at least one of forming and joining to produce a member.

FIG. 1

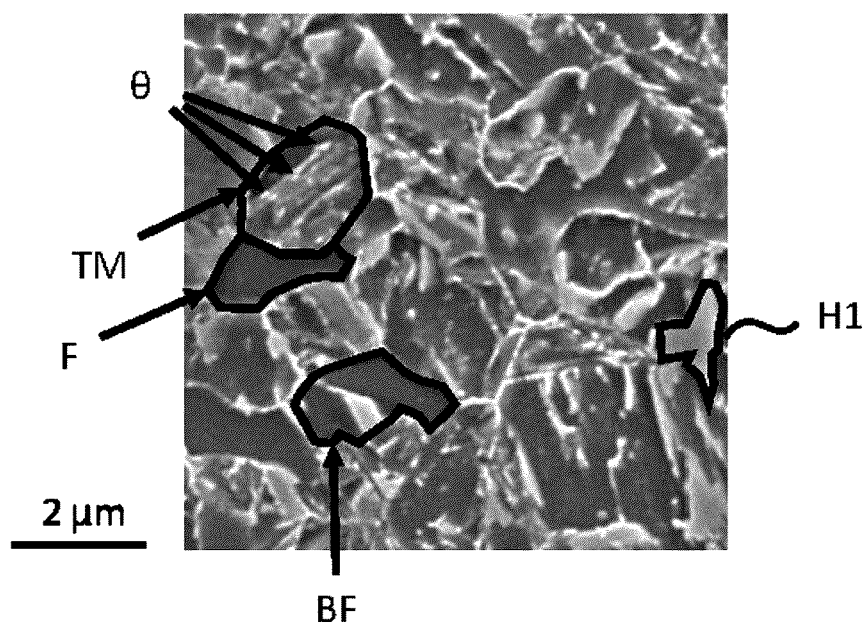
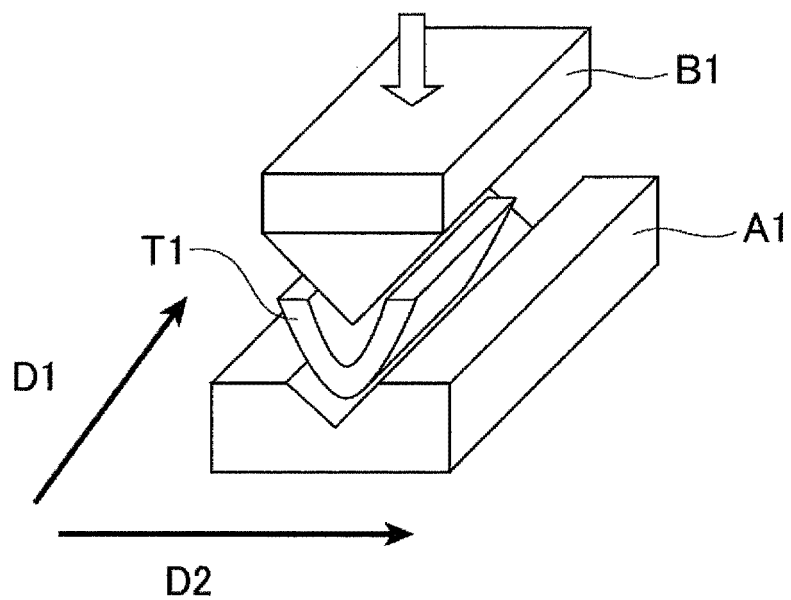


FIG. 2-1

(a)



(b)

