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(54) **STEEL PLATE, PLATED STEEL PLATE, AND PRODUCTION METHOD THEREFOR**

(57) A high-strength steel sheet with excellent formability and high yield ratio and hole expansion formability that has TS of 590 MPa or more and YR of 68 % or more is obtained by providing a predetermined chemical composition and a steel microstructure that contains, in area ratio, 20 % or more and 65 % or less of polygonal ferrite, 8 % or more of non-recrystallized ferrite, and 5 % or more and 25 % or less of martensite, and that contains, in volume fraction, 8 % or more of retained austenite, where

an average aspect ratio of crystal grains of each phase (polygonal ferrite, martensite, and retained austenite) is 2.0 or more and 15.0 or less, wherein the polygonal ferrite has an average grain size of 6 μm or less, the martensite has an average grain size of 3 μm or less, the retained austenite has an average grain size of 3 μm or less, and a value obtained by dividing a Mn content in the retained austenite in mass% by a Mn content in the polygonal ferrite in mass% equals 2.0 or more.

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Description

TECHNICAL FIELD

5 **[0001]** This disclosure relates to a steel sheet, a hot-dip galvanized steel sheet, a hot-dip aluminum-coated steel sheet, and an electrogalvanized steel sheet, and methods for manufacturing the same, and in particular to a steel sheet with excellent formability and hole expansion formability and high yield ratio that is preferably used in parts in the industrial fields of automobiles, electronics, and the like.

10 BACKGROUND

[0002] In recent years, enhancement of fuel efficiency of automobiles has become an important issue from the viewpoint of global environment protection. Consequently, there is an active movement to reduce the thickness of automotive body components through increases in strength of steel sheets as automotive body materials, and thereby reduce the weight of automotive body itself.

15 **[0003]** In general, however, strengthening of steel sheets leads to deterioration in formability, causing the problem of cracking during forming. It is thus not simple to reduce the thickness of steel sheets. Therefore, it is desirable to develop materials with increased strength and good formability. In addition to good formability, steel sheets with a tensile strength (TS) of 590 MPa or more are required to have, in particular, enhanced impact energy absorption properties. To enhance impact energy absorption properties, it is effective to increase yield ratio (YR). The reason is that a higher yield ratio enables the steel sheet to absorb impact energy more effectively with less deformation.

20 **[0004]** Moreover, in the case of using a steel sheet in an automotive body, stretch flanging according to the shape of the automotive body is performed, so that excellent hole expansion formability is required, too.

[0005] For example, JPS61157625A (PTL 1) proposes a high-strength steel sheet with extremely high ductility having a tensile strength of 1000 MPa or higher and a total elongation (EL) of 30 % or more, utilizing deformation induced transformation of retained austenite.

25 **[0006]** In addition, JPH1259120A (PTL 2) proposes a high-strength steel sheet with well-balanced strength and ductility that is obtained from high-Mn steel through heat treatment in a ferrite-austenite dual phase region.

30 **[0007]** Moreover, JP2003138345A (PTL 3) proposes a high-strength steel sheet with improved local ductility that is obtained from high-Mn steel through hot rolling to have a microstructure containing bainite and martensite after subjection to the hot rolling, followed by annealing and tempering to cause fine retained austenite, and subsequently tempered bainite or tempered martensite in the microstructure.

CITATION LIST

35 Patent Literature

[0008]

40 PTL 1: JPS61157625A

PTL 2: JPH1259120A

45 PTL 3: JP2003138345A

SUMMARY

(Technical Problem)

50 **[0009]** The steel sheet described in PTL 1 is manufactured by austenitizing a steel sheet containing C, Si, and Mn as basic components, and subjecting the steel sheet to a so-called austempering process whereby the steel sheet is quenched to and held isothermally in a bainite transformation temperature range. During the austempering process, C concentrates in austenite to form retained austenite.

55 **[0010]** However, while a high concentration of C beyond 0.3 % is required for the formation of a large amount of retained austenite, such a high C concentration above 0.3 % leads to a significant decrease in spot weldability, which may not be suitable for practical use in steel sheets for automobiles. Additionally, the main objective of PTL 1 is improving the ductility of steel sheets, without any consideration for the hole expansion formability, bendability, or yield ratio.

[0011] PTLs 2 and 3 describe techniques for improving the ductility of steel sheets from the perspective of formability,

but do not consider the bendability, yield ratio, or hole expansion formability of the steel sheet.

[0012] To address these issues, it could thus be helpful to provide a steel sheet, a hot-dip galvanized steel sheet, a hot-dip aluminum-coated steel sheet, and an electrogalvanized steel sheet that are excellent in formability and hole expansion formability with TS of 590 MPa or more and YR of 68 % or more, and methods for manufacturing the same.

(Solution to Problem)

[0013] To manufacture a high-strength steel sheet that can solve the above issues, with excellent formability and hole expansion formability as well as high yield ratio and high tensile strength, we made intensive studies from the perspectives of the chemical compositions and manufacturing methods of steel sheets. As a result, we discovered that a high-strength steel sheet with high yield ratio that is excellent in formability such as ductility and hole expansion formability can be manufactured by appropriately controlling the chemical composition and microstructure of steel.

[0014] Specifically, a steel sheet that has a steel composition containing Mn: 2.60 mass% or more and 4.20 mass% or less, with the addition amounts of other alloying elements such as Ti being adjusted appropriately, is hot rolled to obtain a hot-rolled sheet. The hot-rolled sheet is then subjected to pickling to remove scales, retained in a temperature range of $[Ac_1 \text{ transformation temperature} + 20 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 120 \text{ }^\circ\text{C}]$ for 600 s to 21,600 s, and optionally cold rolled at a rolling reduction of less than 30 % to obtain a cold-rolled sheet. Further, the hot-rolled sheet as annealed after the hot rolling or the cold-rolled sheet is retained in a temperature range of $[Ac_1 \text{ transformation temperature} + 10 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 100 \text{ }^\circ\text{C}]$ for 20 s to 900 s, and subsequently cooled.

[0015] Through this process, the hot-rolled sheet or the cold-rolled sheet has a microstructure that contains, in area ratio, 20 % or more and 65 % or less of polygonal ferrite, 8 % or more of non-recrystallized ferrite, and 5 % or more and 25 % or less of martensite, and, in volume fraction, 8 % or more of retained austenite, where the average aspect ratio of crystal grains of each phase (polygonal ferrite, martensite, and retained austenite) is 2.0 or more and 15.0 or less, the polygonal ferrite has an average grain size of 6 μm or less, the martensite has an average grain size of 3 μm or less, and the retained austenite has an average grain size of 3 μm or less. Moreover, the microstructure of the hot-rolled sheet or the cold-rolled sheet can be controlled so that a value obtained by dividing a Mn content in the retained austenite (in mass%) by a Mn content in the polygonal ferrite (in mass%) equals 2.0 or more, making it possible to obtain 8 % or more of retained austenite stabilized with Mn.

[0016] This disclosure has been made based on these discoveries.

[0017] Specifically, the primary features of this disclosure are as described below.

1. A steel sheet comprising: a chemical composition containing (consisting of), in mass%, C: 0.030 % or more and 0.250 % or less, Si: 0.01 % or more and 3.00 % or less, Mn: 2.60 % or more and 4.20 % or less, P: 0.001 % or more and 0.100 % or less, S: 0.0200 % or less, N: 0.0100 % or less, and Ti: 0.005 % or more and 0.200 % or less, and optionally further containing, in mass%, at least one selected from the group consisting of Al: 0.01 % or more and 2.00 % or less, Nb: 0.005 % or more and 0.200 % or less, B: 0.0003 % or more and 0.0050 % or less, Ni: 0.005 % or more and 1.000 % or less, Cr: 0.005 % or more and 1.000 % or less, V: 0.005 % or more and 0.500 % or less, Mo: 0.005 % or more and 1.000 % or less, Cu: 0.005 % or more and 1.000 % or less, Sn: 0.002 % or more and 0.200 % or less, Sb: 0.002 % or more and 0.200 % or less, Ta: 0.001 % or more and 0.010 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0005 % or more and 0.0050 % or less, with the balance consisting of Fe and inevitable impurities; and a steel microstructure that contains, in area ratio, 20 % or more and 65 % or less of polygonal ferrite, 8 % or more of non-recrystallized ferrite, and 5 % or more and 25 % or less of martensite, and that contains, in volume fraction, 8 % or more of retained austenite, where an average aspect ratio of crystal grains of each of the polygonal ferrite, the martensite, and the retained austenite is 2.0 or more and 15.0 or less, wherein the polygonal ferrite has an average grain size of 6 μm or less, the martensite has an average grain size of 3 μm or less, the retained austenite has an average grain size of 3 μm or less, and a value obtained by dividing a Mn content in the retained austenite in mass% by a Mn content in the polygonal ferrite in mass% equals 2.0 or more.

2. The steel sheet according to 1., wherein the retained austenite has a C content that satisfies the following formula in relation to the Mn content in the retained austenite:

$$0.09 * [\text{Mn}] - 0.026 - 0.150 \leq [\text{C}] \leq 0.09 * [\text{Mn}] - 0.026 + 0.150$$

where

[C] is the C content in the retained austenite in mass%, and
[Mn] is the Mn content in the retained austenite in mass%.

3. A coated steel sheet comprising: the steel sheet according to 1. or 2.; and one selected from a hot-dip galvanized layer, a galvanized layer, a hot-dip aluminum-coated layer, and an electrogalvanized layer.

4. A method for manufacturing a steel sheet, the method comprising: heating a steel slab having the chemical composition according to 1.; hot rolling the steel slab with a finisher delivery temperature of 750 °C or higher and 1000 °C or lower to obtain a steel sheet; coiling the steel sheet at 300 °C or higher and 750 °C or lower; then subjecting the steel sheet to pickling to remove scales; retaining the steel sheet in a temperature range of $[Ac_1 \text{ transformation temperature} + 20 \text{ °C}]$ to $[Ac_1 \text{ transformation temperature} + 120 \text{ °C}]$ for 600 s to 21,600 s; optionally cold rolling the steel sheet at a rolling reduction of less than 30 %; and then retaining the steel sheet in a temperature range of $[Ac_1 \text{ transformation temperature} + 10 \text{ °C}]$ to $[Ac_1 \text{ transformation temperature} + 100 \text{ °C}]$ for 20 s to 900 s and subsequently cooling the steel sheet, to manufacture the steel sheet according to 1. or 2.

5. The method according to 4., wherein a value obtained by dividing a volume fraction of the retained austenite after performing tensile working with an elongation value of 10 % by a volume fraction of the retained austenite before the tensile working equals 0.3 or more.

6. The method according to 4., comprising after the cooling, either subjecting the steel sheet to one selected from hot-dip galvanizing treatment, hot-dip aluminum coating treatment, and electrogalvanizing treatment, or subjecting the steel sheet to hot-dip galvanizing treatment and then to alloying treatment at 450 °C or higher and 600 °C or lower, to manufacture the coated steel sheet according to 3.

(Advantageous Effect)

[0018] According to the disclosure, it becomes possible to provide a high-strength steel sheet with excellent formability and hole expansion formability and high yield ratio that exhibits TS of 590 MPa or more and YR of 68 % or more. Steel sheets according to the disclosure are highly beneficial in industrial terms, because they can improve fuel efficiency when applied to, for example, automobile structural parts, by a reduction in the weight of automotive bodies.

BRIEF DESCRIPTION OF THE DRAWING

[0019] In the accompanying drawings:

FIG. 1 illustrates the relationship between the working ratio of tensile working and the volume fraction of retained austenite; and

FIG. 2 illustrates the relationship between the elongation of each steel sheet and the value obtained by dividing the volume fraction of retained austenite remaining in the steel sheet after subjection to tensile working with an elongation value of 10 % by the volume fraction of retained austenite before the tensile working.

DETAILED DESCRIPTION

[0020] The following describes the present disclosure in detail.

[0021] First, the reasons for limiting the chemical composition of the steel to the aforementioned ranges in the present disclosure are explained. The % representations below indicating the chemical composition of the steel or steel slab are in mass% unless stated otherwise. The balance of the chemical composition of the steel or steel slab is Fe and inevitable impurities.

C: 0.030 % or more and 0.250 % or less

[0022] C is an element necessary for causing a low-temperature transformation phase such as martensite to increase strength. C is also a useful element for increasing the stability of retained austenite and the ductility of steel. If the C content is less than 0.030 %, it is difficult to ensure a desired area ratio of martensite, and desired strength is not obtained. It is also difficult to guarantee a sufficient volume fraction of retained austenite, and good ductility is not obtained. On the other hand, if C is excessively added to the steel beyond 0.250 %, hard martensite excessively increases in area ratio, which causes more microvoids at grain boundaries of martensite and facilitates propagation of cracks during bend test and hole expansion test, leading to a reduction in bendability and stretch flangeability. If excessive C is added to steel, hardening of welds and the heat-affected zone (HAZ) becomes significant and the mechanical properties of the welds deteriorate, leading to a reduction in spot weldability, arc weldability, and the like. From these perspectives, the C content is 0.030 % or more and 0.250 % or less. The C content is preferably 0.080 % or more. The C content is preferably 0.200 % or less.

Si: 0.01 % or more and 3.00 % or less

[0023] Si is an element that improves the strain hardenability of ferrite, and is thus a useful element for ensuring good ductility. If the Si content is below 0.01 %, the addition effect is limited. Thus the lower limit is 0.01 %. On the other hand, excessively adding Si beyond 3.00 % not only embrittles the steel, but also causes red scales or the like to deteriorate surface characteristics. Therefore, the Si content is 0.01 % or more and 3.00 % or less. The Si content is preferably 0.20 % or more. The Si content is preferably 2.00 % or less.

Mn: 2.60 % or more and 4.20 % or less

[0024] Mn is one of the very important elements for the disclosure. Mn is an element that stabilizes retained austenite, and is thus a useful element for ensuring good ductility. Mn can also increase the TS of the steel through solid solution strengthening. These effects can be obtained when the Mn content in the steel is 2.60 % or more. On the other hand, excessively adding Mn beyond 4.20 % results in a rise in cost. From these perspectives, the Mn content is 2.60 % or more and 4.20 % or less. The Mn content is preferably 3.00 % or more. The Mn content is preferably 4.20 % or less.

