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(54) **HIGH-STRENGTH STEEL SHEET WITH EXCELLENT WORKABILITY AND MANUFACTURING PROCESS THEREFOR**

HOCHFESTES STAHLBLECH MIT HERVORRAGENDER BEARBEITBARKEIT UND
HERSTELLUNGSVERFAHREN DAFÜR

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JP-A- 2010 065 273 US-A1- 2004 226 635

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Description

Technical Field

- 5 **[0001]** The present invention relates to high-strength steel sheets having excellent workability and having a tensile strength of 590 MPa or more; and methods of manufacturing the steel sheets.

Background Art

- 10 **[0002]** The automobile industry is facing an urgent need of responding to global environmental issues such as CO₂ emission control. On the other hand, from the viewpoint of securing safety of passengers, the safety standards for collision of automobiles have been made stricter, and structural designing sufficiently securing safety in automobile cabins has been progressing. In order to meet both of these requirements, it is effective to use a high-strength steel sheet having a tensile strength of 780 MPa, or more as an automotive structural member and to make the thickness
- 15 further smaller to reduce the body weight. However, a steel sheet generally exhibits inferior workability with an increasing strength. Application of high-strength steel sheets to automotive members inevitably requires improvement in workability.
- [0003]** Transformation induced plasticity (TRIP)-aided steel sheets (TRIP-aided steel sheets) are known as steel sheets having a strength and workability both at certain levels. A TRIP-aided bainitic ferrite (TBF) steel sheet having a bainitic ferrite matrix and containing retained austenite (hereinafter also referred to as "retained Y") is known as one of
- 20 TRIP-aided steel sheets (Patent Literature (PTL) 1 to 4). The TBF steel sheet can have a high strength due to the hard bainitic ferrite and an elongation (EL) and a stretch flangeability (λ) both at satisfactory levels due to the fine retained austenite present at the boundary of the bainitic ferrite.
- [0004]** Techniques disclosed in PTL 5 and 6 are known as techniques for increasing the elongation and stretch flangeability to thereby improve the workability. Of these, the technique disclosed in PTL 5 allows the steel sheet to have a
- 25 higher strength by the action of the martensitic microstructure and to have better workability by forming retained austenite in a predetermined amount. The technique disclosed in PTL 6 allows the steel sheet to have a higher strength by the action of a lower bainitic microstructure and/or a martensitic microstructure and to have better workability by forming retained austenite and tempered martensite in predetermined amounts. The techniques in PTL 5 and 6 control polygonal ferrite area percentage to be 10% or less so as to ensure a tensile strength of 980 MPa or more.
- 30 **[0005]** In order to meet both the requirements, it is also effective to use a high-strength steel sheet having a tensile strength of 590 MPa or more as an automotive structural member and to make the thickness further smaller to reduce the body weight. However, a steel sheet generally exhibits inferior workability with an increasing strength as described above. Application of high-strength steel sheets to automotive members inevitably requires improvement in workability.
- [0006]** Dual-phase (DP) steel sheets and TRIP-aided steel sheets are known as steel sheets having a strength and
- 35 workability both at certain levels. The DP steel sheets have a metal structure including ferrite and martensite. The TRIP-aided steel sheets utilize transformation induced plasticity (TRIP) of retained austenite (retained y).
- [0007]** A steel sheet disclosed in PTL 7 is known as one of such TRIP-aided steel sheets having a strength and workability both at certain levels. PTL 7 discloses a technique of allowing the steel sheet to have, as a metal structure, a composite microstructure including martensite and retained austenite both present in ferrite and to thereby have a
- 40 higher strength and better workability (particularly, a higher elongation).
- [0008]** PTL 8 discloses a technique of allowing a TRIP-aided steel sheet to have a better balance between a strength (TS) and an elongation (EL) (specifically, the product of TS and EL) to thereby have better stamping performance. The technique disclosed in this literature allows the steel sheet to have a metal structure including ferrite, retained austenite, and at least one of bainite and martensite so as to have better stamping performance. The literature mentions that the
- 45 retained austenite functionally improves the steel sheet elongation.
- [0009]** As is disclosed in PTL 7 and PTL 8, a steel sheet, when having a metal structure including retained austenite, can have a strength and elongation properties both at higher levels.

Citation List

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Patent Literature

[0010]

- 55 PTL 1: Japanese Unexamined Patent Application Publication (JP-A) No. 2005-240178
 PTL 2: JP-A No. 2006-274417
 PTL 3: JP-A No. 2007-321236
 PTL 4: JP-A No. 2007-321237

PTL 5: JP-A No. 2010-65272

PTL 6: JP-A No. 2010-65273

PTL 7: JP-A No. H11-279691

PTL 8: JP-A No. 2007-126747

[0011] JP 2008 308717 discloses a high strength steel sheet having workability in which ductility and hole expansibility are consistent.

[0012] JP S61 217529 discloses a steel sheet having superior tensile strength, ductility, and second workability, by heat treating steel sheet having a suitable composition under specified conditions.

Summary of Invention

Technical Problem

[0013] Steel sheets for use typically in pillars and members should be subjected to bulging or drawing under more severe conditions, because more and more demands have recently been made on steel sheet workability. To meet this, the steel sheets desirably have further better workability, particularly a further higher elongation. However, it is known that local formability, such as stretch flangeability (λ) and bendability (R), generally deteriorates when the steel sheets have a higher elongation. To prevent this, TRIP-aided steel sheets desirably have better local formability, such as stretch flangeability (λ) and bendability (R), without deterioration in strength and elongation. The aforementioned TRIP-aided steel sheets, however, are disadvantageously poor in local formability, such as stretch flangeability and bendability, because retained austenite transforms into extremely hard martensite during working.

[0014] The present invention has been made under these circumstances, and an object thereof is to provide high-strength steel sheets excellent in workability, which have a tensile strength of 590 MPa or more and have an elongation and local formability both at higher levels. Another object of the present invention is to provide methods of manufacturing the steel sheets.

Solution to Problem

[0015] Reference is made to a first high-strength steel sheet which contains: C in a content of from 0.10% to 0.3%; Si in a content of from 1.0% to 3.0%; Mn in a content of from 1.5% to 3%; Al in a content of from 0.005% to 3%; P in a content controlled to 0.1% or less; and S in a content controlled to 0.05% or less, in mass percent, with the remainder consisting of iron and inevitable impurities. The steel sheet has a metal structure including bainite, polygonal ferrite, retained austenite, and tempered martensite. (1) When the metal structure is observed with a scanning electron microscope, (1a) the bainite has a composite microstructure including: a high-temperature-formed bainite having an average distance between adjacent regions of retained austenite and/or carbide of 1 μm or more; and a low-temperature-formed bainite having an average distance between adjacent regions of retained austenite and/or carbide of less than 1 μm ; the high-temperature-formed bainite is present in an area percentage "a" of from 10% to 80% of the entire metal structure; the low-temperature-formed bainite and the tempered martensite are present in a total area percentage "b" of from 10% to 80% of the entire metal structure; and (1b) the polygonal ferrite is present in an area percentage "c" of from 10% to 50% of the entire metal structure. (2) The retained austenite is present in a volume percentage of 5% or more of the entire metal structure as determined by a saturation magnetization measurement. This "first high-strength steel sheet" is for reference only. The first high-strength steel sheet satisfactorily has a tensile strength of 780 MPa or more.

[0016] The first high-strength steel sheet, when martensite-austenite constituents including both as-quenched martensite and retained austenite are found upon observation at a cross-section of the metal structure with an optical microscope, martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm are present in a number percentage of from 0% to less than 15% of a total number of the entire martensite-austenite constituents at the observed cross-section.

[0017] Grains of the polygonal ferrite preferably have an average equivalent circle diameter D of from greater than 0 μm to 10 μm .

[0018] The first high-strength steel sheet may further contain one or more elements selected typically from:

- (a) Cr in a content of from greater than 0% to 1% and/or Mo in a content of from greater than 0% to 1%;
- (b) at least one element selected from the group consisting of Ti in a content of from greater than 0% to 0.15%, Nb in a content of from greater than 0% to 0.15%, and V in a content of from greater than 0% to 0.15%;
- (c) Cu in a content of from greater than 0% to 1% and/or Ni in a content of from greater than 0% to 1%;
- (d) B in a content of from greater than 0% to 0.005%; and
- (e) at least one element selected from the group consisting of Ca in a content of from greater than 0% to 0.01%, Mg in a content of from greater than 0% to 0.01%, and a rare-earth element in a content of from greater than 0% to 0.01%.

[0019] Reference is made to a high-strength hot-dip galvanized steel sheet including the first high-strength steel sheet and, on a surface thereof, a hot-dip galvanized layer; and a high-strength hot-dip galvanized steel sheet including the first high-strength steel sheet and, on a surface thereof, a hot-dip galvanized layer.

[0020] The first high-strength steel sheet may be manufactured by a method including the steps of heating a steel sheet to a temperature range of from $[(Ac_1 \text{ point} + Ac_3 \text{ point})/2] + 20^\circ\text{C}$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$; holding the steel sheet in the temperature range for 50 seconds or longer; cooling the steel sheet down to an arbitrary temperature T at an average cooling rate of 2°C or above per second, the temperature T falling within a range specified by Expression (1); holding the steel sheet in the temperature range (temperature range T1) specified by Expression (1) for 10 to 100 seconds; and holding the steel sheet in a temperature range (temperature range T2) specified by Expression (2) for 200 seconds or longer, in this order, Expressions (1) and (2) expressed as follows:

$$400^\circ\text{C} \leq T1 (^\circ\text{C}) \leq 540^\circ\text{C} \quad (1)$$

$$200^\circ\text{C} \leq T2 (^\circ\text{C}) < 400^\circ\text{C} \quad (2)$$

[0021] The present invention, as having achieved the objects, further provides, in a second embodiment, a high-strength steel sheet. This high-strength steel sheet contains: C in a content of from 0.10% to 0.3%; Si in a content of from 1.0% to 3%; Mn in a content of from 1.0% to 2.5%; Al in a content of from 0.005% to 3%; P in a content controlled to 0.1% or less; and S in a content controlled to 0.05% or less, in mass percent, with the remainder consisting of iron and inevitable impurities. The steel sheet has a metal structure including polygonal ferrite, bainite, tempered martensite, and retained austenite. (1) When the metal structure is observed with a scanning electron microscope, (1a) the polygonal ferrite is present in an area percentage "a" of greater than 50% of the entire metal structure; and (1b) the bainite has a composite microstructure including: a high-temperature-formed bainite having an average distance between adjacent regions of retained austenite and/or carbide of $1\mu\text{m}$ or more; and a low-temperature-formed bainite having an average distance between adjacent regions of retained austenite and/or carbide of less than $1\mu\text{m}$, the high-temperature-formed bainite is present in an area percentage "b" of from 5% to 40% of the entire metal structure; and the low-temperature-formed bainite and the tempered martensite are present in a total area percentage "c" of from 5% to 40% of the entire metal structure. (2) The retained austenite is present in a volume percentage of 5% or more of the entire metal structure as determined by a saturation magnetization measurement. The high-strength steel sheet according to the second embodiment is hereinafter also referred to as a "second high-strength steel sheet". The second high-strength steel sheet satisfactorily has a tensile strength of 590 MPa or more.