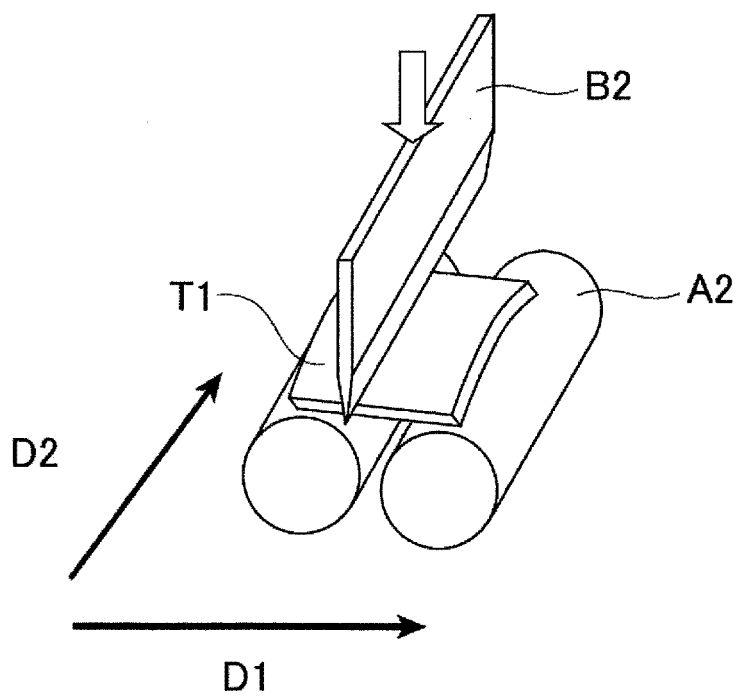
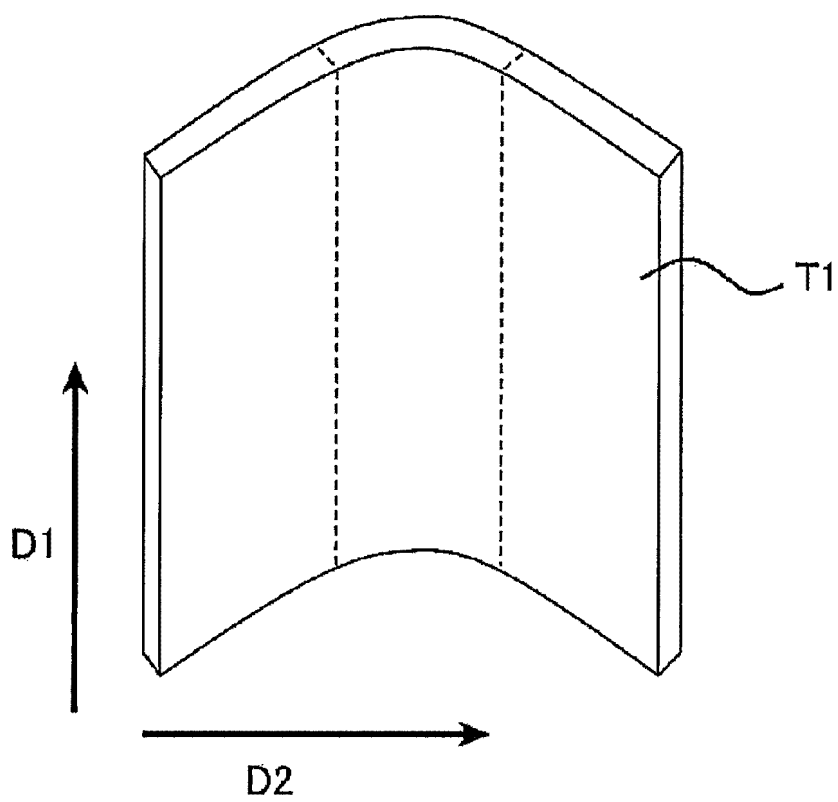


FIG. 2-2

(c)



(d)

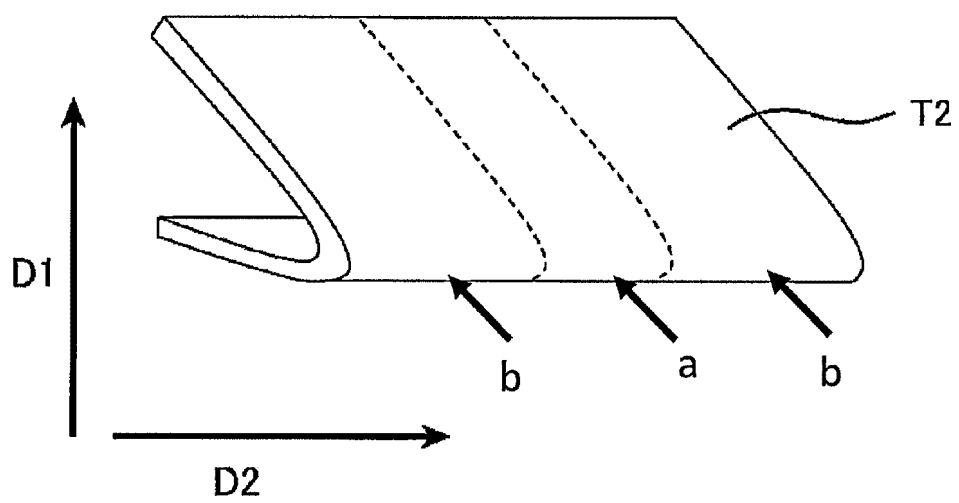


FIG. 2-3

(e)