P: 0.001 % or more and 0.100 % or less

[0025] P is an element that has a solid solution strengthening effect and can be added depending on the desired TS. P also facilitates ferrite transformation, and thus is also a useful element for forming a multi-phase structure in the steel sheet. To obtain this effect, the P content in the steel sheet needs to be 0.001 % or more. However, if the P content exceeds 0.100 %, weldability degrades and, when a galvanized layer is subjected to alloying treatment, the alloying rate decreases, impairing galvanizing quality. Therefore, the P content is 0.001 % or more and 0.100 % or less. The P content is preferably 0.005 % or more. The P content is preferably 0.050 % or less.

S: 0.0200 % or less

[0026] S segregates to grain boundaries, embrittles the steel during hot working, and forms sulfides to reduce the local deformability of the steel sheet. Therefore, the S content is 0.0200 % or less, preferably 0.0100 % or less, and more preferably 0.0050 % or less. Under production constraints, however, the S content is preferably 0.0001 % or more. Therefore, the S content is preferably 0.0001 % or more and 0.0200 % or less. The S content is more preferably 0.0001 % or more. The S content is more preferably 0.0100 % or less. The S content is further preferably 0.0001 % or more. The S content is further preferably 0.0050 % or less.

N: 0.0100 % or less

[0027] N is an element that deteriorates the anti-aging property of the steel. The deterioration in anti-aging property becomes more pronounced, particularly when the N content exceeds 0.0100 %. Accordingly, smaller N contents are more preferable. However, under production constraints, the N content is preferably 0.0005 % or more. Therefore, the N content is preferably 0.0005 % or more and 0.0100 % or less. The N content is more preferably 0.0010 % or more. The N content is more preferably 0.0070 % or less.

Ti: 0.005 % or more and 0.200 % or less

[0028] Ti is one of the very important elements for the disclosure. Ti is useful for achieving strengthening by precipitation of the steel. Ti can also ensure a desired area ratio of non-recrystallized ferrite, and contributes to increasing the yield ratio of the steel sheet. Additionally, making use of relatively hard non-recrystallized ferrite, Ti can reduce the difference in hardness from a hard secondary phase (martensite or retained austenite), and also contributes to improving stretch flangeability. These effects can be obtained when the Ti content is 0.005 % or more. On the other hand, if the Ti content in the steel exceeds 0.200 %, hard martensite excessively increases in area ratio, which causes more microvoids at grain boundaries of martensite and facilitates propagation of cracks during bend test and hole expansion test, leading to a reduction in the bendability and stretch flangeability of the steel sheet. Therefore, the Ti content is 0.005 % or more and 0.200 % or less. The Ti content is preferably 0.010 % or more. The Ti content is preferably 0.100 % or less.

[0029] The basic components according to this disclosure have been described above. The balance other than the components described above is Fe and inevitable impurities. Additionally, the following elements may be optionally contained as appropriate.

[0030] The chemical composition of the steel may further contain at least one selected from the group consisting of Al: 0.01 % or more and 2.00 % or less, Nb: 0.005 % or more and 0.200 % or less, B: 0.0003 % or more and 0.0050 %

or less, Ni: 0.005 % or more and 1.000 % or less, Cr: 0.005 % or more and 1.000 % or less, V: 0.005 % or more and 0.500 % or less, Mo: 0.005 % or more and 1.000 % or less, Cu: 0.005 % or more and 1.000 % or less, Sn: 0.002 % or more and 0.200 % or less, Sb: 0.002 % or more and 0.200 % or less, Ta: 0.001 % or more and 0.010 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0005 % or more and 0.0050 % or less.

[0031] Al is a useful element for increasing the area of a ferrite-austenite dual phase region and reducing annealing temperature dependency, i.e., increasing the stability of the steel sheet as a material. In addition, Al acts as a deoxidizer, and is also a useful element for maintaining the cleanliness of the steel. If the Al content is below 0.01 %, however, the addition effect is limited. Thus the lower limit is 0.01 %. On the other hand, excessively adding Al beyond 2.00 % increases the risk of cracking occurring in a semi-finished product during continuous casting, and inhibits manufacturability. From these perspectives, the Al content is 0.01 % or more and 2.00 % or less. The Al content is preferably 0.20 % or more. The Al content is preferably 1.20 % or less.

[0032] Nb is useful for achieving strengthening by precipitation of the steel. The addition effect can be obtained when the content is 0.005 % or more. Nb can also ensure a desired area ratio of non-recrystallized ferrite, as in the case of adding Ti, and contributes to increasing the yield ratio of the steel sheet. Additionally, making use of relatively hard non-recrystallized ferrite, Nb can reduce the difference in hardness from a hard secondary phase (martensite or retained austenite), and also contributes to improving stretch flangeability. On the other hand, if the Nb content in the steel exceeds 0.200 %, hard martensite excessively increases in area ratio, which causes more microvoids at grain boundaries of martensite and facilitates propagation of cracks during bend test and hole expansion test. This leads to a reduction in the bendability and stretch flangeability of the steel sheet. This also increases cost. Therefore, when added to steel, the Nb content is 0.005 % or more and 0.200 % or less. The Nb content is preferably 0.010 % or more. The Nb content is preferably 0.100 % or less.

[0033] B may be added as necessary, since it has the effect of suppressing the generation and growth of ferrite from austenite grain boundaries and enables microstructure control according to the circumstances. The addition effect can be obtained when the B content is 0.0003 % or more. If the B content exceeds 0.0050 %, however, the formability of the steel sheet degrades. Therefore, when added to steel, the B content is 0.0003 % or more and 0.0050 % or less. The B content is preferably 0.0005 % or more. The B content is preferably 0.0030 % or less.

[0034] Ni is an element that stabilizes retained austenite, and is thus a useful element for ensuring good ductility, and that increases the TS of the steel through solid solution strengthening. The addition effect can be obtained when the Ni content is 0.005 % or more. On the other hand, if the Ni content in the steel exceeds 1.000 %, hard martensite excessively increases in area ratio, which causes more microvoids at grain boundaries of martensite and facilitates propagation of cracks during bend test and hole expansion test. This leads to a reduction in the bendability and stretch flangeability of the steel sheet. This also increases cost. Therefore, when added to steel, the Ni content is 0.005 % or more and 1.000 % or less.

[0035] Cr, V, and Mo are elements that may be added as necessary, since they have the effect of improving the balance between TS and ductility. The addition effect can be obtained when the Cr content is 0.005 % or more, the V content is 0.005 % or more, and/or the Mo content is 0.005 % or more. However, if the Cr content exceeds 1.000 %, the V content exceeds 0.500 %, and/or the Mo content exceeds 1.000 %, hard martensite excessively increases in area ratio, which causes more microvoids at grain boundaries of martensite and facilitates propagation of cracks during bend test and hole expansion test. This leads to a reduction in the bendability and stretch flangeability of the steel sheet, and also causes a rise in cost. Therefore, when added to steel, the Cr content is 0.005 % or more and 1.000 % or less, the V content is 0.005 % or more and 0.500 % or less, and/or the Mo content is 0.005 % or more and 1.000 % or less.

[0036] Cu is a useful element for strengthening of steel and may be added for strengthening of steel, as long as the content is within the range disclosed herein. The addition effect can be obtained when the Cu content is 0.005 % or more. On the other hand, if the Cu content in the steel exceeds 1.000 %, hard martensite excessively increases in area ratio, which causes more microvoids at grain boundaries of martensite and facilitates propagation of cracks during bend test and hole expansion test. This leads to a reduction in the bendability and stretch flangeability of the steel sheet. Therefore, when added to steel, the Cu content is 0.005 % or more and 1.000 % or less.

[0037] Sn and Sb are elements that may be added as necessary from the perspective of suppressing decarbonization of a region extending from the surface layer of the steel sheet to a depth of about several tens of micrometers, which results from nitriding and/or oxidation of the steel sheet surface. Suppressing nitriding and/or oxidation in this way is useful for preventing a reduction in the area ratio of martensite in the steel sheet surface, and for ensuring the TS and stability of the steel sheet as a material. However, excessively adding Sn or Sb beyond 0.200 % reduces toughness. Therefore, when Sn and/or Sb is added to steel, the content of each added element is 0.002 % or more and 0.200 % or less.

[0038] Ta forms alloy carbides or alloy carbonitrides, and contributes to increasing the strength of the steel, as is the case with Ti and Nb. It is also believed that Ta has the effect of effectively suppressing coarsening of precipitates when partially dissolved in Nb carbides or Nb carbonitrides to form complex precipitates, such as (Nb, Ta) (C, N), and providing a stable contribution to increasing the strength of the steel sheet through strengthening by precipitation. Therefore, Ta

is preferably added to the steel according to the disclosure. The addition effect of Ta can be obtained when the Ta content is 0.001 % or more. Excessively adding Ta, however, fails to increase the addition effect, but instead results in a rise in alloying cost. Therefore, when added to steel, the Ta content is 0.001 % or more and 0.010 % or less.

[0039] Ca, Mg, and REM are useful elements for causing spheroidization of sulfides and mitigating the adverse effect of sulfides on hole expansion formability (stretch flangeability). To obtain this effect, it is necessary to add any of these elements to steel in an amount of 0.0005 % or more. However, if the content of each added element exceeds 0.0050 %, more inclusions occur, for example, and some defects such as surface defects and internal defects are caused in the steel sheet. Therefore, when Ca, Mg, and/or REM is added to steel, the content of each added element is 0.0005 % or more and 0.0050 % or less.

[0040] The following provides a description of the microstructure. Sufficient ductility of the steel sheet can be ensured by facilitating the formation of polygonal ferrite in the microstructure. This, however, causes decreases in tensile strength and yield strength. Besides, these mechanical properties also vary depending on the area ratio of martensite, and the ductility is greatly affected by the amount of retained austenite. Hence, the mechanical properties of the high-strength steel sheet can be effectively obtained by controlling the amounts (area ratio, volume fraction) of these phases (microstructures). As a result of conducting studies from this perspective, we newly discovered that the area ratios of polygonal ferrite and non-recrystallized ferrite are controllable by the rolling reduction in cold rolling. We also found out that the area ratio of martensite and the volume fraction of retained austenite are mainly determined by the addition amount of Mn. We further found out that, by omitting cold rolling or by limiting the rolling reduction in cold rolling to 30 % or less, not only the area ratio of polygonal ferrite is reduced (i.e. can be controlled to an appropriate range) (relative to the whole microstructure), but also the microstructure shape of the final product changes greatly, yielding a steel sheet having crystal grains with a high aspect ratio. The value of hole expansion formability λ is thus improved. In detail, the microstructure of a steel sheet with high ductility and favorable hole expansion formability is as follows.

Area ratio of polygonal ferrite: 20 % or more and 65 % or less

[0041] According to the disclosure, the area ratio of polygonal ferrite needs to be 20 % or more to ensure sufficient ductility. On the other hand, to guarantee a TS of 590 MPa or more, the area ratio of soft polygonal ferrite needs to be 65 % or less. The area ratio of polygonal ferrite is preferably 30 % or more. The area ratio of polygonal ferrite is preferably 55 % or less. As used herein, "polygonal ferrite" refers to ferrite that is relatively soft and that has high ductility.

Area ratio of non-recrystallized ferrite: 8 % or more

[0042] In this disclosure, it is very important to set the area ratio of non-recrystallized ferrite to be 8 % or more. In this regard, non-recrystallized ferrite is useful for increasing the strength of the steel sheet. However, non-recrystallized ferrite may cause a significant decrease in the ductility of the steel sheet, and thus is normally reduced in a general process. In contrast, according to the present disclosure, by using polygonal ferrite and retained austenite to provide good ductility and intentionally utilizing relatively hard non-recrystallized ferrite, it is possible to provide the steel sheet with the intended TS, without having to form a large amount of martensite, such as exceeding 25 % in area ratio.

[0043] Moreover, according to the present disclosure, interfaces between different phases, namely, between polygonal ferrite and martensite, are reduced, making it possible to increase the yield point (YP) and YR of the steel sheet.

[0044] To obtain these effects, the area ratio of non-recrystallized ferrite needs to be 8 % or more, preferably 10 % or more. As used herein, "non-recrystallized ferrite" refers to ferrite that contains strain in the grains with a crystal orientation difference of less than 15°, and that is harder than the above-described polygonal ferrite with high ductility.

[0045] In the disclosure, no upper limit is placed on the area ratio of non-recrystallized ferrite, yet a preferred upper limit is around 45 %, considering the possibility of increased material anisotropy in the steel sheet surface.

Area ratio of martensite: 5 % or more and 25 % or less

[0046] To achieve TS of 590 MPa or more, the area ratio of martensite needs to be 5 % or more. On the other hand, to ensure good ductility, the area ratio of martensite needs to be limited to 25 % or less.

[0047] According to the disclosure, the area ratios of ferrite (including polygonal ferrite and non-recrystallized ferrite) and martensite can be determined in the following way.

[0048] Specifically, a cross section of a steel sheet that is taken in the sheet thickness direction to be parallel to the rolling direction (which is an L-cross section) is polished, then etched with 3 vol.% nital, and ten locations are observed at 2000 times magnification under an SEM (scanning electron microscope), at a position of sheet thickness $x \frac{1}{4}$ (which is the position at a depth of one-fourth of the sheet thickness from the steel sheet surface), to capture microstructure micrographs. The captured microstructure micrographs are used to calculate the area ratios of respective phases (ferrite and martensite) for the ten locations using Image-Pro manufactured by Media Cybernetics, the results are averaged,

and each average is used as the area ratio of the corresponding phase. In the microstructure micrographs, polygonal ferrite and non-recrystallized ferrite appear as a gray structure (base steel structure), while martensite as a white structure. [0049] According to the disclosure, the area ratios of polygonal ferrite and non-recrystallized ferrite can be determined in the following way.

[0050] Specifically, low-angle grain boundaries in which the crystal orientation difference is from 2° to less than 15° and large-angle grain boundaries in which the crystal orientation difference is 15° or more are identified using EBSD (Electron Backscatter Diffraction). An IQ Map is then created, considering ferrite that contains low-angle grain boundaries in the grains as non-recrystallized ferrite. Then, low-angle grain boundaries and large-angle grain boundaries are extracted from the created IQ Map at ten locations, respectively, to determine the areas of low-angle grain boundaries and large-angle grain boundaries at the ten locations. Based on the results, the areas of polygonal ferrite and non-recrystallized ferrite are calculated to determine the area ratios of polygonal ferrite and non-recrystallized ferrite for the ten locations. By averaging the results, the above-described area ratios of polygonal ferrite and non-recrystallized ferrite are determined.