[0022] In a preferred embodiment of the second high-strength steel sheet, when martensite-austenite constituents including both as-quenched martensite and retained austenite are found upon observation at a cross-section of the metal structure with an optical microscope, martensite-austenite constituents each having an equivalent circle diameter "d" of greater than $7\mu\text{m}$ are present in a number percentage of from 0% to less than 15% of a total number of entire martensite-austenite constituents at the observed cross-section.

[0023] Grains of the polygonal ferrite preferably have an average equivalent circle diameter D of from greater than $0\mu\text{m}$ to $10\mu\text{m}$.

[0024] The second high-strength steel sheet may further contain one or more elements selected typically from:

- (a) Cr in a content of from greater than 0% to 1% and/or Mo in a content of from greater than 0% to 1%;
- (b) at least one element selected from the group consisting of Ti in a content of from greater than 0% to 0.15%, Nb in a content of from greater than 0% to 0.15%, and V in a content of from greater than 0% to 0.15%;
- (c) Cu in a content of from greater than 0% to 1% and/or Ni in a content of from greater than 0% to 1%;
- (d) B in a content of from greater than 0% to 0.005%; and
- (e) at least one element selected from the group consisting of Ca in a content of from greater than 0% to 0.01%, Mg in a content of from greater than 0% to 0.01%, and a rare-earth element in a content of from greater than 0% to 0.01%.

[0025] The present invention further includes a high-strength hot-dip galvanized steel sheet including the second high-strength steel sheet and, on a surface thereof, a hot-dip galvanized layer; and a high-strength hot-dip galvanized steel sheet including the second high-strength steel sheet and, on a surface thereof, a hot-dip galvanized layer.

[0026] The second high-strength steel sheet according to the present invention may be manufactured by a method including the steps of: heating a steel sheet to a temperature range of from $[Ac_1 \text{ point} + 20^\circ\text{C}]$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$; holding the steel sheet in the temperature range for 50 seconds or longer; cooling the steel sheet down to an arbitrary temperature

T at an average cooling rate of from 2°C to 50°C per second, the temperature T falling within a range specified by Expression (1); holding the steel sheet in the temperature range specified by Expression (1) for 10 to 100 seconds; and holding the steel sheet in a temperature range specified by Expression (2) for 200 seconds or longer, in this order, Expressions (1) and (2) expressed as follows:

$$400^{\circ}\text{C} \leq T1 (^{\circ}\text{C}) \leq 540^{\circ}\text{C} \quad (1)$$

$$200^{\circ}\text{C} \leq T2 (^{\circ}\text{C}) < 400^{\circ}\text{C} \quad (2)$$

[0027] As used herein the term "X and/or Y" refers to that at least one of X and Y is contained.

Advantageous Effects of Invention

[0028] Reference is made to a first high-strength steel sheet, which has elongation and local formability at satisfactory levels and exhibits superior workability even having a high strength of 780 MPa or more. This is achieved by forming, particularly as bainite, both two different bainitic microstructures, i.e., a high-temperature-formed bainite and a low-temperature-formed bainite, and forming polygonal ferrite in a predetermined amount. The high-temperature-formed bainite and the low-temperature-formed bainite differ from each other in existence form of retained austenite and carbides. The high-temperature-formed bainite is formed at a high temperature in the range of from 400°C to 540°C; whereas the low-temperature-formed bainite is formed at a low temperature in the range of from 200°C to lower than 400°C. Reference is made to a method of manufacturing the first high-strength steel sheet having a strength and workability both at high levels.

[0029] The present invention can further provide a second high-strength steel sheet, which has elongation and local formability at satisfactory levels and exhibits superior workability even having a high strength of 590 MPa or more. This can be achieved by forming polygonal ferrite in an area percentage of greater than 50% of the entire metal structure; and forming, particularly as bainite, both two different bainitic microstructures, i.e., a high-temperature-formed bainite and a low-temperature-formed bainite. The high-temperature-formed bainite and the low-temperature-formed bainite differ from each other in existence form of retained austenite and carbides. The high-temperature-formed bainite is formed at a high temperature in the range of from 400°C to 540°C; whereas the low-temperature-formed bainite is formed at a low temperature in the range of from 200°C to lower than 400°C. The present invention can also provide a method of manufacturing the second high-strength steel sheet having a strength and workability both at high levels.

Brief Description of Drawings

[0030]

[Fig. 1] Fig. 1 is a schematic view illustrating an exemplary average distance between adjacent regions of retained austenite and/or carbide.

[Fig. 2] Figs. 2 are diagrams schematically illustrating how the high-temperature-formed bainite and the low-temperature-formed bainite and a similar microstructure (the low-temperature-formed bainite and tempered martensite) are distributed.

[Fig. 3] Fig. 3 is a schematic view illustrating an exemplary heat pattern in the temperature range T1 and the temperature range T2.

[Fig. 4] Fig. 4 is a graph illustrating a relationship between the elongation (EL) and the tensile strength (TS).

[Fig. 5] Fig. 5 is a graph illustrating a relationship between the elongation (EL) and the tensile strength (TS).

Description of Embodiments

[0031] Initially, a first high-strength steel sheet will be illustrated for reference only.

[0032] The present inventors have made intensive investigations to improve the workability, particularly the elongation, and the local formability of a first high-strength steel sheet having a tensile strength of 780 MPa or more. As a result, they have obtained findings (1) to (5) as follows:

(1) There can be provided a first high-strength steel sheet having a higher elongation and better local formability and exhibiting superior workability by:

allowing the steel sheet to have a metal structure as a mixed microstructure including bainite, polygonal ferrite, retained austenite, and tempered martensite; and, forming, particularly as bainite among these microstructures, two different bainitic microstructures including:

- (1a) a high-temperature-formed bainite having an average center-to-center distance of 1 μm or more, the center-to-center distance being between adjacent retained austenite grains, between adjacent carbide grains, or between a retained austenite grain and an adjacent carbide (these are hereinafter also synthetically referred to as "retained austenite or the like"); and
 (1b) a low-temperature-formed bainite having an average center-to-center distance of the retained austenite or the like of less than 1 μm .

(2) Specifically, the high-temperature-formed bainite contributes to a higher steel sheet elongation; whereas the low-temperature-formed bainite contributes to better steel sheet local formability.

(3) The steel sheet can have a further higher elongation without deterioration in local formability by forming a predetermined amount of polygonal ferrite in the metal structure.

(4) The polygonal ferrite in a predetermined amount can be formed by heating the steel sheet in a ferrite-austenite two-phase temperature range [specifically, in a temperature range of from $\{[(Ac_1 \text{ point} + Ac_3 \text{ point})/2] + 20^\circ\text{C}\}$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$].

(5) To form the two different bainitic microstructures in predetermined amounts, the steel sheet may be, after being heated in the two-phase temperature range, cooled down to an arbitrary temperature T in a temperature range of from 400°C to 540°C (this temperature range is hereinafter also referred to as a "temperature range T1") at an average cooling rate of 2°C or above per second; held in the temperature range T1 for 10 to 100 seconds to form a high-temperature-formed bainite; cooled down to a temperature range of from 200°C to lower than 400°C (this temperature range is hereinafter also referred to as a "temperature range T2"); and held in the temperature range T2 for 200 seconds or longer. The present invention has been made based on these findings.

[0033] Initially, the metal structure that features in the first high-strength steel sheet will be illustrated.

Metal Structure

[0034] The first high-strength steel sheet has a metal structure as a mixed microstructure including bainite, polygonal ferrite, retained austenite, and tempered martensite.

Bainite and Tempered Martensite

[0035] Initially, bainite that features prominently will be illustrated. As used herein the "bainite" also includes bainitic ferrite. The bainite microstructure includes precipitated carbides, whereas the bainitic ferrite microstructure does not include precipitated carbides.

[0036] A feature of the first high-strength steel sheet is that the bainite has a composite microstructure including a high-temperature-formed bainite and a low-temperature-formed bainite having a higher strength than that of the high-temperature-formed bainite. The high-temperature-formed bainite contributes to a higher steel sheet elongation, whereas the low-temperature-formed bainite contributes to better steel sheet local formability. The steel sheet, as including the two different bainitic microstructures, can have a higher elongation while surely having satisfactory local formability exhibit better workability in general. This is probably because the combination of the bainitic microstructures differing in strength level causes nonuniform deformation and thereby increases the work hardenability.

[0037] As used herein the term "high-temperature-formed bainite" refers to a bainitic microstructure that is formed in the temperature range T1 of from 400°C to 540°C during a cooling process after heating to a temperature in the range of from $\{[(Ac_1 \text{ point} + Ac_3 \text{ point})/2] + 20^\circ\text{C}\}$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$ (two-phase temperature range). The high-temperature-formed bainite may be defined as a microstructure having an average distance of the retained austenite or the like of 1 μm or more as determined by subjecting a cross section of the steel sheet to Nital etching and observing the etched cross section with a scanning electron microscope (SEM).

[0038] In contrast, the term "low-temperature-formed bainite" refers to a bainitic microstructure that is formed in the temperature range T2 of from 200°C to lower than 400°C during the cooling process after heating to the two-phase temperature range. The low-temperature-formed bainite may be defined as a microstructure having an average distance of the retained austenite or the like of less than 1 μm as determined by subjecting a cross section of the steel sheet to Nital etching and observing the etched cross section with a scanning electron microscope (SEM).