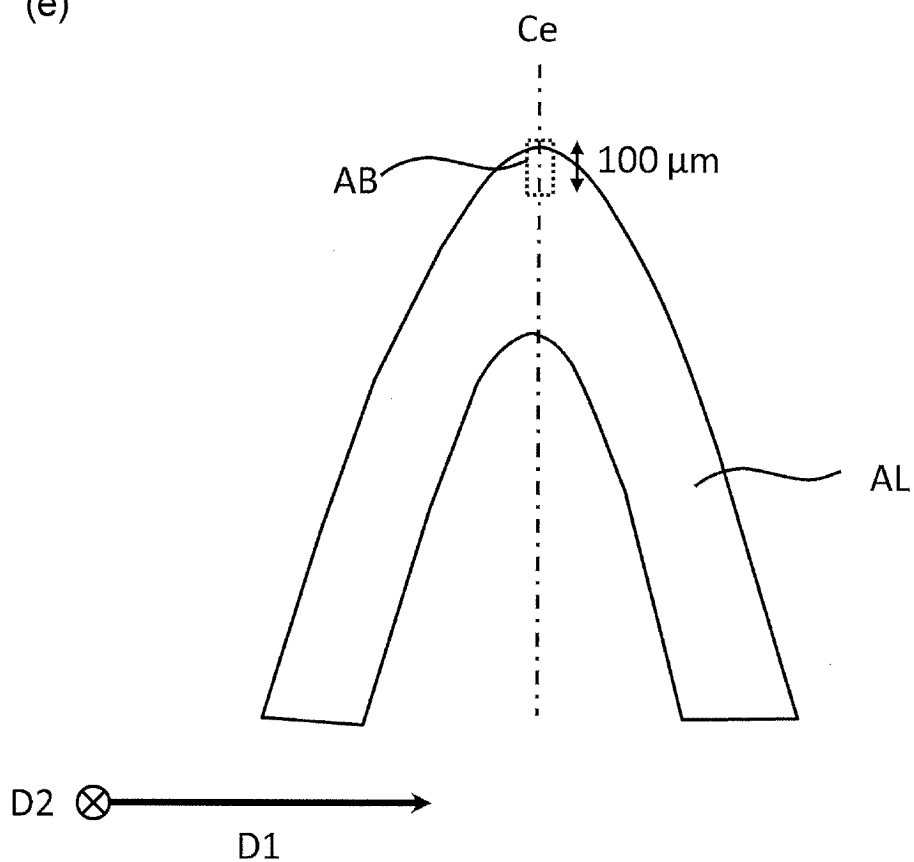


FIG. 3

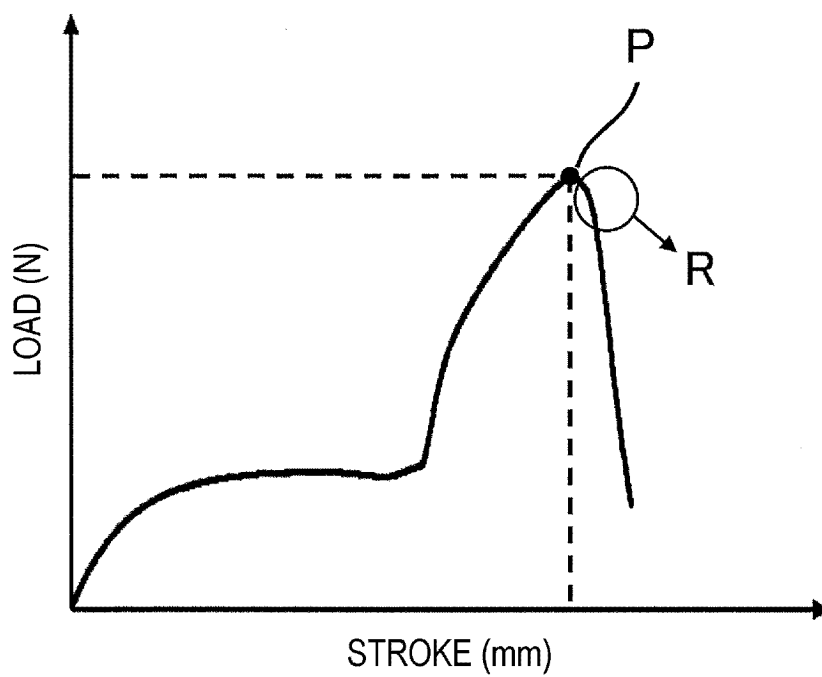