Volume fraction of retained austenite: 8 % or more

[0051] According to the disclosure, the volume fraction of retained austenite needs to be 8 % or more, and is preferably 10 % or more, to ensure sufficient ductility. According to the disclosure, no upper limit is placed on the area ratio of retained austenite, yet a preferred upper limit is around 40 %, considering the risk of formation of increased amounts of unstable retained austenite resulting from insufficient concentration of C, Mn, and the like, which is less effective in improving ductility.

[0052] The volume fraction of retained austenite is calculated by determining the x-ray diffraction intensity of a plane of sheet thickness $x \times 1/4$ (which is the plane at a depth of one-fourth of the sheet thickness from the steel sheet surface), which is exposed by polishing the steel sheet surface to a depth of one-fourth of the sheet thickness. Using an incident x-ray beam of $\text{MoK}\alpha$, the intensity ratio of the peak integrated intensity of the {111}, {200}, {220}, and {311} planes of retained austenite to the peak integrated intensity of the {110}, {200}, and {211} planes of ferrite is calculated for all of the twelve combinations, the results are averaged, and the average is used as the volume fraction of retained austenite.

Average grain size of polygonal ferrite: 6 μm or less

[0053] Refinement of polygonal ferrite grains contributes to improving YP and TS. Thus, to ensure a high YP and a high YR as well as a desired TS, polygonal ferrite needs to have an average grain size of 6 μm or less, and preferably 5 μm or less.

[0054] According to the disclosure, no lower limit is placed on the average grain size of polygonal ferrite, yet, from an industrial perspective, a preferred lower limit is around 0.3 μm .

Average grain size of martensite: 3 μm or less

[0055] Refinement of martensite grains contributes to improving bendability and stretch flangeability (hole expansion formability). Thus, to ensure high bendability and high stretch flangeability (high hole expansion formability), the average grain size of martensite needs to be limited to 3 μm or less, and preferably to 2.5 μm or less.

[0056] According to the disclosure, no lower limit is placed on the average grain size of martensite, yet, from an industrial perspective, a preferred lower limit is around 0.1 μm .

Average grain size of retained austenite: 3 μm or less

[0057] Refinement of retained austenite grains contributes to improving ductility, as well as bendability and stretch flangeability (hole expansion formability). Accordingly, to ensure good ductility, bendability, and stretch flangeability (hole expansion formability) of the steel sheet, the average grain size of retained austenite needs to be 3 μm or less, and preferably 2.5 μm or less. According to the disclosure, no lower limit is placed on the average grain size of retained austenite, yet, from an industrial perspective, a preferred lower limit is around 0.1 μm .

[0058] The average grain sizes of polygonal ferrite, martensite, and retained austenite are respectively determined by averaging the results from calculating equivalent circular diameters from the areas of polygonal ferrite grains, martensite grains, and retained austenite grains measured with Image-Pro as mentioned above. Polygonal ferrite, non-recrystallized ferrite, martensite, and retained austenite are separated using EBSD, and martensite and retained austenite are identified using an EBSD phase map. In this case, each of the above-described average grain sizes is determined from the measurements for grains with a grain size of 0.01 μm or more. The reason is that grains with a grain size of less than 0.01 μm have no effect on the disclosure.

Average aspect ratio of crystal grains of each of polygonal ferrite, martensite, and retained austenite: 2.0 or more and 15.0 or less

[0059] In this disclosure, it is very important to set the average aspect ratio of crystal grains of each of polygonal ferrite, martensite, and retained austenite to 2.0 or more.

[0060] A lower aspect ratio of crystal grains indicates that, during retention in heat treatment after cold rolling (cold-rolled sheet annealing), ferrite and austenite recover and recrystallize and then undergo grain growth, resulting in the formation of crystal grains close to equiaxed grains. The ferrite formed here is soft. In the case where cold rolling is omitted or the rolling reduction in cold rolling is less than 30 %, on the other hand, the amount of strain applied decreases, so that the formation of polygonal ferrite is suppressed and a microstructure mainly composed of crystal grains with a high aspect ratio results. Such a microstructure composed of crystal grains with a high aspect ratio is hard because it contains a large amount of strain or has parts where the distance between grain boundaries is short, as compared with the above-mentioned microstructure. Therefore, not only the TS is improved, but also the difference in hardness from hard phases such as retained austenite and martensite decreases, and the hole expansion formability is improved without loss of ductility. If the aspect ratio is more than 15.0, the TS increases extremely, and favorable ductility cannot be achieved.

[0061] Thus, the average aspect ratio of crystal grains of each of polygonal ferrite, martensite, and retained austenite is limited to 2.0 or more and 15.0 or less. In terms of ductility, the average aspect ratio is more preferably 2.2 or more, and more preferably 2.4 or more.

[0062] The aspect ratio of a crystal grain mentioned here is a value obtained by dividing the major axis length of the crystal grain by the minor axis length of the crystal grain. The average aspect ratio of each type of crystal grains can be calculated as follows.

[0063] For each of polygonal ferrite grains, martensite grains, and retained austenite grains, the major axis length and minor axis length of each of 30 crystal grains are calculated using the above-mentioned Image-Pro, the major axis length is divided by the minor axis length, and the division results are averaged.

A value obtained by dividing the Mn content in the retained austenite (in mass%) by the Mn content in the polygonal ferrite (in mass%): 2.0 or more

[0064] In this disclosure, it is very important that the value obtained by dividing the Mn content in the retained austenite (in mass%) by the Mn content in the polygonal ferrite (in mass%) equals 2.0 or more. The reason is that better ductility requires a larger amount of stable retained austenite with concentrated Mn.

[0065] According to the disclosure, no upper limit is placed on the value obtained by dividing the Mn content in the retained austenite (in mass%) by the Mn content in the polygonal ferrite (in mass%), yet a preferred upper limit is around 16.0 from the perspective of ensuring stretch flangeability.

[0066] The Mn content in the retained austenite (in mass%) and the Mn content in the polygonal ferrite (in mass%) can be determined in the following way.

[0067] Specifically, an EPMA (Electron Probe Micro Analyzer) is used to quantify the distribution of Mn in each phase in a cross section along the rolling direction at a position of sheet thickness $\times 1/4$. Then, 30 retained austenite grains and 30 ferrite grains are analyzed to determine Mn contents, the results are averaged, and each average is used as the Mn content in the corresponding phase.

[0068] In addition to the above-described polygonal ferrite, martensite, and so on, the microstructure according to the disclosure may further include carbides ordinarily found in steel sheets, such as granular ferrite, acicular ferrite, bainitic ferrite, tempered martensite, pearlite, and cementite (excluding cementite in pearlite). Any of these structures may be included as long as the area ratio is 10 % or less, without impairing the effect of the disclosure.

[0069] We made further investigations on the microstructures of steel sheets upon performing press forming and working.

[0070] As a result, it was discovered that there are two types of retained austenite: one transforms to martensite immediately upon the subjection of the steel sheet to press forming or working, while the other persists until the working ratio becomes high enough to cause the retained austenite to eventually transform to martensite, bringing about a TRIP phenomenon (transformation induced plasticity phenomenon). It was also revealed that good elongation can be obtained in a particularly effective way when a large amount of retained austenite transforms to martensite after the working ratio becomes high enough.

[0071] Specifically, as a result of collecting samples with good and poor elongation and measuring the quantity of retained austenite by varying the degree of tensile working from 0 % to 20 %, the working ratio and the quantity of retained austenite showed a tendency as illustrated in FIG. 1. As used herein, "the working ratio" refers to the elongation ratio that is determined from a tensile test performed on a JIS No. 5 test piece sampled from a steel sheet with the tensile direction being perpendicular to the rolling direction of the steel sheet.

[0072] It can be seen from FIG. 1 that the samples with good elongation each showed a gentle decrease in the quantity of retained austenite as the working ratio increased.

[0073] Accordingly, we further measured the quantity of retained austenite in each sample with TS of 780 MPa after subsection to tensile working with an elongation value of 10 %, and examined the effect of the ratio of the quantity of retained austenite after the tensile working to the quantity before the tensile working on the total elongation of the steel sheet. The results are shown in FIG. 2.

[0074] It can be seen from FIG. 2 that elongation is good if the value obtained by dividing the volume fraction of retained austenite remaining in a steel after subsection to tensile working with an elongation value of 10 % by the volume fraction of retained austenite before the tensile working equals 0.3 or more, but otherwise elongation is poor.

[0075] Therefore, it is preferable in the disclosure that the value obtained by dividing the volume fraction of retained austenite remaining in a steel after subsection to tensile working with an elongation value of 10 % by the volume fraction of retained austenite before the tensile working equals 0.3 or more. The reason is that this set up may ensure the transformation of sufficient retained austenite to martensite after the working ratio becomes high enough.

[0076] The above-described TRIP phenomenon requires retained austenite to be present before performing press forming or working. To cause retained austenite to be present before performing press forming or working, the Ms point (martensite transformation start temperature) which depends on the elements contained in the steel microstructure needs to be as low as approximately 15 °C or lower.

[0077] Specifically, in the tensile working with an elongation value of 10 % according to the disclosure, a tensile test is performed on a JIS No. 5 test piece sampled from a steel sheet with the tensile direction being perpendicular to the rolling direction of the steel sheet, and the test is interrupted when the elongation ratio reaches 10 %, thus applying tensile working with an elongation value of 10 % to the test piece.

[0078] The volume fraction of retained austenite can be determined in the above-described way.

[0079] Upon a detailed study of samples satisfying the above conditions, we discovered that a TRIP phenomenon providing high strain hardenability occurs upon working and even better elongation can be achieved if the C content and the Mn content in the retained austenite satisfy the following relation:

$$0.09 * [\text{Mn}] - 0.026 - 0.150 \leq [\text{C}] \leq 0.09 * [\text{Mn}] - 0.026 + 0.150$$

where

[C content] is the C content in the retained austenite in mass%, and

[Mn content] is the Mn content in the retained austenite in mass%.

[0080] When the above requirements are met, it is possible to cause a TRIP phenomenon, which is a key factor of improving ductility, to occur intermittently up until the final stage of working performed on the steel sheet, guaranteeing the generation of so-called stable retained austenite.

[0081] The C content in the retained austenite (in mass%) can be determined in the following way.

[0082] Specifically, an EPMA is used to quantify the distribution of C in each phase in a cross section along the rolling direction at a position of sheet thickness x 1/4. Then, 30 retained austenite grains are analyzed to determine C contents, the results are averaged, and the average is used as the C content.

[0083] Note that the Mn content in the retained austenite (in mass%) can be determined in the same way as the C content in the retained austenite.

[0084] The following describes the production conditions.

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

[0085] Precipitates that are present at the time of heating of a steel slab (hereinafter, also referred to simply as a "slab") will remain as coarse precipitates in the resulting steel sheet, making no contribution to strength. Thus, remelting of any Ti- and Nb-based precipitates formed during casting is required.

[0086] In this respect, if a steel slab is heated at a temperature below 1100 °C, it is difficult to cause sufficient dissolution of carbides, leading to problems such as an increased risk of trouble during the hot rolling resulting from increased rolling load. Therefore, the steel slab heating temperature is preferably 1100 °C or higher.

[0087] In addition, from the perspective of obtaining a smooth steel sheet surface by scaling-off defects in the surface layer of the slab, such as blow hole generation, segregation, and the like, and reducing cracks and irregularities over the steel sheet surface, the steel slab heating temperature is preferably 1100 °C or higher.

[0088] If the steel slab heating temperature exceeds 1300 °C, however, scale loss increases as oxidation progresses. Therefore, the steel slab heating temperature is preferably 1300 °C or lower. For this reason, the steel slab heating

temperature is preferably 1100 °C or higher and 1300 °C or lower. The steel slab heating temperature is further preferably 1150 °C or higher. The steel slab heating temperature is further preferably 1250 °C or lower.

[0089] A steel slab is preferably made with continuous casting to prevent macro segregation, yet may be produced with other methods such as ingot casting or thin slab casting. The steel slab thus produced may be cooled to room temperature and then heated again according to a conventional process. Moreover, energy-saving processes are applicable without any problem, such as hot direct rolling or direct rolling in which either a warm steel slab without being fully cooled to room temperature is charged into a heating furnace, or a steel slab is hot rolled immediately after being subjected to heat retaining for a short period. A steel slab is subjected to rough rolling under normal conditions and formed into a sheet bar. When the heating temperature is low, it is preferable to additionally heat the sheet bar using a bar heater or the like prior to finish rolling, from the viewpoint of preventing troubles during the hot rolling.

Finisher delivery temperature in hot rolling: 750 °C or higher and 1000 °C or lower

[0090] The heated steel slab is hot rolled through rough rolling and finish rolling to form a hot-rolled sheet. At this point, when the finisher delivery temperature exceeds 1000 °C, the amount of oxides (scales) generated suddenly increases and the interface between the steel substrate and oxides becomes rough, which tends to lower the surface quality of the steel sheet after subjection to pickling and cold rolling. In addition, any hot rolling scales persisting after pickling adversely affect the ductility and stretch flangeability of the steel sheet. Moreover, grain size is excessively coarsened, causing surface deterioration in a pressed part during working. On the other hand, if the finisher delivery temperature is below 750 °C, rolling load increases and rolling is performed more often with austenite being in a non-recrystallized state. As a result, an abnormal texture develops in the steel sheet, and the final product has a significant planar anisotropy such that the material properties not only become less uniform (the stability as a material decreases), but the ductility itself also deteriorates. Besides, if the finisher delivery temperature in the hot rolling is lower than 750 °C or higher than 1000 °C, a microstructure having 8 % or more of retained austenite in volume fraction cannot be obtained.

[0091] Therefore, the finisher delivery temperature in the hot rolling needs to be 750 °C or higher and 1000 °C or lower. The finisher delivery temperature is preferably 800 °C or higher. The finisher delivery temperature is preferably 950 °C or lower.