[0039] As used herein the term "average distance of the retained austenite or the like" refers to an average of center-to-center distances between adjacent retained austenite grains, center-to-center distances between adjacent carbide

grains, and center-to-center distances between a retained austenite grain and an adjacent carbide as measured upon SEM observation of the steel sheet cross-section. The term "center-to-center distance" refers to a distance (spacing) between center positions, which center positions are determined on each retained austenite or each carbide upon measurement on most adjacent regions of retained austenite and/or carbide. Each center position is determined by determining a major axis and a minor axis of the retained austenite or carbide and defining a location where the major axis intersects the minor axis as the center position.

[0040] When the retained austenite or carbide precipitates at lath boundaries, two or more retained austenite grains and/or two or more carbide grains lie in a row to be in an acicular form or plate form. In this case, as illustrated in Fig. 1, the center-to-center distance may be defined not as a distance between adjacent grains of retained austenite and/or carbide but a spacing between one row and another which rows are formed by the retained austenite and/or carbide grains lying in a row in the major axis direction. This spacing is also referred to as a lath-to-lath distance.

[0041] The tempered martensitic microstructure functions similarly to the low-temperature-formed bainite and contributes to better steel sheet local formability. The low-temperature-formed bainite and the tempered martensite are undistinguishable from each other even under SEM observation, and they are herein also synthetically referred to as a "low-temperature-formed bainite or the like".

[0042] The first high-strength steel sheet being improved in workability in general. This is achieved by allowing the steel sheet to have a composite bainitic microstructure including the high-temperature-formed bainite and the low-temperature-formed bainite or the like. Specifically, the high-temperature-formed bainite is softer than the low-temperature-formed bainite or the like and helps the steel sheet to have a higher elongation (EL) to thereby have better workability. In contrast, the low-temperature-formed bainite or the like is present as small grains of carbides and retained austenite, thereby relieves the stress concentration upon deformation, and helps the steel sheet to have a higher stretch flangeability (λ) and/or a higher bendability (R) and to have better local formability. This contributes to better workability. The first high-strength steel sheet includes both the high-temperature-formed bainite and the low-temperature-formed bainite or the like, thereby has better work hardenability and a higher elongation, and exhibits better workability.

[0043] In the present invention, bainitic microstructures are classified as the "high-temperature-formed bainite" and the "the low-temperature-formed bainite or the like" by the differences in the forming temperature range and in the average distance of the retained austenite or the like. This is because the bainitic microstructures are not clearly distinguishable from each other by a general academic structural definition. Typically, lathy bainite and bainitic ferrite are classified as upper bainite and lower bainite by the transformation temperature. However, these microstructures, as well as the martensitic microstructure, are undistinguishable from one another by SEM observation in steels containing Si in a high content of 1.0% or more as in the present invention. This is because carbide precipitation associated with bainitic transformation is suppressed in such steels. According to the present invention, therefore, the bainitic microstructures are classified or distinguished not by the academic structural definition but by the differences in the forming temperature range and in the average distance of the retained austenite or the like.

[0044] The high-temperature-formed bainite and the low-temperature-formed bainite or the like may be distributed in any distribution pattern not limited. For example, both the high-temperature-formed bainite and the low-temperature-formed bainite or the like may be present in each prior austenite grain; or the high-temperature-formed bainite and the low-temperature-formed bainite or the like may be formed in different prior austenite grains from each other (in this case, the high-temperature-formed bainite is present in one prior austenite grain, and the low-temperature-formed bainite or the like is present in another prior austenite grain).

[0045] Figs. 2 schematically illustrate how the high-temperature-formed bainite and the low-temperature-formed bainite or the like are distributed. In Figs. 2, the high-temperature-formed bainite is hatched, and the low-temperature-formed bainite or the like is finely dotted. Fig. 2(a) illustrates the high-temperature-formed bainite and the low-temperature-formed bainite or the like both present in each prior austenite grain. Fig. 2(b) illustrates the high-temperature-formed bainite present in one prior austenite grain, and the low-temperature-formed bainite or the like present in another. The filled circles illustrated in Figs. 2 represent martensite-austenite constituents, which will be described later.

[0046] The high-temperature-formed bainite is present in an area percentage of "a" of the entire metal structure; and the low-temperature-formed bainite or the like (the low-temperature-formed bainite and tempered martensite) is present in a total area percentage of "b" of the entire metal structure. In this case, the area percentages "a" and "b" should each fall within the range of from 10% to 80%. Not an area percentage of the low-temperature-formed bainite, but a total area percentage of the low-temperature-formed bainite and the tempered martensite is specified herein. This is because these microstructures are undistinguishable from each other by SEM observation.

[0047] The area percentage "a" is controlled to the range of from 10% to 80%. The high-temperature-formed bainite, if present in an excessively small amount, may fail to help the steel sheet to have a sufficient elongation and to exhibit better workability. To prevent this, the area percentage "a" is 10% or more, preferably 15% or more, and more preferably 20% or more. However, the high-temperature-formed bainite, if present in an excessively large amount, may fail to exhibit sufficient effects of the combination with the low-temperature-formed bainite or the like. To prevent this, the high-temperature-formed bainite is present in an area percentage "a" of 80% or less, preferably 70% or less, more preferably

60% or less, and furthermore preferably 50% or less.

[0048] The total area percentage "b" is controlled to the range of from 10% to 80%. The low-temperature-formed bainite or the like, if present in an excessively small amount, may fail to help the steel sheet to have sufficient local formability and fail to improve the workability. To prevent this, the total area percentage "b" is 10% or more, preferably 15% or more, and more preferably 20% or more. However, the low-temperature-formed bainite or the like, if present in an excessively large amount, may fail to exhibit sufficient effects of the combination with the high-temperature-formed bainite. To prevent this, the low-temperature-formed bainite or the like is present in an area percentage "b" of 80% or less, preferably 70% or less, more preferably 60% or less, and furthermore preferably 50% or less.

[0049] The area percentage "a" and the total area percentage "b" may be in any relationship with each other, as long as they fall within the above-specified ranges respectively. All embodiments where "a" is larger than "b"; where "a" is smaller than "b"; and where "a" equals "b" are included herein.

[0050] The ratio between the high-temperature-formed bainite and the low-temperature-formed bainite or the like may be determined according to properties required of the steel sheet. Specifically, to further improve the local formability (particularly, the stretch flangeability (λ)) among the steel sheet workability, the ratio of the high-temperature-formed bainite may be minimized, whereas the ratio of the low-temperature-formed bainite or the like may be maximized. To further improve the elongation among the steel sheet workability, the ratio of the high-temperature-formed bainite may be maximized, whereas the ratio of the low-temperature-formed bainite or the like may be minimized. To further increase the steel sheet strength, the ratio of the low-temperature-formed bainite or the like may be maximized, whereas the ratio of the high-temperature-formed bainite may be minimized.

Polygonal Ferrite

[0051] The polygonal ferrite microstructure is softer than bainite, functionally increases the steel sheet elongation, and contributes to better workability. To exhibit these actions, the polygonal ferrite is controlled to be present in an area percentage of 10% or more, preferably 12% or more, and more preferably 15% or more, of the entire metal structure. However, the polygonal ferrite, if present in an excessively large amount, may adversely affect the steel sheet strength. To prevent this, the polygonal ferrite is present in an area percentage of 50% or less, preferably 45% or less, and more preferably 40% or less, of the entire metal structure.

[0052] The polygonal ferrite grains preferably have an average equivalent circle diameter D of from greater than 0 μm to 10 μm . The steel sheet can have a further higher elongation by having a small average equivalent circle diameter D of the polygonal ferrite grains and allowing the polygonal ferrite to be dispersed as smaller grains. While the detailed mechanism thereof remains unclear, this is probably because the polygonal ferrite refinement allows the polygonal ferrite to be dispersed more uniformly in the entire metal structure, thereby impedes nonuniform deformation, and contributes to a further higher elongation. Specifically, the first high-strength steel sheet has a mixed metal structure including the bainite, polygonal ferrite, retained austenite, and tempered martensite. Owing to this, increasing sizes of the polygonal ferrite grains may cause variation in sizes of respective microstructures. Thus, nonuniform deformation may occur to cause local strain concentration, and this may probably impede improvements in workability (particularly, effective improvement in elongation due to polygonal ferrite formation). To prevent this, the polygonal ferrite grains have an average equivalent circle diameter D of preferably 10 μm or less, more preferably 8 μm or less, furthermore preferably 5 μm or less, and particularly preferably 3 μm or less.

[0053] The area percentage and average equivalent circle diameter D of the polygonal ferrite can be measured through SEM observation.

Bainite, Tempered Martensite, and Polygonal Ferrite

[0054] The total (a+b+c) of the area percentages "a", "b", and "c" may be 70% or more of the entire metal structure. The area percentage "a" is an area percentage of the high-temperature-formed bainite. The area percentage "b" is a total area percentage of the low-temperature-formed bainite or the like (the low-temperature-formed bainite and tempered martensite). The area percentage "c" is an area percentage of the polygonal ferrite. The steel sheet, if having a total area percentage (a+b+c) of less than 70%, may have an insufficient elongation. The total area percentage (a+b+c) is more preferably 75% or more and furthermore preferably 80% or more. The upper limit of the total area percentage (a+b+c) may be determined in consideration of the retained austenite volume percentage as determined by a saturation magnetization measurement, and is typically 95%.

Retained Austenite (Retained γ)

[0055] The retained austenite transforms to martensite upon deformation of the steel sheet due to stress as received, effectively accelerates the deformed area to be hardened, and prevents strain concentration. This improves the uniform

deformability and allows the steel sheet to exhibit a high elongation. These effects are generally known as "TRIP effects".

[0056] To exhibit the effects, the steel sheet contains the retained austenite in a volume percentage of 5% or more of the entire metal structure as determined by a saturation magnetization measurement. The retained austenite may be present in a volume percentage of preferably 8% or more, and more preferably 10% or more. However, the retained austenite, if present in an excessively large amount, may cause excessive formation and resulting coarsening of the martensite-austenite constituents and adversely affect the local formability (stretch flangeability and bendability). To prevent this, the upper limit of the retained austenite volume percentage may be about 30% and preferably 25%.

[0057] The retained austenite is predominantly formed between laths in the metal structure, but may be present as blocks as part of the martensite-austenite constituents on lathy microstructure aggregates (e.g., blocks and/or packets) or at the prior austenite grain boundary.