FIG. 4

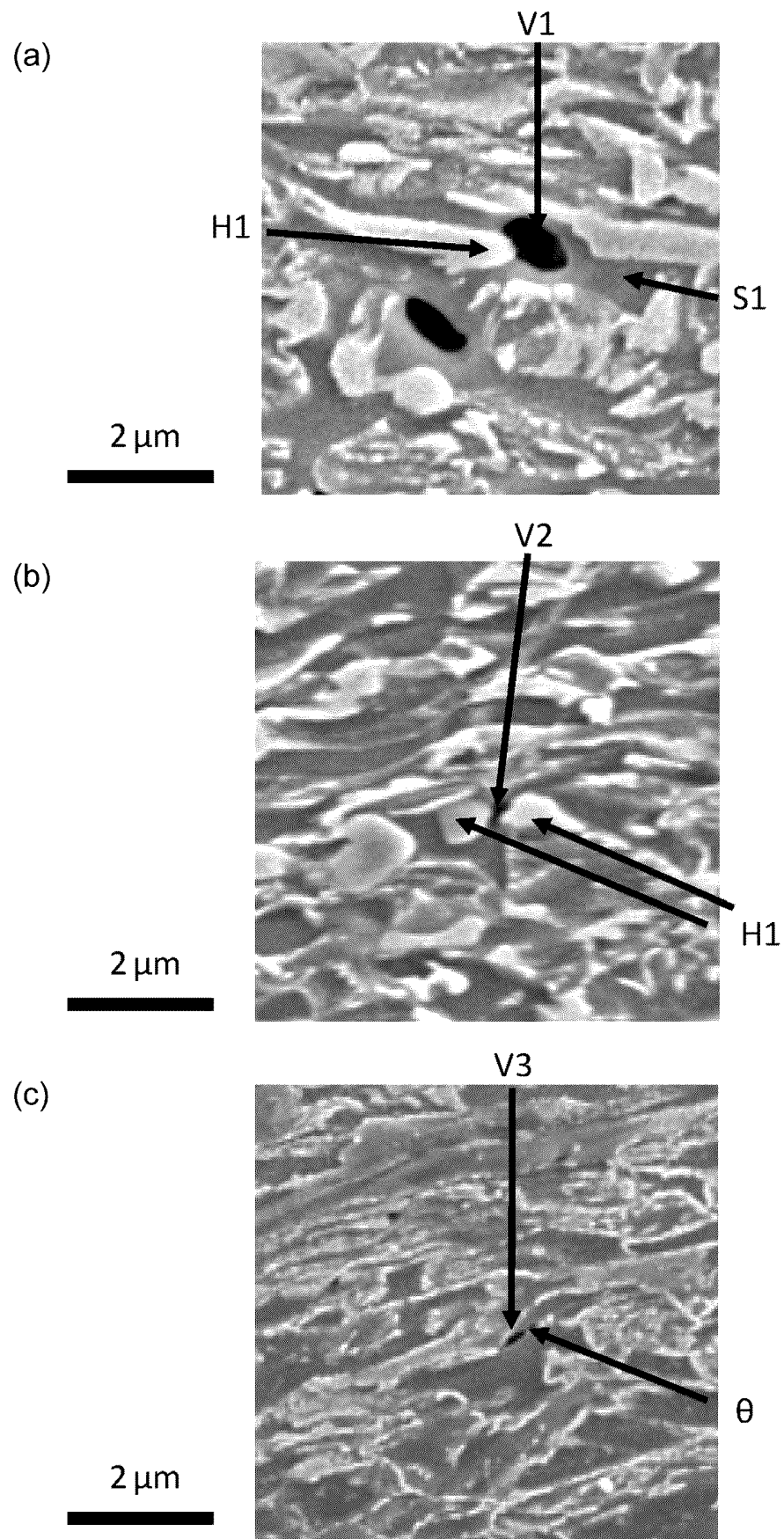
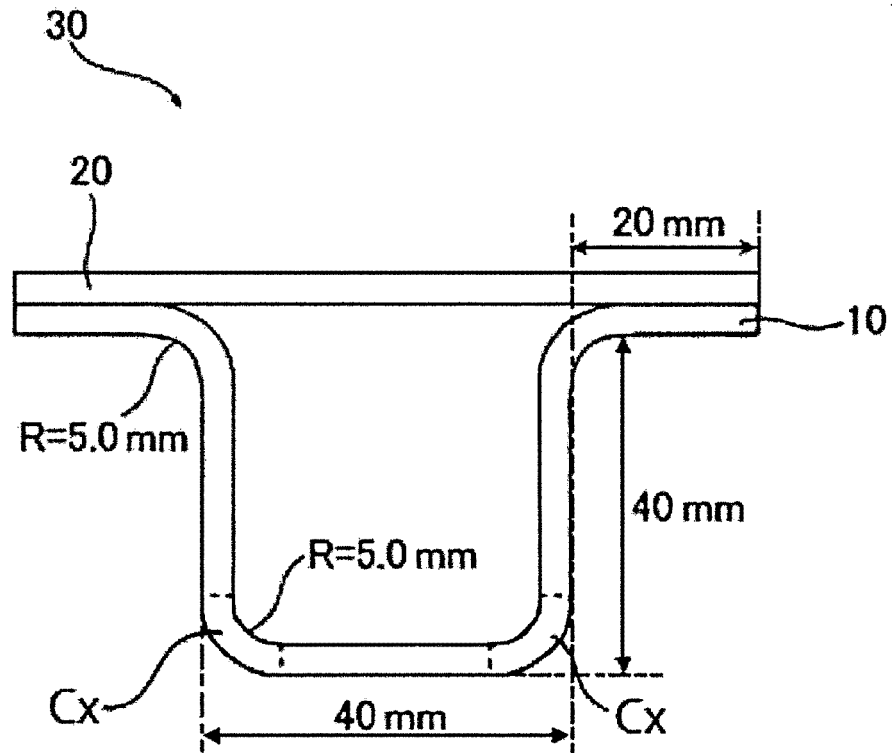