Average coiling temperature after hot rolling: 300 °C or higher and 750 °C or lower

[0092] When the average coiling temperature after the hot rolling is above 750 °C, the grain size of ferrite in the microstructure of the hot-rolled sheet increases, making it difficult to ensure a desired strength of the final-annealed sheet. Besides, when the average coiling temperature after the hot rolling is above 750 °C, a microstructure with an average grain size of polygonal ferrite of 6 μm or less, an average grain size of martensite of 3 μm or less, and an average grain size of retained austenite of 3 μm or less cannot be obtained. On the other hand, when the average coiling temperature after the hot rolling is below 300 °C, there is an increase in the strength of the hot-rolled sheet and in the rolling load for cold rolling, and the steel sheet suffers malformation. As a result, productivity decreases. Therefore, the average coiling temperature after the hot rolling needs to be 300 °C or higher and 750 °C or lower. The average coiling temperature is preferably 400 °C or higher. The average coiling temperature is preferably 650 °C or lower.

[0093] According to the disclosure, finish rolling may be performed continuously by joining rough-rolled sheets during the hot rolling. Rough-rolled sheets may be coiled on a temporary basis. At least part of finish rolling may be conducted as lubrication rolling to reduce the rolling load during the hot rolling. Conducting lubrication rolling in such a manner is effective from the perspective of making the shape and material properties of the steel sheet uniform. In lubrication rolling, the coefficient of friction is preferably 0.10 or more. The coefficient of friction is preferably 0.25 or less.

[0094] The hot-rolled sheet thus produced is subjected to pickling. Pickling enables removal of oxides from the steel sheet surface, and is thus important to ensure that the high-strength steel sheet as the final product has good chemical convertibility and sufficient coating quality. The pickling may be performed in one or more batches.

Hot band annealing (first heat treatment): to retain in a temperature range of [Ac₁ transformation temperature + 20 °C] to [Ac₁ transformation temperature + 120 °C] for 600 s to 21,600 s

[0095] In this disclosure, it is very important to retain the steel sheet in a temperature range of [Ac₁ transformation temperature + 20 °C] to [Ac₁ transformation temperature + 120 °C] for 600 s to 21,600 s.

[0096] If the hot band annealing is performed at an annealing temperature below [Ac₁ transformation temperature + 20 °C] or above [Ac₁ transformation temperature + 120 °C], or if the holding time is shorter than 600 s, concentration of Mn in austenite does not proceed in either case, making it difficult to ensure a sufficient volume fraction of retained austenite after the final annealing. As a result, ductility decreases. Besides, a microstructure in which the value obtained by dividing the Mn content in retained austenite (in mass%) by the Mn content in polygonal ferrite (in mass%) equals

2.0 or more cannot be obtained. On the other hand, if the steel sheet is retained for more than 21,600 s, concentration of Mn in austenite reaches a plateau, and becomes less effective in improving ductility after the final annealing, resulting in a rise in costs.

[0097] Therefore, in the hot band annealing (first heat treatment) according to the disclosure, the steel sheet is retained in a temperature range of $[Ac_1 \text{ transformation temperature} + 20 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 120 \text{ }^\circ\text{C}]$ for 600 s to 21,600 s.

[0098] The above-described heat treatment process may be continuous annealing or batch annealing. After the above-described heat treatment, the steel sheet is cooled to room temperature. The cooling process and cooling rate are not particularly limited, however, and any type of cooling may be performed, including furnace cooling and air cooling in batch annealing and gas jet cooling, mist cooling, and water cooling in continuous annealing. The pickling may be performed according to a conventional process.

Annealing (second heat treatment): to retain in a temperature range of $[Ac_1 \text{ transformation temperature} + 10 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 100 \text{ }^\circ\text{C}]$ for 20 s to 900 s

[0099] In this disclosure, it is very important to retain the steel sheet in a temperature range of $[Ac_1 \text{ transformation temperature} + 10 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 100 \text{ }^\circ\text{C}]$ for 20 s to 900 s. When the annealing temperature is below $[Ac_1 \text{ transformation temperature} + 10 \text{ }^\circ\text{C}]$ or above $[Ac_1 \text{ transformation temperature} + 100 \text{ }^\circ\text{C}]$, or if the holding time is shorter than 20 s, concentration of Mn in austenite does not proceed in either case, making it difficult to ensure a sufficient volume fraction of retained austenite. As a result, ductility decreases. Besides, a microstructure in which the value obtained by dividing the Mn content in retained austenite (in mass%) by the Mn content in polygonal ferrite (in mass%) equals 2.0 or more cannot be obtained. On the other hand, if the steel sheet is retained for more than 900 s, the area ratio of non-crystallized ferrite decreases and the interfaces between different phases, namely, between ferrite and hard secondary phases (martensite and retained austenite), are reduced, leading to a reduction in both YP and YR. Besides, a microstructure with an average grain size of martensite of 3 μm or less and an average grain size of retained austenite of 3 μm or less cannot be obtained.

Rolling reduction in cold rolling: less than 30 %

[0100] Cold rolling may be performed after the hot band annealing and before the annealing (second heat treatment). In this case, the rolling reduction needs to be less than 30 %. By omitting the cold rolling or performing the cold rolling with a rolling reduction of less than 30 %, polygonal ferrite which forms by recrystallization after the heat treatment does not form and a microstructure elongated in the rolling direction remains, and eventually polygonal ferrite, retained austenite, and martensite with a high aspect ratio are obtained. Thus, not only the strength-ductility balance is improved, but also the stretch flangeability (hole expansion formability) is improved. If the rolling reduction is 30 % or more, a microstructure having 20 % or more and 65 % or less of polygonal ferrite in area ratio and a microstructure having an average aspect ratio of crystal grains of each of polygonal ferrite, martensite, and retained austenite of 2.0 or more and 15.0 or less cannot be obtained.

Hot-dip galvanizing treatment

[0101] In hot-dip galvanizing treatment according to the disclosure, the steel sheet subjected to the above-described annealing (second heat treatment) is dipped in a galvanizing bath at 440 $^\circ\text{C}$ or higher and 500 $^\circ\text{C}$ or lower for hot-dip galvanizing. Subsequently, the coating weight on the steel sheet surface is adjusted using gas wiping or the like. Preferably, the hot-dip galvanizing is performed using a galvanizing bath containing 0.10 mass% or more and 0.22 mass% or less of Al.

[0102] Moreover, when a hot-dip galvanized layer is subjected to alloying treatment, the alloying treatment may be performed in a temperature range of 450 $^\circ\text{C}$ to 600 $^\circ\text{C}$ after the above-described hot-dip galvanizing treatment. If the alloying treatment is performed at a temperature above 600 $^\circ\text{C}$, untransformed austenite transforms to pearlite, where a desired volume fraction of retained austenite cannot be ensured and ductility degrades. On the other hand, if the alloying treatment is performed at a temperature below 450 $^\circ\text{C}$, the alloying process does not proceed, making it difficult to form an alloy layer.

[0103] Therefore, when the galvanized layer is subjected to alloying treatment, the alloying treatment is performed in a temperature range of 450 $^\circ\text{C}$ to 600 $^\circ\text{C}$.

[0104] Although other manufacturing conditions are not particularly limited, the series of processes including the annealing, hot-dip galvanizing, and alloying treatment described above may preferably be performed in a continuous galvanizing line (CGL), which is a hot-dip galvanizing line, from the perspective of productivity.

[0105] When hot-dip aluminum coating treatment is performed, the steel sheet subjected to the above-described

annealing treatment is dipped in an aluminum molten bath at 660 °C to 730 °C for hot-dip aluminum coating treatment. Subsequently, the coating weight is adjusted using gas wiping or the like. If the steel sheet has a composition such that the temperature of the aluminum molten bath falls within the temperature range of $[Ac_1 \text{ transformation temperature} + 10 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 100 \text{ }^\circ\text{C}]$, the steel sheet is preferably subjected to hot-dip aluminum coating treatment because finer and more stable retained austenite can be formed, and therefore further improvement in ductility can be achieved.

Electrogalvanizing treatment

[0106] According to the disclosure, electrogalvanizing treatment may also be performed on the steel sheet after the heat treatment. No particular limitations are placed on the electrogalvanizing treatment conditions, yet the electrogalvanizing treatment conditions are preferably set so that the plated layer has a thickness of 5 μm to 15 μm .

[0107] According to the disclosure, the above-described steel sheet, hot-dip galvanized steel sheet, hot-dip aluminum-coated steel sheet, and electrogalvanized steel sheet may be subjected to skin pass rolling for the purposes of straightening, adjustment of roughness on the sheet surface, and the like. The skin pass rolling is preferably performed at a rolling reduction of 0.1 % or more. The skin pass rolling is preferably performed at a rolling reduction of 2.0 % or less.

[0108] When the rolling reduction is less than 0.1 %, the skin pass rolling becomes less effective and more difficult to control. Thus, a preferable range for the rolling reduction has a lower limit of 0.1 %. On the other hand, when the skin pass rolling is performed at a rolling reduction above 2.0 %, the productivity of the steel sheet decreases significantly. Thus, the preferable range for the rolling reduction has an upper limit of 2.0 %.

[0109] The skin pass rolling may be performed on-line or off-line. Skin pass may be performed in one or more batches to achieve a target rolling reduction.

[0110] Moreover, the steel sheet, the hot-dip galvanized steel sheet, the hot-dip aluminum-coated steel sheet, and the electrogalvanized steel sheet according to the disclosure may be subjected to a variety of coating treatment options, such as those using coating of resin, fats and oils, and the like.

EXAMPLES

[0111] Steels having the chemical compositions as presented in Table 1, with the balance consisting of Fe and inevitable impurities, were prepared by steelmaking in a converter, and formed into slabs through continuous casting. The slabs thus obtained were formed into a variety of steel sheets, as described below, by varying the conditions as listed in Table 2.

[0112] After being hot rolled, each steel sheet was annealed in a temperature range of $[Ac_1 \text{ transformation temperature} + 20 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 120 \text{ }^\circ\text{C}]$. After being cold rolled (or without cold rolling), each steel sheet was annealed in a temperature range of $[Ac_1 \text{ transformation temperature} + 10 \text{ }^\circ\text{C}]$ to $[Ac_1 \text{ transformation temperature} + 100 \text{ }^\circ\text{C}]$. Consequently, a cold-rolled steel sheet (CR) was obtained, and subjected to coating treatment to form a hot-dip galvanized steel sheet (GI), a galvanized steel sheet (GA), a hot-dip aluminum-coated steel sheet (AI), an electrogalvanized steel sheet (EG), or the like.

[0113] Used as hot-dip galvanizing baths were a zinc bath containing 0.19 mass% of Al for hot-dip galvanized steel sheets (GI) and a zinc bath containing 0.14 mass% of Al for galvanized steel sheets (GA). In either case, the bath temperature was 465 °C and the coating weight per side was 45 g/m² (in the case of both-sided coating). For GA, the Fe concentration in the coating layer was adjusted to be 9 mass% or more and 12 mass% or less. The bath temperature of the hot-dip aluminum molten bath for hot-dip aluminum-coated steel sheets was set at 700 °C.

[0114] For each of the steel sheets thus obtained, the cross-sectional microstructure, tensile property, hole expansion formability, bendability, and the like were investigated. The results are listed in Tables 3 to 5.

[0115] The Ac_1 transformation temperature was calculated by:

$$\begin{aligned}
 & [Ac_1 \text{ transformation temperature (}^\circ\text{C)}] \\
 & = 751 - 16 * (\%C) + 11 * (\%Si) - 28 * (\%Mn) - 5.5 * (\%Cu) - 16 * (\%Ni) \\
 & \quad + 13 * (\%Cr) + 3.4 * (\%Mo)
 \end{aligned}$$

where (%C), (%Si), (%Mn), (%Ni), (%Cu), (%Cr), and (%Mo) each represent the content in steel (in mass%) of the element in the parentheses.

[0116] Tensile test was performed in accordance with JIS Z 2241 (2011) to measure YP, YR, TS, and EL using JIS No. 5 test pieces, each of which was sampled in a manner that the tensile direction was perpendicular to the rolling direction of the steel sheet. Note that YR is YP divided by TS, expressed as a percentage. In this case, the results were determined to be good when $YR \geq 68 \%$ and when $TS * EL \geq 24,000 \text{ MPa} \cdot \%$. Also, EL was determined to be good when

EL $\geq$ 34 % for TS 590 MPa grade, EL $\geq$ 30 % for TS 780 MPa grade, and EL $\geq$ 24 % for TS 980 MPa grade. In this case, a steel sheet of TS 590 MPa grade refers to a steel sheet with TS of 590 MPa or more and less than 780 MPa, a steel sheet of TS 780 MPa grade refers to a steel sheet with TS of 780 MPa or more and less than 980 MPa, and a steel sheet of TS 980 MPa grade refers to a steel sheet with TS of 980 MPa or more and less than 1180 MPa.

[0117] Bend test was performed according to the V-block method specified in JIS Z 2248 (1996). Each steel sheet was visually observed under a stereoscopic microscope for cracks on the outside of the bent portion, and the minimum bending radius without cracks was used as the limit bending radius R. In this case, the bendability of the steel sheet was determined to be good if the following condition was satisfied: limit bending radius R at 90° V-bending / t $\leq$ 1.5 (where t is the thickness of the steel sheet).

[0118] Hole expansion test was performed in accordance with JIS Z 2256 (2010). Each of the steel sheets obtained was cut to a size of 100 mm * 100 mm, and a hole of 10 mm in diameter was drilled through each sample with clearance 12 % $\pm$ 1 %. Then, each steel sheet was clamped into a die having an inner diameter of 75 mm with a blank holding force of 9 tons (88.26 kN). In this state, a conical punch of 60° was pushed into the hole, and the hole diameter at the crack initiation limit was measured. Then, to evaluate hole expansion formability, the maximum hole expansion ratio (%) was calculated by:

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

where D_f is a hole diameter at the time of occurrence of cracking (mm) and D_0 is an initial hole diameter (mm).

[0119] In this case, the maximum hole expansion ratio was determined to be good when $\lambda \geq$ 34 % for TS 590 MPa grade, $\lambda \geq$ 30 % for TS 780 MPa grade, and $\lambda \geq$ 25 % for TS 980 MPa grade.