Others

[0058] The first high-strength steel sheet has a metal structure including bainite, polygonal ferrite, retained austenite, and tempered martensite as described above. The metal structure may include these microstructures exclusively, but may further include any of other microstructures within ranges not adversely affecting advantageous effects of the present invention. The other microstructures are exemplified by (a) a martensite-austenite constituent including both as-quenched martensite and retained austenite in combination; and (b) pearlite.

(a) Martensite-austenite Constituent

[0059] The martensite-austenite constituent (MA constituent) is generally known as a composite phase of as-quenched martensite (fresh martensite) and retained austenite and is a microstructure formed so that part of a microstructure, which has been present as untransformed austenite before final cooling, transforms to martensite during the final cooling, and the remainder remains as austenite. The resulting martensite-austenite constituent is a very hard microstructure because carbon is enriched to a high concentration in the microstructure during a heat treatment process (particularly, austempering process) and part of the microstructure transforms to a martensitic microstructure. Because of large difference in hardness from the bainite, the martensite-austenite constituent may readily cause voids as a result of stress concentration thereon during deformation. The martensite-austenite constituent, if present in an excessively large amount, may cause the steel sheet to have insufficient stretch flangeability and/or bendability, resulting in insufficient local formability. The martensite-austenite constituent, if present in an excessively large amount, may readily cause the steel sheet to have an excessively high strength. The martensite-austenite constituent more readily forms with an increasing retained austenite amount and an increasing Si content. The amount of the formed martensite-austenite constituent is preferably minimized.

[0060] The metal structure may include the martensite-austenite constituents in an area percentage of preferably 30% or less, more preferably 25% or less, and furthermore preferably 20% or less, of the entire metal structure upon observation of the metal structure with an optical microscope.

[0061] Martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm may be present in a number percentage of from 0% to less than 15% of the total number of the entire martensite-austenite constituents. Such coarse martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm may adversely affect the local formability. The number percentage of the martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm is more preferably less than 10% and furthermore preferably less than 5% of the total number of the entire martensite-austenite constituents.

[0062] The number percentage of the martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm may be determined under observation of a surface of a cross-section in parallel to the rolling direction with an optical microscope.

[0063] The martensite-austenite constituents are recommended to be minimized in size because it has been experimentally demonstrated that martensite-austenite constituents, when having large grain sizes, may readily cause void formation.

(b) Pearlite

[0064] The metal structure may include the pearlite in an area percentage of 20% or less of the entire metal structure upon SEM observation of the metal structure. The pearlite, if contained in an area percentage of greater than 20%, may cause the steel sheet to have an insufficient elongation, and this may impede improvements in workability. The area percentage of the pearlite is more preferably 15% or less, furthermore preferably 10% or less, and particularly preferably 5% or less of the entire metal structure.

[0065] The metal structure may be determined or measured by procedures as follows.

[0066] The high-temperature-formed bainite, the low-temperature-formed bainite or the like (the low-temperature-formed bainite and tempered martensite), polygonal ferrite, and pearlite may be identified by subjecting a cross-section parallel to the steel sheet rolling direction at a depth of one-fourth the sheet thickness to Nital etching, and observing the etched cross-section with a SEM at a magnification of about 3000 times.

[0067] The high-temperature-formed bainite and the low-temperature-formed bainite or the like are observed mainly as gray microstructures, in which the retained austenite or the like is dispersed in the grains. The retained austenite or the like is observed as a white or pale gray microstructure. Upon SEM observation, the high-temperature-formed bainite and the low-temperature-formed bainite or the like are therefore observed as including the retained austenite and carbides, and the area percentage thereof is calculated as one including the retained austenite or the like. The polygonal ferrite is observed as grains that do not include the retained austenite or the like. The retained austenite or the like, if present, is observed as a white or pale gray microstructure as described above. The pearlite is observed as a layered microstructure including both carbides and ferrite.

[0068] When the steel sheet cross-section is etched with a Nital solution, the carbide and the retained austenite are observed both as white or pale gray microstructures and are undistinguishable from each other. Among them, the carbide (e.g., cementite) tends to precipitate in laths rather than between laths when formed in a lower temperature range. Based on this, the carbide grains, when dispersed with a large spacing, may be considered to be formed in a high temperature range; and, when dispersed with a small spacing, may be considered to be formed in a low temperature range. The retained austenite is generally formed between laths. Such laths have smaller sizes with a decreasing forming temperature of the microstructure. Based on this, the retained austenite microstructures, when dispersed with a large spacing, may be considered to be formed in a high temperature range; and, when dispersed with a small spacing, may be considered to be formed in a low temperature range. The present invention therefore focuses attention on retained austenite or the like, which is observed as a white or pale gray microstructure in an observation view field upon SEM observation of a Nital-etched cross section of the steel sheet. Assume that center-to-center distances of adjacent retained austenite or the like are measured, and the measured distances are averaged to give an average (average center-to-center distance). A microstructure having the average (average distance) of 1 μm or more is defined herein as a high-temperature-formed bainite; whereas a microstructure having the average (average distance) of less than 1 μm is defined as a low-temperature-formed bainite or the like.

[0069] The retained austenite microstructure is unidentifiable by SEM observation, and the volume percentage thereof is determined by a saturation magnetization measurement. The measured volume percentage can be read as an "area percentage" thereof without modification. A detailed measurement principle of the saturation magnetization measurement may be found in "R&D KOBE STEEL ENGINEERING REPORTS, Vol. 52, Sample No. 3, 2002, p. 43-46".

[0070] As has been described above, the volume percentage (area percentage) of the retained austenite is determined by a saturation magnetization measurement, whereas the area percentages of other microstructures such as the high-temperature-formed bainite are measured through SEM observation as including the retained austenite. The total of these area percentages may therefore exceed 100%.

[0071] The martensite-austenite constituents may be observed as white microstructures by subjecting a cross-section parallel to the steel sheet rolling direction at a depth one-fourth the sheet thickness to Nital etching, and observing the etched cross-section with an optical microscope at a magnification of about 1000 times.

[0072] Next, a chemical composition of the first high-strength steel sheet will be illustrated.

Chemical Composition

[0073] The first high-strength steel sheet satisfactorily contains C in a content of from 0.10% to 0.3%; Si in a content of from 1.0% to 3.0%; Mn in a content of from 1.5% to 3%; and Al in a content of from 0.005% to 3% and is controlled to contain P in a content of from greater than 0% to 0.1%; and S in a content of from greater than 0% to 0.05%.

[0074] Carbon (C) element essentially helps the steel sheet to have a higher strength and allows the formation of retained austenite. For this reason, the carbon content is controlled to 0.10% or more, preferably 0.13% or more, and more preferably 0.15% or more. However, carbon, if contained in excess, may cause the steel sheet to have insufficient weldability. To prevent this, the carbon content is controlled to 0.3% or less, preferably 0.25% or less, and more preferably 0.20% or less.

[0075] Silicon (Si) element acts as a solute strengthening element, extremely importantly contributes to a higher strength of the steel sheet, suppresses precipitation of carbides during holding in the after-mentioned temperature range T1 and in the temperature range T2 (during austemper process), and thereby allows effective formation of the retained austenite. For these reasons, the Si content is controlled to 1.0% or more, preferably 1.2% or more, and more preferably 1.3% or more. However, Si, if contained in excess, may impede reverse transformation to the austenite phase during heating/soaking in annealing, and this may cause the steel sheet to have an insufficient strength due to a large amount of residual polygonal ferrite. The excess Si may also cause silicon scales on the steel sheet surface during hot rolling and cause the steel sheet to have poor surface quality. To prevent this, the Si content is controlled to 3.0% or less,

preferably 2.5% or less, and more preferably 2.0% or less.

[0076] Manganese (Mn) element is necessary for obtaining bainite and tempered martensite. The Mn element also effectively functionally stabilizes austenite (γ) to form the retained austenite. To exhibit these actions, the Mn content is controlled to 1.5% or more, preferably 1.8% or more, and more preferably 2.0% or more. However, Mn, if contained in excess, may remarkably impede the formation of the high-temperature-formed bainite. Such excess Mn may also cause deterioration in weldability and in workability due to segregation. To prevent this, the Mn content is controlled to 3% or less, preferably 2.8% or less, and more preferably 2.7% or less.

[0077] Aluminum (Al) element suppresses the precipitation of carbides during the austemper process and contributes to the formation of the retained austenite, as with Si. The Al element also acts as a deoxidizer during a steel-making process. For these reasons, the Al content is controlled to 0.005% or more, preferably 0.01% or more, and more preferably 0.03% or more. However, Al, if contained in excess, may cause the steel sheet to contain excessively large amounts of inclusions to thereby have insufficient ductility. To prevent this, the Al content is controlled to 3% or less, preferably 1.5% or less, more preferably 1% or less, and furthermore preferably 0.5% or less.

[0078] Phosphorus (P) element is an impurity to be inevitably contained in the steel. Phosphorus, if contained in excess, may cause the steel sheet to have insufficient weldability. To prevent this, the phosphorus content is controlled to 0.1% or less, preferably 0.08% or less, and more preferably 0.05% or less. The phosphorus content is desirably minimized, but is industrially hardly reduced to 0%.

[0079] Sulfur (S) element is an impurity to be inevitably contained in the steel and adversely affects the steel sheet weldability as with phosphorus. Sulfur forms sulfide inclusions in the steel sheet, and large amounts of such sulfide inclusions may adversely affect the weldability. To prevent this, the sulfur content is controlled to 0.05% or less, preferably 0.01% or less, and more preferably 0.005% or less. The sulfur content is desirably minimized, but is industrially hardly reduced to 0%.

[0080] The first high-strength steel sheet has a chemical composition within the above-specified ranges, with the remainder consisting of iron and inevitable impurities other than P and S. The inevitable impurities are exemplified by N (nitrogen), O (oxygen), and tramp elements (e.g., Pb, Bi, Sb, and Sn). Of the inevitable impurities, the content of nitrogen is preferably from greater than 0% to 0.01%, and the content of oxygen is preferably from greater than 0% to 0.01%.