FIG. 5-1

(a)



(b)

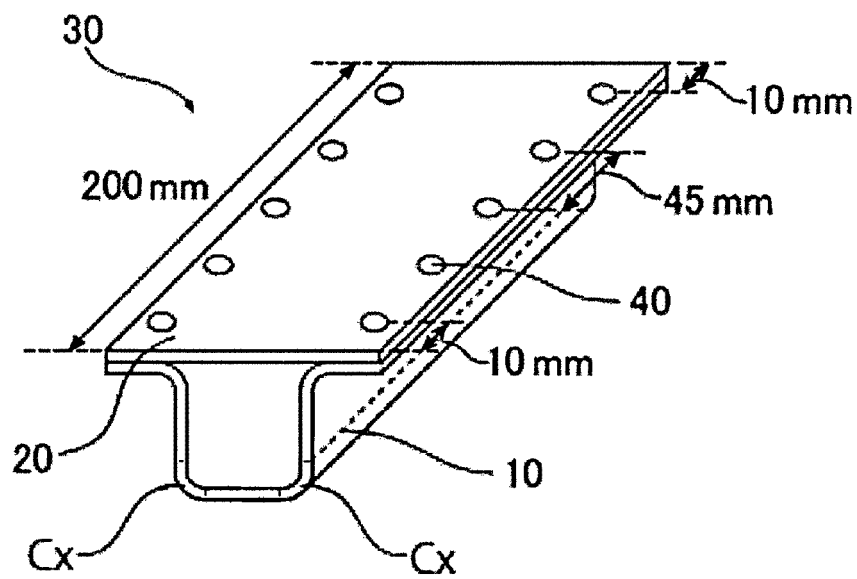
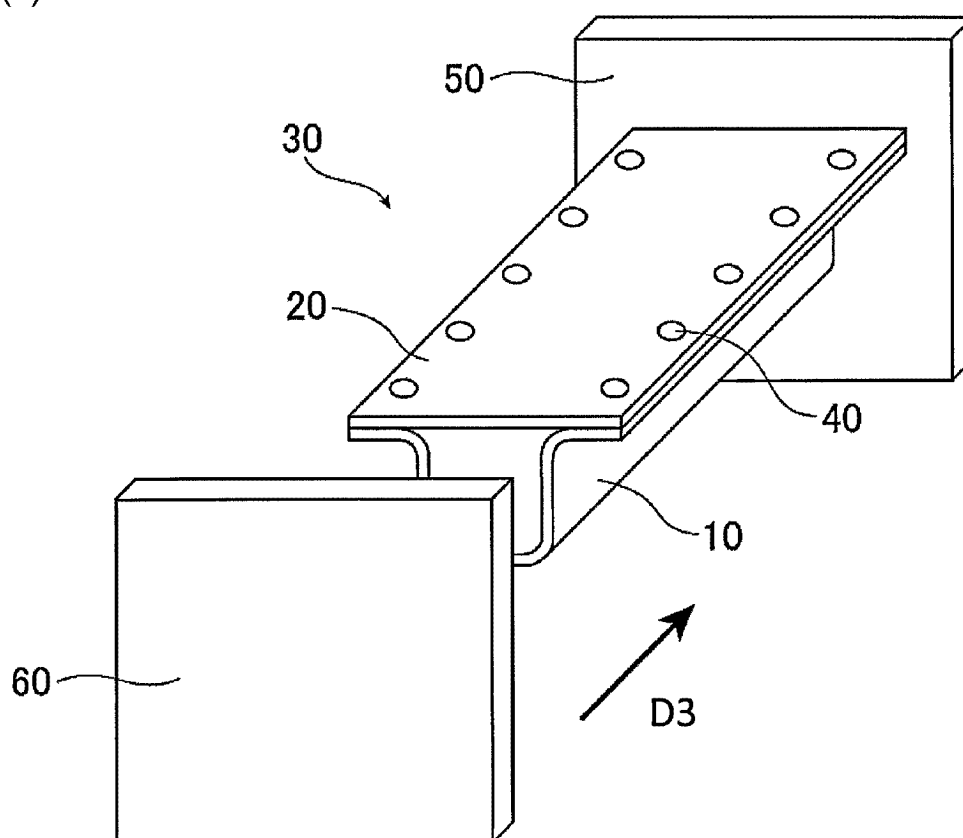


FIG. 5-2

(c)



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2023/006923

A. CLASSIFICATION OF SUBJECT MATTER

C21D 9/46(2006.01)i; *C22C 38/00*(2006.01)i; *C22C 38/06*(2006.01)i; *C22C 38/60*(2006.01)i; *C23C 2/02*(2006.01)i;
C23C 2/06(2006.01)i; *C23C 2/28*(2006.01)i

FI: C22C38/00 301S; C22C38/00 301T; C22C38/06; C22C38/60; C23C2/02; C23C2/06; C23C2/28; C21D9/46 H

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; C22C38/00; C22C38/06; C22C38/60; C23C2/02; C23C2/06; C23C2/28

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

Published examined utility model applications of Japan 1922-1996
 Published unexamined utility model applications of Japan 1971-2023
 Registered utility model specifications of Japan 1996-2023
 Published registered utility model applications of Japan 1994-2023

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	KR 10-1828699 B1 (HYUNDAI STEEL COMPANY) 12 February 2018 (2018-02-12)	1-12
A	WO 2022/004819 A1 (JFE STEEL CORP.) 06 January 2022 (2022-01-06)	1-12
A	WO 2022/004820 A1 (JFE STEEL CORP.) 06 January 2022 (2022-01-06)	1-12
A	US 2009/0098408 A1 (NUCOA CORP.) 16 April 2009 (2009-04-16)	1-12

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

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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Date of the actual completion of the international search	Date of mailing of the international search report
19 April 2023	09 May 2023
Name and mailing address of the ISA/JP	Authorized officer
Japan Patent Office (ISA/JP) 3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915 Japan	Telephone No.

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

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/006923

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				KR	10-2023-0013272	A
				CN	115768915	A
WO	2022/004820	A1	06 January 2022	EP	4141132	A1
				KR	10-2023-0013273	A
				CN	115715332	A
US	2009/0098408	A1	16 April 2009	WO	2009/048838	A1

REFERENCES CITED IN THE DESCRIPTION

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- JP 5953693 B [0007]
- JP 6052472 B [0007]