[0120] The sheet passage ability during hot rolling was determined to be low when it was considered that the risk of troubles, such as malformation during hot rolling due to increased rolling load, would increase because, for example, the hot-rolling finisher delivery temperature was low and rolling would be performed more often with austenite being in a non-crystallized state, or rolling would be performed in an austenite-ferrite dual phase region.

[0121] The sheet passage ability during cold rolling was determined to be low when it was considered that the risk of troubles, such as malformation during cold rolling due to increased rolling load, would increase because, for example, the coiling temperature during hot rolling was low and the hot-rolled sheet had a steel microstructure in which low-temperature transformation phases, such as bainite and martensite, were dominantly present.

[0122] The surface characteristics of each final-annealed sheet were determined to be poor when defects such as blow hole generation and segregation on the surface layer of the slab could not be scaled-off, cracks and irregularities on the steel sheet surface increased, and a smooth steel sheet surface could not be obtained. The surface characteristics of each final-annealed sheet were also determined to be poor when the amount of oxides (scales) generated suddenly increased, interfaces between the steel substrate and oxides were roughened, and the surface quality after pickling and cold rolling degraded, or when hot-rolling scales persisted at least in part after pickling.

[0123] In this case, productivity was evaluated according to the lead time costs, including: (1) malformation of a hot-rolled sheet occurred; (2) a hot-rolled sheet requires straightening before proceeding to the subsequent steps; and (3) a prolonged holding time during the annealing treatment. The productivity was determined to be "high" when none of (1) to (3) applied and "low" when any of (1) to (3) applied.

[0124] Tensile working was performed in accordance with JIS Z 2241 (2011) using JIS No. 5 test pieces, each of which was sampled in a manner that the tensile direction was perpendicular to the rolling direction of the steel sheet. A value was obtained by dividing the volume fraction of retained austenite remaining in each steel sheet after subjection to tensile working with an elongation value of 10 % by the volume fraction of retained austenite before the working (10 % application). The volume fraction of retained austenite was measured in accordance with the above procedure.

[0125] The measurement results are also listed in Table 4.

[0126] The C content in the retained austenite (in mass%) and the Mn content in the retained austenite (in mass%) were measured in accordance with the above procedure.

[0127] The measurement results are also listed in Table 4.

Steel sample ID		Chemical composition (mass%)																				Ac ₁ transformation temperature (°C)	Remarks	
		C	Si	Mn	P	S	N	Ti	Al	Nb	B	Ni	Cr	V	Mo	Cu	Sn	Sb	Ta	Ca	Mg			REM
A	B	0.111	0.34	3.55	0.023	0.0022	0.0037	0.035	-	-	-	-	-	-	-	-	-	-	-	-	-	-	654	Conforming steel
		0.156	0.65	3.91	0.028	0.0019	0.0035	0.038	-	-	-	-	-	-	-	-	-	-	-	-	-	-	646	Conforming steel
C	D	0.170	1.24	4.11	0.034	0.0023	0.0033	0.035	-	-	-	-	-	-	-	-	-	-	-	-	-	-	647	Conforming steel
		0.070	1.25	3.51	0.027	0.0020	0.0031	0.033	-	-	-	-	-	-	-	-	-	-	-	-	-	-	665	Conforming steel
E	F	0.155	0.80	3.78	0.031	0.0019	0.0035	0.033	-	-	-	-	-	-	-	-	-	-	-	-	-	-	651	Conforming steel
		0.141	0.05	3.80	0.021	0.0025	0.0032	0.015	-	-	-	-	-	-	-	-	-	-	-	-	-	-	643	Conforming steel
G	H	0.198	0.87	3.78	0.025	0.0020	0.0041	0.022	-	-	-	-	-	-	-	-	-	-	-	-	-	-	652	Conforming steel
		0.166	0.74	2.87	0.025	0.0020	0.0034	0.035	-	-	-	-	-	-	-	-	-	-	-	-	-	-	676	Conforming steel
I	JA	0.160	0.52	3.91	0.028	0.0025	0.0031	0.041	-	-	-	-	-	-	-	-	-	-	-	-	-	-	645	Conforming steel
		0.030	0.42	3.55	0.027	0.0021	0.0031	0.041	-	-	-	-	-	-	-	-	-	-	-	-	-	-	656	Conforming steel
IB	IC	0.152	3.00	3.87	0.028	0.0020	0.0032	0.042	-	-	-	-	-	-	-	-	-	-	-	-	-	-	673	Conforming steel
		0.115	0.52	2.60	0.021	0.0021	0.0035	0.035	-	-	-	-	-	-	-	-	-	-	-	-	-	-	670	Conforming steel
ID	IE	0.156	0.51	2.99	0.001	0.0019	0.0034	0.035	-	-	-	-	-	-	-	-	-	-	-	-	-	-	668	Conforming steel
		0.151	0.34	3.01	0.100	0.0021	0.0029	0.036	-	-	-	-	-	-	-	-	-	-	-	-	-	-	664	Conforming steel
IF	IG	0.152	0.36	3.15	0.031	0.0001	0.0035	0.038	-	-	-	-	-	-	-	-	-	-	-	-	-	-	671	Conforming steel
		0.118	0.51	3.00	0.034	0.0200	0.0031	0.039	-	-	-	-	-	-	-	-	-	-	-	-	-	-	663	Conforming steel
IH	II	0.124	0.45	3.25	0.025	0.0022	0.0005	0.041	-	-	-	-	-	-	-	-	-	-	-	-	-	-	657	Conforming steel
		0.147	0.48	3.45	0.031	0.0023	0.0100	0.041	-	-	-	-	-	-	-	-	-	-	-	-	-	-	649	Conforming steel
IJ	IK	0.142	0.35	3.69	0.028	0.0018	0.0031	0.005	-	-	-	-	-	-	-	-	-	-	-	-	-	-	653	Conforming steel
		0.145	0.41	3.57	0.029	0.0025	0.0032	0.200	-	-	-	-	-	-	-	-	-	-	-	-	-	-	687	Comparative steel
IL	IM	0.148	4.22	3.87	0.031	0.0025	0.0035	0.042	-	-	-	-	-	-	-	-	-	-	-	-	-	-	659	Comparative steel
		0.115	0.55	3.45	0.031	0.0019	0.0034	0.210	-	-	-	-	-	-	-	-	-	-	-	-	-	-	667	Comparative steel
J	K	0.010	0.52	3.21	0.031	0.0021	0.0031	0.039	-	-	-	-	-	-	-	-	-	-	-	-	-	-	727	Comparative steel
		0.199	4.51	2.51	0.028	0.0025	0.0038	0.024	-	-	-	-	-	-	-	-	-	-	-	-	-	-	696	Comparative steel
L	M	0.186	1.01	2.25	0.025	0.0025	0.0034	0.025	-	-	-	-	-	-	-	-	-	-	-	-	-	-	650	Comparative steel
		0.181	0.78	3.80	0.022	0.0021	0.0038	0.001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	659	Conforming steel
N	O	0.205	0.89	3.51	0.024	0.0029	0.0038	0.033	0.45	-	-	-	-	-	-	-	-	-	-	-	-	-	653	Conforming steel
		0.200	1.02	3.78	0.028	0.0025	0.0034	0.033	-	0.042	-	-	-	-	-	-	-	-	-	-	-	-	658	Conforming steel
P	Q	0.191	0.83	3.54	0.027	0.0024	0.0041	0.035	-	-	0.0015	-	-	-	-	-	-	-	-	-	-	-	654	Conforming steel
		0.210	1.01	3.57	0.029	0.0023	0.0032	0.021	-	-	-	0.312	-	-	-	-	-	-	-	-	-	-	643	Conforming steel
R	S	0.212	0.55	4.11	0.029	0.0022	0.0031	0.025	-	-	-	0.355	-	-	-	-	-	-	-	-	-	-	651	Conforming steel
		0.225	0.78	3.76	0.031	0.0023	0.0032	0.023	-	-	-	-	0.035	-	-	-	-	-	-	-	-	-	668	Conforming steel
T	U	0.201	0.98	3.29	0.031	0.0022	0.0041	0.035	-	-	-	-	-	0.329	-	-	-	-	-	-	-	-	674	Conforming steel
		0.202	1.32	3.12	0.025	0.0025	0.0033	0.041	-	-	-	-	-	-	-	0.259	-	-	-	-	-	-	660	Conforming steel
V	W	0.189	1.02	3.55	0.026	0.0029	0.0034	0.045	-	-	-	-	-	-	-	-	0.006	-	-	-	-	-	661	Conforming steel
		0.190	0.88	3.45	0.025	0.0025	0.0035	0.033	-	-	-	-	-	-	-	-	-	-	0.005	-	-	-	658	Conforming steel
X	Y	0.199	0.78	3.52	0.026	0.0025	0.0033	0.035	-	0.047	-	-	-	-	-	-	-	0.007	-	-	-	-	663	Conforming steel
		0.208	0.51	3.23	0.029	0.0027	0.0041	0.036	-	0.032	-	-	-	-	-	-	-	-	-	0.008	-	-	649	Conforming steel
Z	AA	0.204	0.29	3.65	0.027	0.0019	0.0031	0.034	-	0.038	-	-	-	-	-	-	-	-	-	0.0021	-	-	651	Conforming steel
		0.199	1.01	3.87	0.025	0.0025	0.0037	0.037	-	-	-	-	-	-	-	-	-	-	-	-	-	-	649	Conforming steel
AB	AC	0.210	1.28	4.02	0.029	0.0029	0.0041	0.033	-	-	-	-	-	-	-	-	-	-	-	-	-	-	646	Conforming steel
		0.199	1.11	4.09	0.031	0.0021	0.0035	0.033	-	-	-	-	-	-	-	-	-	-	-	-	-	-	658	Conforming steel
AD		0.188	0.81	3.54	0.028	0.0020	0.0039	0.026	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0028	Conforming steel

Underline: outside range according to present disclosure

Table 2

No.	Steel sample ID	Slab heating temperature (°C)	Finisher delivery temperature (°C)	Average coiling temperature (°C)	hot-rolled sheet heat treatment		Rolling reduction in cold rolling (%)	Annealing treatment		Type*	Remarks
					Heat treatment temperature (°C)	Heat treatment time (s)		Heat treatment temperature (°C)	Heat treatment time (s)		
1	A	1230	900	540	703	18000	276	688	500	CR	Example
2	B	1240	890	500	688	20000	27.6	673	300	CR	Example
3	C	1200	890	600	690	15000	28.6	675	350	GA	Example
4	C	1100	890	600	690	20000	28.6	680	500	CR	Example
5	C	1300	880	580	700	21000	28.6	680	350	CR	Example
6	C	1200	750	600	690	20000	22.2	675	350	CR	Example
7	C	1200	1000	680	710	18000	29.6	690	400	GA	Example
8	C	1150	880	300	690	19000	28.6	675	400	GA	Example
9	C	1180	870	750	690	20000	25.9	690	400	CR	Example
10	C	1180	870	600	670	19000	25.9	700	350	CR	Example
11	C	1190	860	550	760	18000	28.6	690	500	CR	Example
12	C	1200	850	600	690	600	25.0	680	500	GA	Example
13	C	1210	850	540	680	17000	25.0	740	500	GA	Example
14	C	1200	890	540	680	17000	22.2	680	20	GA	Example
15	C	1250	870	660	690	19000	28.6	670	900	CR	Example
16	C	1220	<u>700</u>	540	690	20000	28.6	675	250	CR	Comparative Example
17	C	1230	<u>1100</u>	490	690	10000	27.6	675	350	CR	Comparative Example
18	C	1240	860	<u>850</u>	690	7000	29.6	675	800	CR	Comparative Example
19	C	1250	870	510	<u>500</u>	16000	25.9	675	700	EG	Comparative Example

(continued)

No.	Steel sample ID	Slab heating temperature (°C)	Finisher delivery temperature (°C)	Average coiling temperature (°C)	hot-rolled sheet heat treatment		Rolling reduction in cold rolling (%)	Annealing treatment		Type*	Remarks
					Heat treatment temperature (°C)	Heat treatment time (s)		Heat treatment temperature (°C)	Heat treatment time (s)		
20	C	1240	880	490	<u>850</u>	17000	25.0	675	500	CR	Comparative Example
21	C	1250	890	570	690	<u>300</u>	27.6	675	600	CR	Comparative Example
22	C	1250	890	600	690	19000	10.3	675	550	CR	Example
23	C	1240	890	600	690	20000	0.0	675	550	CR	Example
24	C	1230	860	610	690	19000	<u>57.5</u>	675	650	CR	Comparative Example
25	C	1230	860	610	690	6000	<u>36.4</u>	675	650	CR	Comparative Example
26	C	1240	880	590	690	6000	28.6	<u>520</u>	750	CR	Comparative Example
27	C	1210	880	560	690	10000	29.6	<u>850</u>	400	AI	Comparative Example
28	C	1230	860	560	690	16000	28.6	675	<u>2</u>	CR	Comparative Example
29	C	1200	890	570	690	20000	28.6	675	1500	CR	Comparative Example
30	D	1240	860	530	696	18000	27.6	688	600	CR	Example
31	E	1240	890	520	689	6000	27.6	674	700	GI	Example
32	F	1250	900	550	690	18000	24.1	675	500	CR	Example
33	G	1240	890	590	687	7000	25.0	672	550	AI	Example
34	H	1260	860	560	715	9000	28.6	700	540	CR	Example
35	I	1240	920	600	691	15000	28.6	676	290	GA	Example

(continued)

No.	Steel sample ID	Slab heating temperature (°C)	Finisher delivery temperature (°C)	Average coiling temperature (°C)	hot-rolled sheet heat treatment		Rolling reduction in cold rolling (%)	Annealing treatment		Type*	Remarks
					Heat treatment temperature (°C)	Heat treatment time (s)		Heat treatment temperature (°C)	Heat treatment time (s)		
36	IA	1250	890	600	700	15000	28.6	680	650	GA	Example
37	IB	1250	890	600	710	18000	28.6	690	650	CR	Example
38	IC	1240	890	560	750	18000	28.6	710	550	CR	Example
39	ID	1230	880	570	700	18000	28.6	700	600	CR	Example
40	IE	1250	890	580	710	19000	28.6	700	600	GA	Example
41	IF	1240	860	560	710	18000	28.6	690	600	GA	Example
42	IG	1230	860	560	710	18000	28.6	690	650	CR	Example
43	IH	1250	860	570	715	18000	28.6	690	650	CR	Example
44	II	1250	870	600	712	18000	28.6	680	600	CR	Example
45	IJ	1250	890	580	720	18000	28.6	690	550	CR	Example
46	IK	1230	880	580	690	18000	28.6	710	580	GA	Example
47	IL	1240	870	590	710	18000	28.6	710	600	GA	Comparative Example
48	IM	1250	870	570	710	18000	28.6	680	600	GA	Comparative Example
49	J ₋	1220	860	630	717	17000	25.9	702	300	GI	Comparative Example
50	K ₋	1210	870	620	764	20000	29.6	749	200	EG	Comparative Example
51	L ₋	1240	840	570	729	19000	29.6	714	280	CR	Comparative Example
52	M	1250	830	540	688	5000	28.6	673	360	EG	Comparative Example