[0081] Nitrogen (N) element precipitates as nitrides in the steel sheet and contributes to the steel sheet strengthening. However, nitrogen, if contained in excess, may cause precipitation of nitrides in large amounts and cause the steel sheet to deteriorate in elongation, stretch flangeability, and bendability. To prevent this, the nitrogen content is preferably 0.01% or less, more preferably 0.008% or less, and furthermore preferably 0.005% or less.

[0082] Oxygen (O) element, if contained in excess, may cause deterioration in elongation, stretch flangeability, and bendability. To prevent this, the oxygen content is preferably 0.01% or less, more preferably 0.005% or less, and furthermore preferably 0.003% or less.

[0083] The first high-strength steel sheet may further contain at least one element selected typically from:

- (a) Cr in a content of from greater than 0% to 1% and/or Mo in a content of from greater than 0% to 1%;
- (b) at least one element selected from the group consisting of Ti in a content of from greater than 0% to 0.15%, Nb in a content of from greater than 0% to 0.15%, and V in a content of from greater than 0% to 0.15%;
- (c) Cu in a content of from greater than 0% to 1% and/or Ni in a content of from greater than 0% to 1%;
- (d) B in a content of from greater than 0% to 0.005%; and
- (e) at least one element selected from the group consisting of Ca in a content of from greater than 0% to 0.01%, Mg in a content of from greater than 0% to 0.01%, and a rare-earth element in a content of from greater than 0% to 0.01%.

[0084]

(a) Chromium (Cr) and molybdenum (Mo) elements effectively contribute to the formation of bainite and tempered martensite, as with Mn as mentioned above. Each of these elements may be used alone or in combination. To exhibit these actions effectively, Cr and Mo may be contained separately in a content of preferably 0.1% or more and more preferably 0.2% or more. However, Cr and Mo, if separately contained in a content of more than 1%, may remarkably impede the formation of the high-temperature-formed bainite. Such excessive addition may also cause a higher cost. To prevent these, the Cr and Mo contents are each preferably 1% or less, more preferably 0.8% or less, and furthermore preferably 0.5% or less. A total content of Cr and Mo, when used in combination, is recommended to be 1.5% or less.

(b) Titanium (Ti), niobium (Nb), and vanadium (V) elements form carbides, nitrides, and other precipitates in the steel sheet to strengthen the steel sheet and induce the refinement of prior austenite grains, thus contributing to the refinement of polygonal ferrite grains. To exhibit the actions effectively, Ti, Nb, and V may be contained each in a

content of preferably 0.01% or more and more preferably 0.02% or more. However, these elements, if contained in excess, may cause the precipitation of carbides at grain boundaries and cause the steel sheet to have stretch flangeability and/or bendability at insufficient level. To prevent this, the Ti, Nb, and V contents are each preferably 0.15% or less, more preferably 0.12% or less, and furthermore preferably 0.1% or less. Each of Ti, Nb, and V may

(c) Copper (Cu) and nickel (Ni) elements effectively stabilize austenite to form retained austenite. Each of these elements may be used alone or in combination. To exhibit the actions effectively, Cu and Ni may be contained each in a content of preferably 0.05% or more and more preferably 0.1% or more. However, Cu and Ni, if contained in excess, may adversely affect the hot workability. To prevent this, the Cu and Ni contents are each preferably 1% or less, more preferably 0.8% or less, and furthermore preferably 0.5% or less. Cu, if contained alone in a content of greater than 1%, may cause deterioration in hot workability. A combination use of Cu with Ni, however, suppresses the deterioration in hot workability. In this combination use, Cu may be added in a content of greater than 1%, though resulting in a higher cost.

(d) Boron (B) element effectively contributes to the formation of bainite and tempered martensite, as with Mn, Cr, and Mo. To exhibit the actions effectively, boron may be contained in a content of preferably 0.0005% or more and more preferably 0.001% or more. However, boron, if contained in excess, may form borides in the steel sheet to impair the ductility. Such excessive boron may also remarkably impede the formation of the high-temperature-formed bainite, as with Cr and Mo. To prevent this, boron may be contained in a content of preferably 0.005% or less, more preferably 0.004% or less, and furthermore preferably 0.003% or less.

(e) Calcium (Ca), magnesium (Mg), and rare-earth elements (REMs) functionally allow inclusions to be finely dispersed in the steel sheet. To exhibit the actions effectively, Ca, Mg, and a rare-earth element may be contained each in a content of preferably 0.0005% or more and more preferably 0.001% or more. However, these elements, if contained in excess, may adversely affect the castability and the hot workability, and this may impede steel sheet manufacturing. Such excess elements may also cause deterioration in steel sheet ductility. To prevent this, the contents of Ca, Mg, and rare-earth elements are controlled each to preferably 0.01% or less, more preferably 0.005% or less, and furthermore preferably 0.003% or less.

[0085] As used herein the term "rare-earth element(s)" refers to and includes lanthanoid elements (fifteen elements ranging from La to Lu) as well as Sc (scandium) and Y (yttrium). Of these elements, at least one element selected from the group consisting of La, Ce, and Y is preferred, of which La and/or Ce is more preferred.

[0086] The first high-strength steel sheet has a tensile strength of 780 MPa or more, has local formability and an elongation at satisfactory levels, and exhibits excellent workability. The first high-strength steel sheet is advantageously used as materials for automotive structural parts. The automotive structural parts are exemplified by bumping parts such as front and rear side members and crush boxes; as well as pillars and other reinforcing members (e.g., center-pillar reinforcements); roof rail reinforcing members; side sills, floor members, kick-up parts, and other body-constituting parts; shock absorbing parts such as bumper reinforcing members and door impact beams; and seat parts.

[0087] The first high-strength steel sheet also has good warm workability and is advantageously usable as materials for warm forming. The term "warm working (warm forming)" refers to forming or shaping in a temperature range of from about 50°C to about 500°C.

[0088] The metal structure and the chemical composition of the first high-strength steel sheet have been described above.

[0089] Next, a method capable of manufacturing the first high-strength steel sheet will be illustrated. The first high-strength steel sheet can be manufactured by a method including the steps of heating a steel sheet to a temperature range of from $\{[(Ac_1 \text{ point} + Ac_3 \text{ point})/2] + 20^\circ\text{C}\}$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$ (two-phase temperature range), the steel sheet having a chemical composition within the above specified ranges; holding the steel sheet in the temperature range for 50 seconds or longer; cooling the steel sheet down to an arbitrary temperature T at an average cooling rate of 2°C or above per second, the temperature T falling within the range specified by Expression (1); holding the steel sheet in the temperature range specified by Expression (1) for 10 to 100 seconds; and holding the steel sheet in a temperature range specified by Expression (2) for 200 seconds or longer, in this order. The respective steps will be illustrated in order below. Expressions (1) and (2) are expressed as follows:

$$400^\circ\text{C} \leq T_1 (^\circ\text{C}) \leq 540^\circ\text{C} \quad (1)$$

$$200^\circ\text{C} \leq T_2 (^\circ\text{C}) < 400^\circ\text{C} \quad (2)$$

[0090] Initially, a high-strength steel sheet is prepared by hot-rolling a slab according to a common procedure to give a hot-rolled steel sheet; and cold-rolling the hot-rolled steel sheet. This is prepared as a high-strength steel sheet to be heated to the two-phase temperature range [temperature range of from $\{(Ac_1 \text{ point} + Ac_3 \text{ point})/2\} + 20^\circ\text{C}$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$]. The hot rolling may be performed at a finishing mill delivery temperature of typically 800°C or higher and a coiling temperature of typically 700°C or lower. The cold rolling may be performed to a cold rolling reduction in a range of typically from 10% to 70%.

[0091] The cold-rolled steel sheet obtained through cold rolling is heated to the temperature range of from $\{(Ac_1 \text{ point} + Ac_3 \text{ point})/2\} + 20^\circ\text{C}$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$ and held in the temperature range for 50 seconds or longer for soaking in a continuous annealing line.

[0092] The heating to a temperature falling within the ferrite-austenite two-phase temperature range allows the polygonal ferrite formation in a predetermined amount. Specifically, heating to an excessively high temperature may cause the steel sheet to have a temperature falling within the austenite single-phase range, thereby suppress the formation of polygonal ferrite, and cause the steel sheet to fail to have a higher elongation and better workability. To prevent this, the heating temperature is controlled to $[Ac_3 \text{ point} + 20^\circ\text{C}]$ or lower, preferably $[Ac_3 \text{ point} + 10^\circ\text{C}]$ or lower, and more preferably lower than the Ac_3 point. The steel sheet, when heated to a temperature equal to or higher than the Ac_3 point, has a temperature falling within the austenite single-phase temperature range. However, when heating is performed to a temperature of equal to or lower than $[Ac_3 \text{ point} + 20^\circ\text{C}]$, a small amount of polygonal ferrite can remain even after soaking (holding) for a duration on the order of the soaking time as specified in the present invention. Thus, a predetermined amount of polygonal ferrite can be formed by regulating the average cooling rate after soaking as mentioned later. In contrast, heating performed to a temperature of lower than $\{(Ac_1 \text{ point} + Ac_3 \text{ point})/2\} + 20^\circ\text{C}$ may cause the formation of polygonal ferrite in an excessively large area percentage of more than 50%, and this may inhibit the steel sheet from surely having a desired strength. To prevent this, the heating temperature is controlled to $\{(Ac_1 \text{ point} + Ac_3 \text{ point})/2\} + 20^\circ\text{C}$ or higher, preferably $\{(Ac_1 \text{ point} + Ac_3 \text{ point})/2\} + 30^\circ\text{C}$ or higher, and more preferably $\{(Ac_1 \text{ point} + Ac_3 \text{ point})/2\} + 50^\circ\text{C}$ or higher.

[0093] Soaking in the two-phase temperature range, if performed for a time of shorter than 50 seconds, may fail to heat the steel sheet uniformly, and this may impede the formation of the retained austenite and cause the steel sheet to have an elongation and local formability at insufficient levels and to exhibit unsatisfactory workability. To prevent this, the soaking time is controlled to 50 seconds or longer and preferably 100 seconds or longer. However, soaking, if performed for an excessively long time, may cause the austenite grains to have larger sizes, sequentially cause the polygonal ferrite grains to have larger sizes, and readily cause the steel sheet to have an elongation and local formability at insufficient levels. To prevent this, the soaking time is preferably 500 seconds or shorter and more preferably 450 seconds or shorter.

[0094] The heating of the cold-rolled steel sheet to the two-phase temperature range may be performed at an average heating rate of typically 1°C or above per second.

[0095] The Ac_1 point and the Ac_3 point can be calculated from following Expressions (a) and (b), which are described in "Leslie Tekko Zaiyo Kagaku (in Japanese; translation of "The Physical Metallurgy of Steels" by Leslie)", Maruzen Co., Ltd., May 31, 1985, p. 273. In Expressions (a) and (b), a numerical value in brackets represents the content (in mass percent) of each element. When an element is not contained in the steel sheet, calculation can be performed while making the content of the element be 0% (in mass percent). Expressions (a) and (b) are expressed as follows:

$$Ac_1 (^\circ\text{C}) = 723 - 10.7 \times [\text{Mn}] - 16.9 \times [\text{Ni}] + 29.1 \times [\text{Si}] + 16.9 \times [\text{Cr}] \quad (\text{a})$$

$$Ac_3 (^\circ\text{C}) = 910 - 203 \times [\text{C}]^{1/2} + 44.7 \times [\text{Si}] - 30 \times [\text{Mn}] - 11 \times [\text{Cr}] + 31.5 \times [\text{Mo}] - 20 \times [\text{Cu}] - 15.2 \times [\text{Ni}] + 400 \times [\text{Ti}] + 104 \times [\text{V}] + 700 \times [\text{P}] + 400 \times [\text{Al}] \quad (\text{b})$$

[0096] After being heated to the two-phase temperature range and held in the range for 50 seconds or longer for soaking, the steel sheet is cooled down to an arbitrary temperature T at an average cooling rate of 2°C or above per second. The temperature T falls within a range specified by Expression (1). Thus, the steel sheet is cooled at an average cooling rate at the predetermined level or higher in a temperature range of from the two-phase temperature range down to the arbitrary temperature T falling within the range specified by Expression (1). This allows the formation of polygonal ferrite in a predetermined amount and allows the formation of both the high-temperature-formed bainite and the low-temperature-formed bainite or the like. Cooling in this temperature range, if performed at an average cooling rate of lower than 2°C per second, may cause pearlite transformation to form pearlite in excess, and this may cause the steel sheet to have an insufficient elongation and to exhibit unsatisfactory workability. The average cooling rate in this temperature range is preferably 5°C or above per second, and more preferably 10°C or above per second. The upper limit

of the average cooling rate in this temperature range is not critical, but may be typically about 100°C per second, because cooling, if performed at an excessively high average cooling rate, may impede the temperature control.

[0097] After being cooled down to the arbitrary temperature T falling within the range specified by Expression (1), the steel sheet is held in the temperature range T1 specified by Expression (1) for 10 to 100 seconds, and then held in the temperature range T2 specified by Expression (2) for 200 seconds or longer. Suitable separate controls of the holding times in the temperature range T1 and in the temperature range T2 allow the formation of predetermined amounts of the high-temperature-formed bainite and the low-temperature-formed bainite or the like, respectively. Specifically, holding of the steel sheet in the temperature range T1 for a predetermined time enables the control of the amount of the high-temperature-formed bainite. The austempering process of holding the steel sheet in the temperature range T2 for a predetermined time allows untransformed austenite to transform to the low-temperature-formed bainite or martensite and allows carbon to be enriched in austenite to form retained austenite. This gives a metal structure as specified in the present invention.

[0098] The combination of holding in the temperature range T1 and holding in the temperature range T2 also effectively suppresses the formation of martensite-austenite constituents. A mechanism of this is probably as follows. Si and Al, when added, generally suppress carbide precipitation. This allows the presence of free carbon in the steel and induces a phenomenon during the austempering process, in which the free carbon is enriched in the untransformed austenite along with bainitic transformation. The enrichment of carbon in the untransformed austenite allows the retained austenite to be formed in a large amount.

[0099] The phenomenon, in which carbon is enriched in the untransformed austenite, will be described below. It is known that the amount of enriched carbon is limited to the content indicated by a T_0 curve where free energy of the ferrite and austenite becomes equal, and therefore bainitic transformation also stops. The T_0 curve shifts to the lower carbon content side with an elevating temperature. When an austempering process is performed at a relatively high temperature, bainitic transformation comes to stop at a certain degree even if the process time is made long. At this time, coarse martensite-austenite constituents are formed due to poor stability of the untransformed austenite.

[0100] In consideration of this, the steel sheet is held in the temperature range T2 after being held in the temperature range T1 according to the present invention. This allows carbon to be enriched in a larger content in the untransformed austenite. This also allows the bainitic transformation to proceed more in a low temperature range than in a high temperature range and helps the martensite-austenite constituents to be smaller. Lathy microstructures become smaller in size in the case of holding the steel sheet in the temperature range T2 than in the case of holding the steel sheet in the temperature range T1. This helps the martensite-austenite constituents themselves, even when present, to be finely divided. In addition, the high-temperature-formed bainite has already been formed at the time when holding of the steel sheet in the temperature range T2 starts, because the steel sheet is held in the temperature range T2 after being held in the temperature range T1 for a predetermined time. The high-temperature-formed bainite triggers and accelerates the transformation of the low-temperature-formed bainite in the temperature range T2, and this advantageously effectively shortens the austempering process time.

[0101] The size reduction of the lathy microstructures and resulting size reduction of the martensite-austenite constituents can also be achieved by a simple austempering process of holding a steel sheet at a low temperature. In the simple austempering process, the steel sheet is not held in the temperature range T1 but cooled from the two-phase temperature range directly to an arbitrary temperature falling within the range specified by Expression (2) and held only in the temperature range T2 specified by Expression (2). In this process, however, the high-temperature-formed bainite is little formed, and the lathy microstructure in the matrix have a large dislocation density because the steel sheet is not held in the temperature range T1. The resulting steel sheet has an elongation and local formability at insufficient levels and exhibits poor workability.

[0102] The temperature range T1 specified by Expression (1) herein specifically ranges from 400°C to 540°C. Holding of the steel sheet in the temperature range for a predetermined time allows the high-temperature-formed bainite to be formed. Specifically, holding of the steel sheet, if performed at a temperature of higher than 540°C, may suppress the formation of the high-temperature-formed bainite, but cause excessive formation of polygonal ferrite and formation of pseudo-pearlite. The resulting steel sheet fails to have desired properties. To prevent this, the upper limit of the temperature range T1 is controlled to 540°C, preferably 520°C, and more preferably 500°C. In contrast, holding of the steel sheet, if performed at a temperature of lower than 400°C, may fail to induce the formation of the high-temperature-formed bainite and cause the steel sheet to have an insufficient elongation and to exhibit unsatisfactory workability. To prevent this, the lower limit of the temperature range T1 is controlled to 400°C and preferably 420°C.

[0103] The steel sheet is held in the temperature range T1 for a holding time of from 10 to 100 seconds. The holding, if performed for a holding time of longer than 100 seconds, may cause excessive formation of the high-temperature-formed bainite, and this may impede the formation of a sufficient amount of the low-temperature-formed bainite or the like even when the steel sheet is subsequently held in the temperature range T2 for a predetermined time in a manner described later. This may cause the steel sheet to fail to have a strength and workability both at satisfactory levels. Such long-term holding in the temperature range T1 may also cause excessive enrichment of carbon in the austenite. This

may cause the formation of coarse martensite-austenite constituents even when the austemper process is performed in the temperature range T2 and cause the steel sheet to exhibit poor workability. To prevent this, the holding time is controlled to 100 seconds or shorter, preferably 90 seconds or shorter, and more preferably 80 seconds or shorter. However, holding in the temperature range T1, if performed for an excessively short time, may cause the high-temperature-formed bainite to be formed in a smaller amount. This may cause the steel sheet to have an insufficient elongation and to exhibit unsatisfactory workability. To prevent this, the holding time in the temperature range T1 is controlled to 10 seconds or longer, preferably 15 seconds or longer, more preferably 20 seconds or longer, and furthermore preferably 30 seconds or longer.

[0104] As used herein the term "holding time in the temperature range T1" refers to a time (duration) from the time point when the steel sheet surface temperature reaches the upper limit temperature of the temperature range T1 to the time point when the steel sheet surface temperature reaches the lower limit temperature of the temperature range T1. Specifically, the term refers to a time from the time point when steel sheet surface temperature reaches 540°C to the time point when it reaches 400°C.

[0105] To hold the steel sheet in the temperature range T1 specified by Expression (1), any of heat patterns (i), (ii), and (iii) illustrated in Fig. 3 may be employed.

[0106] The heat pattern (i) in Fig. 3 is an embodiment, in which the steel sheet is rapidly cooled from the two-phase temperature range down to an arbitrary temperature T falling within the range specified by Expression (1) and is then isothermally held at the temperature T for a predetermined time. After being isothermally held, the steel sheet is cooled down to an arbitrary temperature falling within the range specified by Expression (2). The heat pattern (i) in Fig. 3 illustrates a one-stage isothermal holding. Isothermal holding, however, is not limited to this, and an isothermal holding in two or more stages at different holding temperatures may also be performed, as long as the steel sheet surface temperature fall within the temperature range T1.

[0107] The heat pattern (ii) in Fig. 3 is an embodiment, in which the steel sheet is rapidly cooled from the two-phase temperature range down to an arbitrary temperature T falling within the range specified by Expression (1), then cooled in the temperature range T1 at a changed cooling rate over a predetermined time, and cooled down to an arbitrary temperature falling within the range specified by Expression (2) at a further changed cooling rate. The heat pattern (ii) in Fig. 3 illustrates an embodiment where the steel sheet is cooled in the temperature range T1 over a predetermined time. The heat pattern in the present invention is not limited to this, and the process may further include the step of heating over a predetermined time or may further include the step of suitably repeating cooling and heating, as long as the steel sheet surface temperature fall within the temperature range T1. Instead of a one-stage cooling as in the heat pattern (ii) in Fig. 3, a multistage cooling, in which cooling is performed in two or more stages at different cooling rates, may be employed. A one-stage heating or a multistage heating (two or more stages) may also be performed (not shown).

[0108] The heat pattern (iii) in Fig. 3 is an embodiment, in which the steel sheet is rapidly cooled from the two-phase temperature range down to an arbitrary temperature T falling within the range specified by Expression (1) and is then slowly cooled down to an arbitrary temperature falling within the range specified by Expression (2) at a changed but constant cooling rate. Even such slow cooling is accepted herein, as long as the residence time of the steel sheet within the temperature range T1 be from 10 to 100 seconds.