(continued)

No.	Steel sample ID	Slab heating temperature (°C)	Finisher delivery temperature (°C)	Average coiling temperature (°C)	hot-rolled sheet heat treatment		Rolling reduction in cold rolling (%)	Annealing treatment		Type*	Remarks
					Heat treatment temperature (°C)	Heat treatment time (s)		Heat treatment temperature (°C)	Heat treatment time (s)		
53	N	1260	850	580	684	6000	21.4	669	370	GI	Example
54	O	1270	870	540	695	15000	28.6	680	400	CR	Example
55	P	1220	900	520	695	18000	28.6	680	300	GA	Example
56	Q	1260	840	600	696	19000	27.6	681	320	CR	Example
57	R	1270	830	560	683	14000	28.6	668	300	EG	Example
58	S	1240	880	620	690	8000	27.6	675	300	Al	Example
59	T	1250	820	600	700	8000	29.6	685	200	GI	Example
60	U	1250	850	530	715	15000	29.6	700	250	GI	Example
61	V	1240	920	570	692	13000	28.6	677	280	GI	Example
62	W	1230	910	500	705	10000	27.6	690	250	EG	Example
63	X	1250	890	590	695	16000	22.2	680	300	Al	Example
64	Y	1260	900	520	702	9000	25.0	687	340	GA	Example
65	Z	1250	880	540	686	18000	28.6	671	600	GI	Example
66	AA	1260	900	520	686	9000	29.6	671	500	Al	Example
67	AB	1250	880	540	694	15000	29.6	679	500	CR	Example
68	AC	1260	860	530	686	6000	29.6	671	350	CR	Example
69	AD	1250	870	540	696	8000	28.6	692	400	CR	Example
70	B	1230	890	550	695	10000	25.9	657	200	CR	Example
71	B	1250	870	530	698	8000	28.6	658	180	CR	Example

Underline: outside range according to present disclosure
 * CR: cold-rolled steel sheet (no coating). GI: hot-dip galvanized steel sheet (no galvannealing), GA: galvannealed steel sheet
 Al: hot-dip aluminum-coated steel sheet.. EG electrogalvanized steel sheet

Table 3

No.	Steel sample ID	Rolling reduction in cold rolling (%)	Area ratio of F (%)	Area ratio of F' (%)	Area ratio of M (%)	Volume fraction of RA (%)	Average grain size (μm)			Aspect ratio of crystal grains			Balance	Remarks
							F	M	RA	F	M	RA		
1	A	27.6	64.9	80	6.3	13.1	4.9	2.6	2.4	4.3	3.5	4.2	BF,P,0	Example
2	B	27.6	55.2	92	10.6	19.2	4.3	1.7	1.8	4.5	4.0	4.3	BF,P,0	Example
3	C	28.6	42.5	16.9	13.5	24.6	3.2	1.0	1.1	4.4	4.1	4.3	BF,P,0	Example
4	C	28.6	45.1	8.5	13.5	22.5	4.2	2.1	1.2	4.5	4.1	4.2	BP,P,0	Example
5	C	28.6	42.1	9.2	12.6	23.4	4.1	2.0	1.1	4.8	4.0	4.3	BP,P,0	Example
6	C	22.2	42.5	10.2	15.4	22.1	3.2	1.9	1.3	4.5	4.1	4.3	BF,P,0	Example
7	C	29.6	43.1	9.8	12.5	20.6	3.0	1.8	2.1	4.4	4.2	4.2	BF,P,0	Example
8	C	28.6	42.5	9.1	14.1	25.1	3.5	1.3	2.2	5.1	4.5	4.3	BP,P,0	Example
9	C	25.9	41.6	9.1	13.8	22.6	3.6	1.5	2.5	4.8	4.2	4.1	BF,P,0	Example
10	C	25.9	38.1	10.1	12.8	22.4	3.8	2.0	1.2	4.5	4.1	4.1	BP,P,0	Example
11	C	28.6	50.6	11.2	14.1	23.5	5.0	2.1	1.3	4.5	4.2	4.2	BF,P,0	Example
12	C	25.0	32.1	17.2	17.8	24.8	4.5	2.3	1.5	4.7	4.0	4.2	BF,P,0	Example
13	C	25.0	46.9	12.1	12.9	25.1	3.9	1.5	1.5	4.8	4.0	4.3	BF,P,0	Example
14	C	22.2	41.0	11.2	14.1	22.6	5.0	1.9	1.6	4.7	4.1	4.4	BF,P,0	Example
15	C	28.6	42.6	12.5	16.5	23.9	4.1	2.1	1.4	4.8	4.1	4.1	BF,P,0	Example
16	C	28.6	55.2	10.2	12.8	<u>7.1</u>	3.9	1.5	1.6	4.4	4.2	4.5	BF,P,0	Comparative Example
17	C	27.6	60.8	10.8	13.4	<u>7.4</u>	4.1	1.8	1.4	3.5	4.0	4.2	BF,P,0	Comparative Example
18	C	29.6	55.9	10.3	12.5	18.6	<u>7.8</u>	<u>4.2</u>	<u>4.1</u>	5.5	4.1	4.5	BF,P,0	Comparative Example
19	C	25.9	59.1	10.4	15.4	<u>6.4</u>	5.4	1.8	1.7	4.4	4.3	4.4	BF,P,0	Comparative Example
20	C	25.0	59.3	12.1	16.8	<u>6.9</u>	5.2	1.5	1.4	4.6	4.4	4.1	BF,P,0	Comparative Example

(continued)

No.	Steel sample ID	Rolling reduction in cold rolling (%)	Area ratio of F (%)	Area ratio of F' (%)	Area ratio of M (%)	Volume fraction of RA (%)	Average grain size (μm)			Aspect ratio of crystal grains			Balance	Remarks
							F	M	RA	F	M	RA		
21	C	27.6	50.2	11.4	14.9	<u>6.2</u>	5.1	1.6	1.5	4.7	4.4	4.3	BP,P, $\emptyset$	Comparative Example
22	C	10.3	40.1	9.3	10.4	18.5	4.2	2.1	2.0	5.8	4.8	4.1	BP,P, $\emptyset$	Example
23	C	0.0	45.3	9.3	10.4	18.5	4.2	2.1	2.0	8.1	4.2	4.1	BF,P, $\emptyset$	Example
24	C	<u>57.5</u>	<u>70.0</u>	10.8	8.0	8.0	<u>6.5</u>	2.7	2.9	<u>1.4</u>	<u>1.4</u>	<u>1.5</u>	BP,P, $\emptyset$	Comparative Example
25	C	<u>36.4</u>	<u>65.5</u>	10.8	8.5	8.1	5.1	2.7	2.9	<u>1.9</u>	<u>1.8</u>	<u>1.9</u>	BF,P, $\emptyset$	Comparative Example
26	C	28.6	55.8	10.4	18.1	<u>6.2</u>	4.5	2.3	2.1	3.8	4.2	4.3	BF,P, $\emptyset$	Comparative Example
27	C	29.6	53.8	10.9	17.1	<u>6.5</u>	4.6	2.1	2.4	4.2	4.5	4.6	BF,P, $\emptyset$	Comparative Example
28	C	28.6	54.2	11.2	18.5	<u>6.3</u>	4.2	2.3	2.2	3.9	4.0	4.7	BF,P, $\emptyset$	Comparative Example
29	C	28.6	58.2	<u>1.2</u>	8.4	23.4	5.6	<u>4.1</u>	<u>3.9</u>	4.1	3.8	4.1	BP,P, $\emptyset$	Comparative Example
30	D	27.6	50.1	9.8	10.4	18.4	4.2	1.8	1.8	4.2	4.2	5.0	BF,P, $\emptyset$	Example
31	E	27.6	52.1	10.1	10.6	16.8	4.1	1.5	1.9	4.5	4.4	4.2	BF,P, $\emptyset$	Example
32	F	24.1	50.1	9.8	10.9	19.2	3.9	1.9	1.8	4.5	4.7	4.4	BP,P, $\emptyset$	Example
33	G	25.0	64.5	8.1	8.5	12.8	5.1	2.7	2.3	4.4	4.8	4.3	BP,P, $\emptyset$	Example
34	H	28.6	63.1	8.5	8.8	13.8	4.8	2.5	2.2	4.6	4.6	4.3	BF,P, $\emptyset$	Example
35	I	28.6	64.7	8.0	8.8	13.5	4.6	2.4	2.4	4.7	4.5	4.2	BF,P, $\emptyset$	Example
36	IA	28.6	64.8	8.5	8.5	12.6	5.1	2.5	1.8	4.5	4.5	4.2	BF,P, $\emptyset$	Example
37	IB	28.6	65.0	9.1	8.5	13.5	5.5	2.6	1.5	4.5	4.5	4.3	BF,P, $\emptyset$	Example
38	IC	28.6	64.8	8.1	8.9	14.0	5.1	2.4	2.2	4.4	4.6	4.1	BF,P, $\emptyset$	Example

(continued)

No.	Steel sample ID	Rolling reduction in cold rolling (%)	Area ratio of F (%)	Area ratio of F' (%)	Area ratio of M (%)	Volume fraction of RA (%)	Average grain size (μm)			Aspect ratio of crystal grains			Balance	Remarks
							F	M	RA	F	M	RA		
39	ID	28.6	55.1	9.1	10.1	18.1	4.9	2.1	1.9	4.2	4.2	4.2	BF,P,B	Example
40	IE	28.6	52.0	9.2	10.2	15.6	4.6	2.2	2.0	4.4	4.1	4.3	BF,P,0	Example
41	IF	28.6	54.0	9.8	10.1	15.7	4.2	2.3	2.1	4.2	4.6	4.2	BF,P,0	Example
42	IG	28.6	53.1	8.7	10.2	16.8	4.5	2.1	2.2	4.5	4.3	4.1	BF,P,0	Example
43	IH	28.6	59.1	10.1	10.5	17.2	5.1	2.5	1.9	4.1	4.2	4.4	BF,P,0	Example
44	II	28.6	60.1	8.9	10.5	18.1	4.9	2.4	1.5	4.5	4.1	4.1	BF,P,0	Example
45	IJ	28.6	58.1	9.5	10.9	15.4	4.6	2.5	1.8	4.7	4.2	4.5	BF,P,0	Example
46	IK	28.6	61.2	8.5	11.1	16.9	4.5	2.4	1.5	4.6	4.1	4.3	BF,P,0	Example
47	IL	28.6	66.1	8.0	10.5	10.2	5.6	2.0	1.9	4.1	4.1	4.1	BF,P,0	Comparative Example
48	IM	28.6	63.5	12.5	14.5	9.0	4.0	2.1	2.1	4.5	4.5	4.2	BF,P,0	Comparative Example
49	J	25.9	65.0	8.9	3.8	3.6	7.4	0.6	0.5	4.3	4.4	4.2	BF,P,0	Comparative Example
50	K	29.6	50.4	18.4	15.4	6.8	5.4	3.9	3.8	4.4	4.1	4.1	BF,P,0	Comparative Example
51	L	29.6	60.3	13.2	15.9	6.2	5.8	4.5	3.9	4.4	4.1	4.1	BF,P,0	Comparative Example
52	M	28.6	50.3	2.2	11.4	13.2	7.1	4.1	4.0	4.2	4.1	3.9	BF,P,0	Comparative Example
53	N	21.4	55.1	10.4	11.4	18.4	4.2	1.6	1.9	4.3	4.2	4.1	BF,P,0	Example
54	O	28.6	54.2	10.5	9.8	17.4	4.3	1.7	1.4	4.2	4.3	4.2	BF,P,0	Example
55	P	28.6	55.7	10.1	10.5	19.5	4.1	1.4	1.5	3.9	4.3	4.6	BF,P,0	Example
56	Q	27.6	56.1	10.3	10.8	19.6	4.3	1.7	1.6	4.0	4.2	4.3	BF,P,0	Example
57	R	28.6	65.0	8.2	7.5	12.8	5.1	2.5	2.3	3.9	4.1	4.5	BF,P.0	Example

(continued)

No.	Steel sample ID	Rolling reduction in cold rolling (%)	Area ratio of F (%)	Area ratio of F' (%)	Area ratio of M (%)	Volume fraction of RA (%)	Average grain size (μm)			Aspect ratio of crystal grains			Balance	Remarks
							F	M	RA	F	M	RA		
58	S	27.6	64.8	8.1	8.2	12.4	4.8	2.4	2.1	4.3	4.2	4.3	BF, P, θ	Example
59	T	29.6	60.9	8.0	7.2	14.2	4.6	2.3	2.1	4.2	4.5	4.4	BF, P, θ	Example
60	U	29.6	63.9	8.1	7.6	13.5	4.5	2.4	2.5	4.4	4.2	4.5	BF, P, θ	Example
61	V	28.6	65.0	8.7	7.5	12.9	4.8	2.1	2.4	4.0	4.1	4.7	BF, P, θ	Example
62	W	27.6	64.9	8.0	6.8	13.2	4.7	2.3	2.1	3.9	3.9	4.1	BF, P, θ	Example
63	X	22.2	50.7	10.4	10.2	18.4	4.1	1.6	1.7	3.7	3.1	4.2	BF, P, θ	Example
64	Y	25.0	62.8	10.5	10.6	15.0	4.5	1.7	1.8	3.9	4.2	4.4	BF, P, θ	Example
65	Z	28.6	55.5	98	9.8	20.1	4.2	1.8	1.6	4.2	4.2	4.3	BF, P, θ	Example
66	AA	29.6	50.8	10.6	10.6	19.4	3.9	1.9	1.5	4.1	4.1	4.2	BF, P, θ	Example
67	AB	29.6	52.1	10.1	9.6	18.4	4.1	1.7	1.5	4.2	4.5	4.6	BF, P, θ	Example
68	AC	29.6	529	9.9	10.3	18.2	4.2	1.6	1.8	4.4	4.5	4.7	BF, P, θ	Example
69	AD	28.6	51.2	11.1	12.1	19.6	3.9	1.4	1.6	4.3	4.3	4.1	BF, P, θ	Example
70	B	25.9	48.0	10.1	11.2	18.4	4.5	1.9	1.7	4.1	4.2	4.2	BF, P, θ	Example
71	B	28.6	50.5	10.5	10.8	19.1	4.6	1.8	1.8	3.9	4.4	4.4	BF, P, θ	Example