[0109] The present invention is not limited to the heat patterns (i) to (iii) illustrated in Fig. 3, but can also employ any of other heat patterns than above, as long as the conditions specified herein be satisfied.

[0110] The temperature range T2 herein specified by Expression (2) is specifically from 200°C to lower than 400°C. Holding the steel sheet in the temperature range for a predetermined time allows the untransformed austenite, which has not transformed in the temperature range T1, to transform to the low-temperature-formed bainite, or martensite. The holding performed for such a sufficient holding time allows the bainitic transformation to proceed, gives the retained austenite finally, and allows the martensite-austenite constituents to be finer. The martensite is present as as-quenched martensite immediately after transformation, but is tempered during holding in the temperature range T2, and remains as tempered martensite. The tempered martensite has properties similar to those of the low-temperature-formed bainite that is formed in such a temperature range where martensitic transformation occurs. However, holding at a temperature of 400°C or higher may cause the formation of coarse martensite-austenite constituents, and this may cause the steel sheet to have an elongation and local formability at insufficient levels and to fail to exhibit better workability. To prevent this, the temperature range T2 is set to lower than 400°C, preferably 390°C or lower, and more preferably 380°C or lower. In contrast, holding at a temperature lower than 200°C may impede the formation of the low-temperature-formed bainite, and this may invite a low carbon content in the austenite, an insufficient amount of the retained austenite, and a larger amount of as-quenched martensite. The resulting steel sheet may thereby have an excessively high strength and have an insufficient elongation and poor local formability. The steel sheet may also fail to have a higher elongation due to the low carbon content in the austenite and the insufficient amount of the retained austenite. To prevent these, the lower limit of the temperature range T2 is controlled to 200°C, preferably 250°C, and more preferably 280°C.

[0111] The steel sheet is held in the temperature range T2 specified by Expression (2) for a time of 200 seconds or longer. The holding, if performed for a time of shorter than 200 seconds, may cause the low-temperature-formed bainite

or the like to be formed in an insufficient amount, and this may invite a low carbon content in the austenite, an insufficient amount of the retained austenite, and a larger amount of the as-quenched martensite. The resulting steel sheet may thereby have an excessively high strength and have an insufficient elongation and poor local formability. The steel sheet may fail to have a higher elongation due to the low carbon content in the austenite and the insufficient amount of the retained austenite. The steel sheet may fail to have better local formability because the martensite-austenite constituents formed in the temperature range T1 are not refined (not become smaller). To prevent these, the holding time is controlled to 200 seconds or longer, preferably 250 seconds or longer, and more preferably 300 seconds or longer. Though the upper limit of the holding time is not critical, holding, if performed for an excessively long time, may induce poor productivity and cause the enriched carbon to precipitate as carbides. This may impede the formation of retained austenite and cause the steel sheet to have a low elongation and poor workability. To prevent these, the upper limit of the holding time may be set typically to 1800 seconds.

[0112] As used herein the term "holding time in the temperature range T2" refers to a time (duration) from the time point at which the steel sheet surface temperature reaches the upper limit temperature of the temperature range T2 to the time point at which the steel sheet surface temperature reaches the lower limit temperature of the temperature range T2. Specifically, the term refers to a time from the time point at which the surface temperature reaches lower than 400°C to the time point at which it reaches 200°C.

[0113] A way to hold the steel sheet in the temperature range T2 is not limited, as long as the residence time of the steel sheet in the temperature range T2 be 200 seconds or longer. As in the heat patterns in the temperature range T1, the steel sheet may be isothermally held (held at a constant temperature), or may be cooled and/or heated within the temperature range T2. A multistage holding at different holding temperatures may also be employed.

[0114] After being held in the temperature range T2 for a predetermined time, the steel sheet is cooled down to room temperature and yields a first high-strength steel sheet.

[0115] The first high-strength steel sheet may bear a hot-dip galvanized layer or a hot-dip galvanized layer on a surface thereof.

[0116] The hot-dip galvanized layer or the hot-dip galvanized layer may be formed under any conditions not limited, such as known conditions.

[0117] Typically, the hot-dip galvanized layer may be formed at a plating bath temperature of preferably from 400°C to 500°C and more preferably from 440°C to 470°C. The plating bath may have any chemical composition not limited, and a known hot-dip galvanization bath can be employed.

[0118] A hot-dip galvanized steel sheet may be manufactured by subjecting a hot-dip galvanized steel sheet bearing a hot-dip galvanized layer to an alloying treatment according to a common procedure. The alloying treatment may be performed typically by holding the hot-dip galvanized steel sheet at a temperature of typically from about 450°C to about 600°C (particularly preferably from about 480°C to about 570°C) for a duration of from about 5 to about 30 seconds (particularly preferably from about 10 to about 25 seconds). The alloying treatment may be performed typically with a heating furnace, a direct fire, or an infrared heating furnace. The heating process is also not limited and is exemplified by gas heating, induction heater heating (heating with induction heating equipment), or another customary process.

[0119] The technique according to the present invention is advantageously applied particularly to thin steel sheets having a thickness of 3 mm or less.

[0120] The first high-strength steel sheet has been described above.

[0121] Next, a second high-strength steel sheet according to the present invention will be illustrated.

[0122] The present inventors have made intensive investigations to improve the workability, particularly elongation, and local formability of a second high-strength steel sheet having a tensile strength of 590 MPa or more. As a result, they have obtained findings (1) to (3) as follows:

(1) There can be provided a second high-strength steel sheet having better local formability without deterioration in elongation and exhibiting superior workability by:

allowing the steel sheet to have a metal structure mainly including polygonal ferrite (specifically, including polygonal ferrite in an area percentage of greater than 50% of the entire metal structure) and being a mixed microstructure further including bainite, tempered martensite, and retained austenite, and forming, particularly as bainite, two different microstructures including:

(1a) a high-temperature-formed bainite having an average center-to-center distance of 1 μm or more, the center-to-center distance being between adjacent retained austenite grains, between adjacent carbide grains, or between a retained austenite grain and an adjacent carbide grain (these are hereinafter also synthetically referred to as "retained austenite or the like"); and

(1b) a low-temperature-formed bainite having an average center-to-center distance of the retained austenite or the like of less than 1 μm .

(2) Specifically, the high-temperature-formed bainite contributes to a higher steel sheet elongation; whereas the low-temperature-formed bainite contributes to better steel sheet local formability.

(3) To form the two different bainitic microstructures in predetermined amounts, the steel sheet may be, after being heated in the two-phase temperature range, cooled down to an arbitrary temperature T in a temperature range of from 400°C to 540°C (this temperature range is hereinafter also referred to as a "temperature range T1") at an average cooling rate of 2°C or above per second; held in the temperature range T1 for 10 to 100 seconds to form a high-temperature-formed bainite; cooled down to a temperature range of from 200°C to lower than 400°C (this temperature range is hereinafter also referred to as "temperature range T2"); and held in the temperature range T2 for 200 seconds or longer. The present invention has been made based on these findings.

[0123] Initially, the metal structure that features in the second high-strength steel sheet according to the present invention will be illustrated.

Metal Structure

[0124] The second high-strength steel sheet according to the present invention has a metal structure as a mixed microstructure including polygonal ferrite, bainite, tempered martensite, and retained austenite.

Polygonal Ferrite

[0125] The second high-strength steel sheet according to the present invention has a metal structure mainly including polygonal ferrite. The term "mainly including" refers to that polygonal ferrite is present in an area percentage of greater than 50% of the entire metal structure. The polygonal ferrite microstructure is softer than bainite and functionally increases the steel sheet elongation to contribute to better workability. To exhibit these actions, the polygonal ferrite is present in an area percentage of greater than 50%, preferably 55% or more, and more preferably 60% or more, of the entire metal structure. The upper limit of the polygonal ferrite area percentage may be determined in consideration of the volume percentage (volume fraction) of the retained austenite as determined by a saturation magnetization measurement, but may for example be 85%.

[0126] Grains of the polygonal ferrite preferably have an average equivalent circle diameter D of from greater than 0 μm to 10 μm . The steel sheet can have a further higher elongation by having a small average equivalent circle diameter D of the polygonal ferrite grains and allowing the polygonal ferrite to be dispersed as smaller grains. While the detailed mechanism thereof remains unclear, this is probably because the polygonal ferrite refinement allows the polygonal ferrite to be dispersed more uniformly in the entire metal structure, this impedes nonuniform deformation and contributes to a further higher elongation. Specifically, the second high-strength steel sheet according to the present invention has a mixed metal structure including the polygonal ferrite, bainite, tempered martensite, and retained austenite. Owing to this, increasing sizes of the polygonal ferrite grains may cause variation in size of respective microstructures. Thus, nonuniform deformation may occur to cause local strain concentration, and this may probably impede improvements in workability (particularly, effective improvement in elongation due to polygonal ferrite formation). To prevent this, the polygonal ferrite grains have an average equivalent circle diameter D of preferably 10 μm or less, more preferably 8 μm or less, furthermore preferably 5 μm or less, and particularly preferably 4 μm or less.

[0127] The area percentage and average equivalent circle diameter D of the polygonal ferrite can be measured through observation with a scanning electron microscope (SEM).

Bainite and Tempered Martensite

[0128] A feature of the second high-strength steel sheet according to the present invention is that the bainite has a composite microstructure including a high-temperature-formed bainite; and a low-temperature-formed bainite having a higher strength than that of the high-temperature-formed bainite. The high-temperature-formed bainite contributes to a higher steel sheet elongation; whereas the low-temperature-formed bainite contributes to better steel sheet local formability. The steel sheet, as including the two different bainitic microstructures, can have better local formability without deterioration in elongation and exhibit better workability in general. This is probably because the combination of the bainitic microstructures differing in strength level causes nonuniform deformation and thereby increases the work hardenability.

[0129] As used herein the term "high-temperature-formed bainite" refers to a bainitic microstructure that is formed in the temperature range T1 of from 400°C to 540°C during a cooling process after heating to a temperature in the range of from $[\text{Ac}_1 \text{ point} + 20^\circ\text{C}]$ to $[\text{Ac}_3 \text{ point} + 20^\circ\text{C}]$ (two-phase temperature range). The high-temperature-formed bainite may be defined as a microstructure having an average distance of the retained austenite or the like of 1 μm or more as determined by subjecting a cross section of the steel sheet to Nital etching and observing the etched cross section with

a SEM.