Underline: outside range according to present disclosure
F: polygonal ferrite, F': non-recrystallized ferrite, BF: bainitic ferrite, RA: retained austenite, M: martensite, P: pearlite, θ: carbide (such as cementite)

Table 4

No.	Steel sample ID	Average Mn content in RA (mass%)	Average Mn content in F (mass%)	Average Mn content in RA /Average Mn content in F	$0.09 \times (\text{Mn content in RA}) - 0.026 - 0.150$ (mass%)	$0.09 \times (\text{Mn content in RA}) - 0.026 + 0.150$ (mass%)	C content in RA (mass%)	Value obtained by dividing RA remaining volume fraction after 10% tensile working by RA volume fraction before working	Remarks
1	A	6.89	2.84	2.43	0.444	0.744	0.63	0.77	Example
2	B	7.68	3.02	2.54	0.515	0.815	0.71	0.81	Example
3	C	8.22	3.08	2.67	0.564	0.864	0.75	0.68	Example
4	C	7.88	2.87	2.75	0.533	0.833	0.75	0.65	Example
5	C	8.02	2.88	2.78	0.546	0.846	0.75	0.68	Example
6	C	7.55	3.01	2.51	0.504	0.804	0.78	0.74	Example
7	C	8.01	3.01	2.66	0.545	0.845	0.68	0.74	Example
8	C	7.89	3.05	2.59	0.534	0.834	0.74	0.65	Example
9	C	7.99	2.98	2.68	0.543	0.843	0.78	0.68	Example
10	C	7.75	2.99	2.59	0.522	0.822	0.75	0.71	Example
11	C	7.98	3.01	2.65	0.542	0.842	0.75	0.64	Example
12	C	5.87	2.89	2.03	0.352	0.652	0.62	0.51	Example
13	C	7.89	2.89	2.73	0.534	0.834	0.76	0.71	Example
14	C	7.99	3.05	2.62	0.543	0.843	0.74	0.72	Example
15	C	7.84	3.01	2.60	0.530	0.830	0.76	0.74	Example
16	C	7.45	2.79	2.67	0.495	0.795	0.43	0.25	Comparative Example
17	C	7.35	2.89	2.54	0.486	0.786	0.65	0.42	Comparative Example
18	C	6.89	2.97	2.32	0.444	0.744	0.63	0.51	Comparative Example
19	C	5.41	3.57	<u>1.52</u>	0.311	0.611	0.50	0.39	Comparative Example

(continued)

No.	Steel sample ID	Average Mn content in RA (mass%)	Average Mn content in F (mass%)	Average Mn content in RA /Average Mn content in F	$0.09 \times (\text{Mn content in RA}) - 0.026 - 0.150$ (mass%)	$0.09 \times (\text{Mn content in RA}) - 0.026 + 0.150$ (mass%)	C content in RA (mass%)	Value obtained by dividing RA remaining volume fraction after 10% tensile working by RA volume fraction before working	Remarks
20	C	5.32	3.67	<u>1.45</u>	0.303	0.603	0.49	0.52	Comparative Example
21	C	5.26	3.68	<u>1.43</u>	0.297	0.597	0.49	0.44	Comparative Example
22	C	7.48	2.99	2.50	0.497	0.797	0.69	0.69	Example
23	C	7.48	2.99	2.50	0.497	0.797	0.69	0.69	Example
24	C	7.55	2.75	2.75	0.504	0.804	0.79	0.19	Comparative Example
25	C	7.32	2.75	2.66	0.483	0.783	0.79	0.19	Comparative Example
26	C	5.67	3.64	<u>1.56</u>	0.334	0.634	0.29	0.22	Comparative Example
27	C	5.54	3.75	1.48	0.323	0.623	0.46	0.46	Comparative Example
28	C	5.28	3.87	<u>1.36</u>	0.299	0.599	0.49	0.53	Comparative Example
29	C	8.26	2.67	3.09	0.567	0.867	0.76	0.39	Comparative Example
30	D	7.54	2.89	2.61	0.503	0.803	0.69	0.71	Example
31	E	7.32	2.78	2.63	0.483	0.783	0.62	0.75	Example
32	F	7.84	2.97	2.64	0.530	0.830	0.72	0.64	Example
33	G	6.95	2.85	2.44	0.450	0.750	0.62	0.69	Example
34	H	7.08	2.76	2.57	0.461	0.761	0.63	0.70	Example
35	I	6.85	2.66	2.58	0.441	0.741	0.61	0.74	Example

(continued)

No.	Steel sample ID	Average Mn content in RA (mass%)	Average Mn content in F (mass%)	Average Mn content in RA /Average Mn content in F	$0.09 \times (\text{Mn content in RA}) - 0.026 - 0.150$ (mass%)	$0.09 \times (\text{Mn content in RA}) - 0.026 - 0.150$ (mass%)	C content in RA (mass%)	Value obtained by dividing RA remaining volume fraction after 10% tensile working by RA volume fraction before working	Remarks
36	IA	7.55	3.15	2.40	0.504	0.804	0.55	0.48	Example
37	IB	7.15	2.58	2.77	0.468	0.768	0.52	0.55	Example
38	IC	4.51	1.55	2.91	0.230	0.530	0.51	0.38	Example
39	ID	6.95	3.15	2.21	0.450	0.750	0.61	0.68	Example
40	IE	7.10	3.21	2.21	0.463	0.763	0.58	0.70	Example
41	IF	6.88	3.01	2.29	0.443	0.743	0.58	0.74	Example
42	IG	7.15	3.21	2.23	0.468	0.768	0.61	0.74	Example
43	IH	6.99	2.89	2.42	0.453	0.753	0.62	0.75	Example
44	II	7.15	2.97	2.41	0.468	0.768	0.65	0.76	Example
45	IJ	7.10	2.88	2.47	0.463	0.763	0.58	0.81	Example
46	IK	7.02	2.78	2.53	0.456	0.756	0.58	0.56	Example
47	IL	6.87	3.10	2.22	0.442	0.742	0.55	0.25	Comparative Example
48	IM	6.55	3.15	2.08	0.414	0.714	0.35	0.21	Comparative Example
49	J	6.45	2.79	2.31	0.405	0.705	0.38	0.24	Comparative Example
50	K	7.29	2.87	2.54	0.480	0.780	0.67	0.52	Comparative Example
51	L	3.40	2.08	<u>1.63</u>	0.130	0.430	0.30	0.43	Comparative Example
52	M	7.28	2.89	2.52	0.479	0.779	0.65	0.46	Comparative Example
53	N	7.59	2.98	2.55	0.507	0.807	0.70	0.62	Example

(continued)

No.	Steel sample ID	Average Mn content in RA (mass%)	Average Mn content in F (mass%)	Average Mn content in RA /Average Mn content in F	$0.09 \times (\text{Mn content in RA}) - 0.026 - 0.150$ (mass%)	$0.09 \times (\text{Mn content in RA}) - 0.026 - 0.150$ (mass%)	C content in RA (mass%)	Value obtained by dividing RA remaining volume fraction after 10% tensile working by RA volume fraction before working	Remarks
54	O	7.64	2.85	2.68	0.512	0.812	0.65	0.68	Example
55	P	7.49	2.89	2.59	0.498	0.798	0.69	0.74	Example
56	Q	7.39	2.98	2.48	0.489	0.789	0.63	0.84	Example
57	R	6.58	2.75	2.39	0.416	0.716	0.59	0.86	Example
58	S	6.87	2.81	2.44	0.442	0.742	0.58	0.81	Example
59	T	6.89	2.74	2.51	0.444	0.744	0.63	0.75	Example
60	U	6.99	2.65	2.64	0.453	0.753	0.61	0.78	Example
61	V	6.48	2.71	2.39	0.407	0.707	0.55	0.74	Example
62	W	6.78	2.68	2.53	0.434	0.734	0.59	0.76	Example
63	X	7.85	2.89	2.72	0.531	0.831	0.69	0.79	Example
64	Y	7.46	2.79	2.67	0.495	0.795	0.66	0.83	Example
65	Z	7.59	2.68	2.83	0.507	0.807	0.68	0.74	Example
66	AA	7.36	2.89	2.55	0.486	0.786	0.63	0.78	Example
67	AB	7.56	2.78	2.72	0.504	0.804	0.67	0.77	Example
68	AC	7.54	2.79	2.70	0.503	0.803	0.64	0.68	Example
69	AD	7.94	2.91	2.73	0.539	0.839	0.70	0.72	Example
70	B	7.24	3.24	2.23	0.476	0.776	0.45	0.29	Example
71	B	7.18	3.28	2.19	0.470	0.770	0.46	0.28	Example
Underline: outside range according to present disclosure F: polygonal ferrite, F': non-recrystallized ferrite, BF: bainitic ferrite, RA: retained austenite, M: martensite, P: pearlite, θ : carbide (such as cementite)									

Table 5

No.	Steel sample ID	Sheet thickness (mm)	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Productivity	YP (MPa)	YR (%)	TS (MPa)	EL (%)	TS×EL (MPa·%)	R/t	λ (%)	Remarks
1	A	2.1	Good	Good	Good	Good	515	79.2	650	38.2	24830	0.1	61	Example
2	B	2.1	Good	Good	Good	Good	691	85.1	812	35.1	28501	0.2	52	Example
3	C	2.0	Good	Good	Good	Good	996	97.8	1018	31.4	31965	0.5	40	Example
4	C	2.0	Good	Good	Good	Good	990	97.9	1011	32.0	32352	0.5	49	Example
5	C	2.0	Good	Good	Good	Good	950	96.4	985	31.5	31028	0.5	52	Example
6	C	2.1	Good	Good	Good	Good	950	96.5	984	31.4	30898	0.5	51	Example
7	C	1.9	Good	Good	Good	Good	960	958	1002	35.1	35170	0.5	52	Example
8	C	2.0	Good	Good	Good	Good	950	96.3	987	32.6	32176	0.5	51	Example
9	C	2.0	Good	Good	Good	Good	940	94.9	990	35.1	34749	0.5	49	Example
10	C	2.0	Good	Good	Good	Good	950	94.1	1010	33.1	33431	0.5	52	Example
11	C	2.0	Good	Good	Good	Good	950	94.8	1002	31.2	31262	0.5	55	Example
12	C	2.1	Good	Good	Good	Good	980	97.5	1005	31.8	31959	0.5	56	Example
13	C	2.1	Good	Good	Good	Good	900	91.5	984	31.5	30996	0.5	52	Example
14	C	2.1	Good	Good	Good	Good	910	91.9	990	31.4	31086	0.5	51	Example
15	C	2.0	Good	Good	Good	Good	950	950	1000	32.1	32100	0.5	51	Example
16	C	2.0	Poor	Poor	Poor	Poor	695	82.7	840	21.9	18396	1.5	25	Comparative Example
17	C	2.1	Good	Poor	Poor	Poor	689	83.5	825	22.4	18480	1.4	30	Comparative Example
18	C	1.9	Good	Good	Good	Good	501	91.3	549	28.4	15592	1.1	28	Comparative Example
19	C	2.0	Good	Poor	Good	Good	699	82.8	844	22.5	18990	0.5	44	Comparative Example

(continued)

No.	Steel sample ID	Sheet thickness (mm)	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Productivity	YP (MPa)	YR (%)	TS (MPa)	EL (%)	TS×EL (MPa·%)	R/t	λ (%)	Remarks
20	C	2.1	Good	Good	Good	Good	691	80.3	861	23.5	20234	0.5	43	Comparative Example
21	C	2.1	Good	Poor	Good	Good	663	809	820	23.7	19434	0.5	42	Comparative Example
22	C	2.6	Good	Good	Good	Good	653	76.8	850	35.9	30515	0.6	56	Example
23	C	2.8	Good	Good	Good	Good	649	76.7	846	35.9	30371	0.5	56	Example
24	C	1.7	Good	Good	Good	Good	659	79.4	830	21.6	17928	1.9	22	Comparative Example
25	C	2.1	Good	Good	Good	Good	654	79.7	821	21.6	17734	1.5	22	Comparative Example
26	C	2.0	Good	Good	Good	Good	697	80.1	870	21.5	18705	0.5	31	Comparative Example
27	C	1.9	Good	Good	Good	Poor	705	82.0	860	20.6	17716	0.5	41	Comparative Example
28	C	2.0	Good	Good	Good	Good	694	79.0	878	20.9	18350	0.5	40	Comparative Example
29	C	2.0	Good	Good	Good	Good	488	58.8	830	36.2	30046	1.3	25	Comparative Example
30	D	2.1	Good	Good	Good	Good	693	84.0	825	34.9	28793	0.2	41	Example
31	E	2.1	Good	Good	Good	Good	661	77.6	852	32.8	27946	0.4	45	Example
32	F	2.2	Good	Good	Good	Good	702	82.8	848	35.1	29765	0.2	46	Example
33	G	2.1	Good	Good	Good	Good	518	79.7	650	37.8	24570	0.1	59	Example
34	H	2.0	Good	Good	Good	Good	512	81.4	629	38.6	24279	0.1	65	Example
35	I	2.0	Good	Good	Good	Good	519	82.6	628	38.9	24429	0.1	65	Example
36	IA	2.0	Good	Good	Good	Good	510	85.7	595	41.0	24395	0.5	60	Example

(continued)

No.	Steel sample ID	Sheet thickness (mm)	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Productivity	YP (MPa)	YR (%)	TS (MPa)	EL (%)	TS×EL (MPa·%)	R/t	λ (%)	Remarks
37	IB	2.0	Good	Good	Good	Good	610	93.8	650	38.0	24700	0.5	62	Example
38	IC	2.0	Good	Good	Good	Good	550	92.0	598	42.0	25116	0.5	58	Example
39	ID	2.0	Good	Good	Good	Good	600	91.9	653	38.0	24814	0.5	55	Example
40	IE	2.0	Good	Good	Good	Good	580	93.1	623	40.2	25045	0.5	56	Example
41	IF	2.0	Good	Good	Good	Good	560	88.9	630	39.1	24633	0.5	60	Example
42	IG	2.0	Good	Good	Good	Good	550	88.3	623	38.6	24048	0.5	55	Example
43	IH	2.0	Good	Good	Good	Good	510	85.4	597	42.5	25373	0.5	52	Example
44	II	2.0	Good	Good	Good	Good	560	82.4	680	35.8	24344	0.5	55	Example
45	IJ	2.0	Good	Good	Good	Good	560	86.2	650	39.7	25805	0.5	50	Example
46	IK	2.0	Good	Good	Good	Good	650	82.5	788	32.1	25295	0.5	56	Example
47	IL	2.0	Good	Good	Good	Good	660	84.0	786	30.1	<u>23659</u>	0.5	55	Comparative Example
48	IM	2.0	Good	Good	Good	Good	660	83.7	789	21.4	<u>16885</u>	0.5	53	Comparative Example
49	J	2.0	Good	Good	Good	Good	330	60.6	545	31.9	17386	0.1	63	Comparative Example
50	K	1.9	Good	Good	Poor	Good	905	75.7	1195	15.8	18881	1.3	12	Comparative Example
51	L	1.9	Good	Good	Good	Good	631	76.0	830	20.8	17264	0.8	37	Comparative Example
52	M	2.0	Good	Good	Good	Good	499	59.1	845	28.9	24421	1.0	15	Comparative Example
53	N	2.2	Good	Good	Good	Good	674	81.2	830	36.4	30212	0.2	40	Example
54	O	2.0	Good	Good	Good	Good	661	77.7	851	35.8	30466	0.3	45	Example

(continued)

No.	Steel sample ID	Sheet thickness (mm)	Sheet passage ability during hot rolling	Sheet passage ability during cold rolling	Surface characteristics of final-annealed sheet	Productivity	YP (MPa)	YR (%)	TS (MPa)	EL (%)	TS×EL (MPa·%)	R/t	λ (%)	Remarks
55	P	2.0	Good	Good	Good	Good	709	87.5	810	35.9	29079	0.4	51	Example
56	Q	2.1	Good	Good	Good	Good	710	89.0	798	36.4	29047	0.2	48	Example
57	R	2.0	Good	Good	Good	Good	505	80.8	625	39.4	24625	0.1	53	Example
58	S	2.1	Good	Good	Good	Good	531	83.0	640	39.5	25280	0.1	58	Example
59	T	1.9	Good	Good	Good	Good	501	83.4	601	41.2	24761	0.1	55	Example
60	U	1.9	Good	Good	Good	Good	534	78.1	684	37.5	25650	0.1	65	Example
61	V	2.0	Good	Good	Good	Good	550	83.5	659	36.9	24317	0.1	55	Example
62	W	2.1	Good	Good	Good	Good	545	82.1	664	36.7	24369	0.1	59	Example
63	X	2.1	Good	Good	Good	Good	726	83.5	869	34.8	30241	0.2	48	Example
64	Y	2.1	Good	Good	Good	Good	709	82.5	859	35.1	30151	0.4	45	Example
65	Z	2.0	Good	Good	Good	Good	710	85.5	830	36.4	30212	0.3	50	Example
66	AA	1.9	Good	Good	Good	Good	678	82.6	821	36.9	30295	0.4	47	Example
67	AB	1.9	Good	Good	Good	Good	661	81.1	815	34.8	28362	0.3	53	Example
68	AC	1.9	Good	Good	Good	Good	702	84.9	827	35.2	29110	0.3	44	Example
69	AD	2.0	Good	Good	Good	Good	785	79.2	991	32.6	32307	0.3	42	Example
70	B	2.0	Good	Good	Good	Good	591	74.6	792	31.5	24948	0.5	40	Example
71	B	2.0	Good	Good	Good	Good	598	75.3	794	30.8	24455	0.5	41	Example

[0128] From above, it can be seen that the steel sheets according to the disclosure each exhibited TS of 590 MPa or more and YR of 68 % or more, and are thus considered as high-strength steel sheets having excellent formability and high yield ratio and hole expansion formability. In contrast, the comparative examples are inferior in terms of at least one of YR, TS, EL, λ , or R/t.

INDUSTRIAL APPLICABILITY

[0129] According to the disclosure, it becomes possible to manufacture high-strength steel sheets with excellent formability and high yield ratio and hole expansion formability that exhibit TS of 590 MPa or more and YR of 68 % or more and that satisfy the condition of $TS * EL \geq 24,000 \text{ MPa}\cdot\%$. Steel sheets according to the disclosure are highly beneficial in industrial terms, because they can improve fuel efficiency when applied to, for example, automobile structural parts, by a reduction in the weight of automotive bodies.

Claims

1. A steel sheet comprising:

a chemical composition containing, in mass%,

C: 0.030 % or more and 0.250 % or less,

Si: 0.01 % or more and 3.00 % or less,

Mn: 2.60 % or more and 4.20 % or less,

P: 0.001 % or more and 0.100 % or less,

S: 0.0200 % or less,

N: 0.0100 % or less, and

Ti: 0.005 % or more and 0.200 % or less, and

optionally further containing, in mass%, at least one selected from the group consisting of

Al: 0.01 % or more and 2.00 % or less,

Nb: 0.005 % or more and 0.200 % or less,

B: 0.0003 % or more and 0.0050 % or less,

Ni: 0.005 % or more and 1.000 % or less,

Cr: 0.005 % or more and 1.000 % or less,

V: 0.005 % or more and 0.500 % or less,

Mo: 0.005 % or more and 1.000 % or less,

Cu: 0.005 % or more and 1.000 % or less,

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

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

Ta: 0.001 % or more and 0.010 % or less,

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

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

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

with the balance consisting of Fe and inevitable impurities; and

a steel microstructure that contains, in area ratio,

20 % or more and 65 % or less of polygonal ferrite,

8 % or more of non-recrystallized ferrite,

and 5 % or more and 25 % or less of martensite, and

that contains, in volume fraction, 8 % or more of retained austenite, where an average aspect ratio of crystal grains of each of the polygonal ferrite, the martensite, and the retained austenite is 2.0 or more and 15.0 or less,

wherein the polygonal ferrite has an average grain size of 6 μm or less, the martensite has an average grain size of 3 μm or less, the retained austenite has an average grain size of 3 μm or less, and a value obtained by dividing a Mn content in the retained austenite in mass% by a Mn content in the polygonal ferrite in mass%

equals 2.0 or more.

2. The steel sheet according to claim 1, wherein the retained austenite has a C content that satisfies the following formula in relation to the Mn content in the retained austenite:

$$0.09 * [\text{Mn}] - 0.026 - 0.150 \leq [\text{C}] \leq 0.09 * [\text{Mn}] - 0.026 + 0.150$$

where

[C] is the C content in the retained austenite in mass%, and
[Mn] is the Mn content in the retained austenite in mass%.

3. A coated steel sheet comprising:

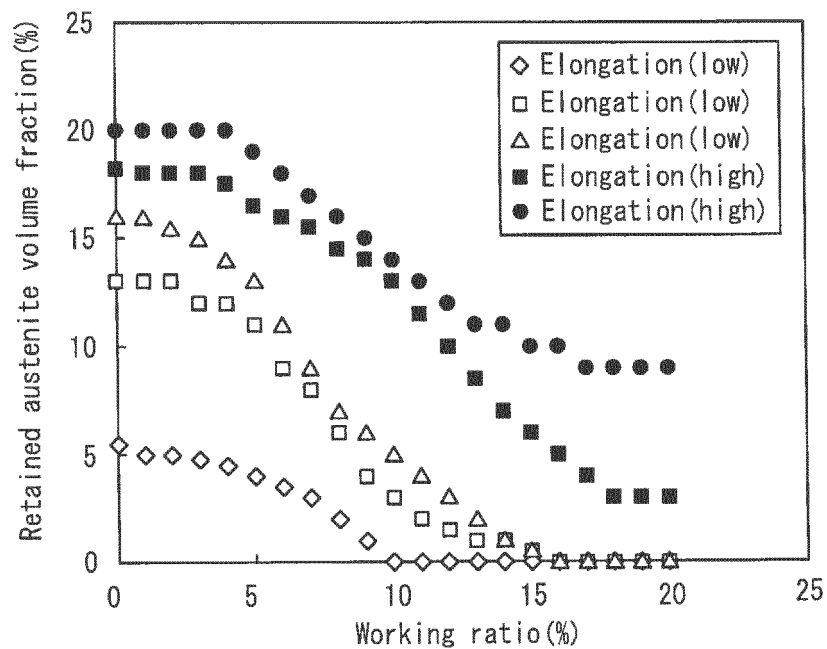
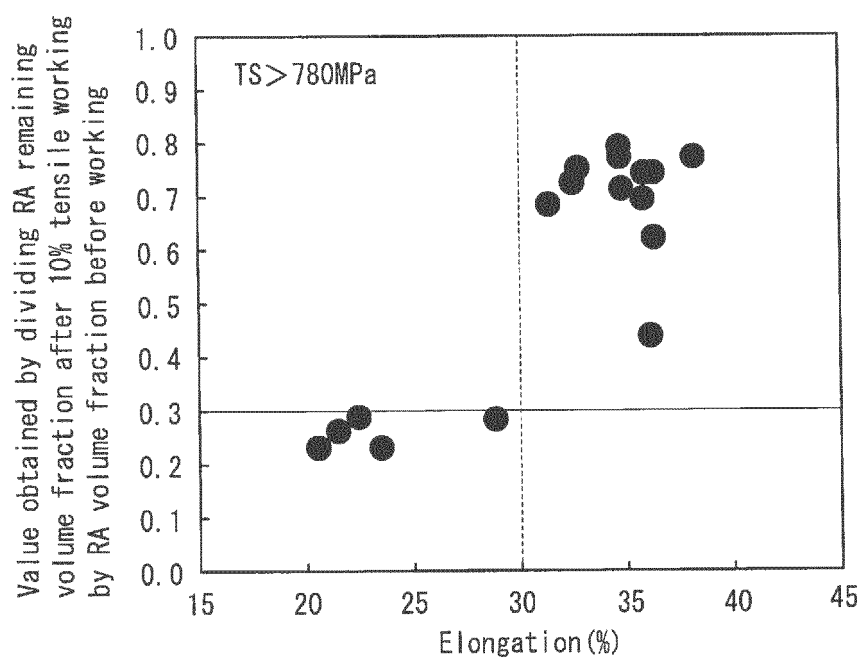
the steel sheet according to claim 1 or 2; and
one selected from a hot-dip galvanized layer, a galvanized layer, a hot-dip aluminum-coated layer, and an electrogalvanized layer.

4. A method for manufacturing a steel sheet, the method comprising:

heating a steel slab having the chemical composition according to claim 1;
hot rolling the steel slab with a finisher delivery temperature of 750 °C or higher and 1000 °C or lower to obtain a steel sheet;
coiling the steel sheet at 300 °C or higher and 750 °C or lower;
then subjecting the steel sheet to pickling to remove scales;
retaining the steel sheet in a temperature range of [Ac₁ transformation temperature + 20 °C] to [Ac₁ transformation temperature + 120 °C] for 600 s to 21,600 s;
optionally cold rolling the steel sheet at a rolling reduction of less than 30 %; and
then retaining the steel sheet in a temperature range of [Ac₁ transformation temperature + 10 °C] to [Ac₁ transformation temperature + 100 °C] for 20 s to 900 s and subsequently cooling the steel sheet, to manufacture the steel sheet according to claim 1 or 2.

5. The method according to claim 4,
wherein a value obtained by dividing a volume fraction of the retained austenite after performing tensile working with an elongation value of 10 % by a volume fraction of the retained austenite before the tensile working equals 0.3 or more.

6. The method according to claim 4, comprising
after the cooling, either subjecting the steel sheet to one selected from hot-dip galvanizing treatment, hot-dip aluminum coating treatment, and electrogalvanizing treatment, or subjecting the steel sheet to hot-dip galvanizing treatment and then to alloying treatment at 450 °C or higher and 600 °C or lower, to manufacture the coated steel sheet according to claim 3.

FIG. 1*FIG. 2*

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2017/009300

A. CLASSIFICATION OF SUBJECT MATTER

C22C38/00(2006.01)i, C21D9/46(2006.01)i, C22C38/14(2006.01)i, C22C38/60(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C38/00, C21D9/46, C22C38/14, C22C38/60

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

Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2017
Kokai Jitsuyo Shinan Koho 1971-2017 Toroku Jitsuyo Shinan Koho 1994-2017

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	JP 2013-185196 A (JFE Steel Corp.), 19 September 2013 (19.09.2013), claims 1, 2; paragraphs [0008], [0039]; tables 1, 2 & EP 2824210 A1 claims 1, 2; paragraphs [0015], [0062] to [0064]; tables 1, 2	1-6
A	JP 2012-229466 A (JFE Steel Corp.), 22 November 2012 (22.11.2012), claims 1, 7; paragraphs [0004], [0041] to [0045]; tables 1 to 3 (Family: none)	1-6

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

* Special categories of cited documents:

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search
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Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2017/009300

C (Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2013-14824 A (Nippon Steel & Sumitomo Metal Corp.), 24 January 2013 (24.01.2013), claim 1; paragraphs [0013], [0081] to [0084]; tables 1, 2 & EP 2730666 A1 claim 1; paragraphs [0013], [0104] to [0108]; tables 1, 2	1-6
A	JP 2016-50343 A (Nippon Steel & Sumitomo Metal Corp.), 11 April 2016 (11.04.2016), claims 1, 7; paragraphs [0009], [0039] to [0047]; tables 1, 2 (Family: none)	1-6
P, A	WO 2016/067623 A1 (JFE Steel Corp.), 06 May 2016 (06.05.2016), claims 1 to 11; tables 1, 2 (Family: none)	1-6

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REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2003138345 A [0007] [0008]