[0130] In contrast, the term "low-temperature-formed bainite" refers to a bainitic microstructure that is formed in the temperature range T₂ of from 200°C to lower than 400°C during the cooling process after heating to the two-phase temperature range. The low-temperature-formed bainite may be defined as a microstructure having an average distance of the retained austenite or the like of less than 1 μm as determined by subjecting a cross section of the steel sheet to Nital etching and observing the etched cross section with a SEM.

[0131] As used herein the term "average distance of the retained austenite or the like" is defined as in the first high-strength steel sheet.

[0132] The tempered martensitic microstructure functions similarly to the low-temperature-formed bainite and contributes to better steel sheet local formability. The low-temperature-formed bainite and the tempered martensite are undistinguishable from each other even under SEM observation, and they are herein also synthetically referred to as a "low-temperature-formed bainite or the like".

[0133] The present invention can provide a second high-strength steel sheet being improved in general workability as allowing the steel sheet to have a composite bainitic microstructure including the high-temperature-formed bainite and the low-temperature-formed bainite or the like. Specifically, the high-temperature-formed bainite is softer than the low-temperature-formed bainite or the like and contributes to a higher steel sheet elongation (EL) and better workability. In contrast, the low-temperature-formed bainite or the like is present as small grains of carbides and retained austenite, thereby relieves stress concentration upon deformation, and helps the steel sheet to have a higher stretch flangeability (λ) and/or a higher bendability (R) and to have better local formability, resulting in better workability. The second steel sheet according to the present invention includes both the high-temperature-formed bainite and the low-temperature-formed bainite or the like as a mixture, thereby has better work hardenability, and can exhibit better local formability without deterioration in elongation.

[0134] In the present invention, bainitic microstructures are classified as the "high-temperature-formed bainite" and the "the low-temperature-formed bainite or the like" by the differences in the forming temperature range and in the average distance of the retained austenite or the like. This is because the bainitic microstructures are not clearly distinguishable from each other by a general academic structural definition. Typically, lathy bainite and bainitic ferrite are classified as upper bainite and lower bainite by the transformation temperature. However, these microstructures, as well as the martensitic microstructure, are undistinguishable from one another by SEM observation in steels containing Si in a large content of 1.0% or more as in the present invention. This is because carbide precipitation associated with bainitic transformation is suppressed in such steels. According to the present invention, therefore, the bainitic microstructures are classified or distinguished not by the academic structural definition but by the differences in the forming temperature range and in the average distance of the retained austenite or the like.

[0135] The high-temperature-formed bainite and the low-temperature-formed bainite or the like may be distributed in any distribution pattern not limited. For example, both the high-temperature-formed bainite and the low-temperature-formed bainite or the like may be present in each prior austenite grain; or the high-temperature-formed bainite and the low-temperature-formed bainite or the like may be present in different prior austenite grains from each other (in this case, the high-temperature-formed bainite is present in one prior austenite grain, and the low-temperature-formed bainite or the like is present in another prior austenite grain).

[0136] How the high-temperature-formed bainite and the low-temperature-formed bainite or the like are distributed is schematically illustrated in Figs. 2.

[0137] In an embodiment, the high-temperature-formed bainite is present in an area percentage of "b" of the entire metal structure; and that the low-temperature-formed bainite or the like (the low-temperature-formed bainite and the tempered martensite) is present in a total area percentage of "c" of the entire metal structure. In this case, the area percentages "b" and "c" should each fall within the range of from 5% to 40%. Not an area percentage of the low-temperature-formed bainite, but a total area percentage of the low-temperature-formed bainite and the tempered martensite is specified herein. This is because these microstructures are undistinguishable from each other by SEM observation, as described above.

[0138] The area percentage "b" is controlled to the range of from 5% to 40%. The high-temperature-formed bainite, if present in an excessively small amount, may fail to help the steel sheet to have a sufficient elongation and to exhibit better workability. To prevent this, the area percentage "b" is 5% or more, preferably 8% or more, and more preferably 10% or more. However, the high-temperature-formed bainite, if present in an excessively large amount, may be present in an amount with poor balance with respect to the low-temperature-formed bainite or the like and fail to exhibit sufficient effects due to combination between the high-temperature-formed bainite and the low-temperature-formed bainite or the like. To prevent this, the high-temperature-formed bainite is present in an area percentage "b" of 40% or less, preferably 35% or less, more preferably 30% or less, and furthermore preferably 25% or less.

[0139] The total area percentage "c" is controlled to be from 5% to 40%. The low-temperature-formed bainite or the like, if present in an excessively small amount, may cause the steel sheet to have insufficient local formability and to fail to exhibit better workability. To prevent this, the total area percentage "c" is 5% or more, preferably 8% or more, and

more preferably 10% or more. However, the low-temperature-formed bainite or the like, if present in an excessively large amount, may have poor balance in amount with respect to the high-temperature-formed bainite and fail to exhibit sufficient effects of the combination with the high-temperature-formed bainite. To prevent this, the low-temperature-formed bainite or the like is present in an area percentage "c" of 40% or less, preferably 35% or less, more preferably 30% or less, and furthermore preferably 25% or less.

[0140] The area percentage "b" and the total area percentage "c" may be in any relationship with each other, as long as they fall within the above-specified ranges respectively. All embodiments where "b" is larger than "c"; where "b" is smaller than "c"; and where "b" equals "c" are included herein.

[0141] The ratio between the high-temperature-formed bainite and the low-temperature-formed bainite or the like may be determined according to properties required of the steel sheet. Specifically, to further improve the local formability (particularly, stretch flangeability (λ)) among the steel sheet workability, the ratio of the high-temperature-formed bainite may be minimized, whereas the ratio of the low-temperature-formed bainite or the like may be maximized. To further improve the elongation among the steel sheet workability, the ratio of the high-temperature-formed bainite may be maximized, whereas the ratio of the low-temperature-formed bainite or the like may be minimized. To further increase the steel sheet strength, the ratio of the low-temperature-formed bainite or the like may be maximized, whereas the ratio of the high-temperature-formed bainite may be minimized.

[0142] The term "bainite" herein also includes bainitic ferrite. The bainite is a microstructure where a carbide is precipitated; whereas the bainitic ferrite is a microstructure where no carbide is precipitated.

Polygonal Ferrite, Bainite, and Tempered Martensite

[0143] In a preferred embodiment of the present invention, the total (a+b+c) of the area percentages "a", "b", and "c" is 70% or more of the entire metal structure. The area percentage "a" is an area percentage of the polygonal ferrite. The area percentage "b" is an area percentage of the high-temperature-formed bainite. The area percentage "c" is a total area percentage of the low-temperature-formed bainite or the like (the low-temperature-formed bainite and tempered martensite). The steel sheet, if having a total area percentage (a+b+c) of less than 70%, may have an insufficient elongation. The total area percentage (a+b+c) is more preferably 75% or more, and furthermore preferably 80% or more. The upper limit of the total area percentage (a+b+c) may be decided in consideration of the volume percentage of the retained austenite as determined by a saturation magnetization measurement, but may for example be 95%.

Retained Austenite

[0144] The retained austenite is specified herein as in the first high-strength steel sheet, and the explanation thereof is omitted.

Others

[0145] The second high-strength steel sheet according to the present invention has a metal structure including polygonal ferrite, bainite, tempered martensite, and retained austenite as described above. The metal structure may include these microstructures exclusively, but may further include any of other microstructures within ranges not adversely affecting advantageous effects of the present invention. The other microstructures are exemplified by (a) a martensite-austenite constituent including both as-quenched martensite and retained austenite in combination; and (b) pearlite.

[0146] The (a) martensite-austenite constituents and (b) pearlite are specified as in the first high-strength steel sheet, and the explanation thereof is omitted.

[0147] The measurement procedure of the metal structure is as with the procedure illustrated in the first high-strength steel sheet, and the explanation thereof is omitted.

[0148] Next, a chemical composition of the second high-strength steel sheet according to the present invention will be illustrated.

Chemical Composition

[0149] The second high-strength steel sheet according to the present invention satisfactorily contains C in a content of from 0.10% to 0.3%; Si in a content of from 1.0% to 3%; Mn in a content of from 1.0% to 2.5%; and Al in a content of from 0.005% to 3% and is controlled to contain P in a content of from greater than 0% to 0.1%; and S in a content of from greater than 0% to 0.05%. Reasons for specifying these ranges are as in the first high-strength steel sheet, except for Si and Mn. Hereinafter the reasons for specifying the Si and Mn contents alone will be described.

[0150] Silicon (Si) element serves as a solute strengthening element and very importantly contributes to a higher strength of the steel sheet, suppresses carbide precipitation during the holding in the temperature range T1 and the

temperature range T2 (during the austempering process), and allows effective formation of the retained austenite. To exhibit these actions, the Si content is controlled to 1.0% or more, preferably 1.2% or more, and more preferably 1.3% or more. However, Si, if contained in excess, may impede reverse transformation to the austenite phase during heating/soaking in annealing, thereby cause a large amount of the polygonal ferrite to remain, and cause the steel sheet to have an insufficient strength. Such excessive Si may form silicon scales on the steel sheet surface upon hot rolling and cause the steel sheet to have poor surface quality. To prevent these, the Si content is controlled to 3% or less, preferably 2.50% or less, and more preferably 2.0% or less.

[0151] Manganese (Mn) element is necessary for obtaining the bainite and tempered martensite and effectively stabilizes austenite to form the retained austenite. To exhibit these actions, the Mn content is controlled to 1.0% or more, preferably 1.5% or more, and more preferably 1.8% or more. However, Mn, if contained in excess, may significantly impede the formation of the high-temperature-formed bainite and invite deterioration in weldability and in workability due to segregation. To prevent this, the Mn content is controlled to 2.5% or less, preferably 2.4% or less, and more preferably 2.3% or less.

[0152] As with the first high-strength steel sheet, the second high-strength steel sheet according to the present invention may further contain at least one element selected typically from:

- (a) Cr in a content of from greater than 0% to 1% and/or Mo in a content of from greater than 0% to 1%;
- (b) at least one element selected from the group consisting of Ti in a content of from greater than 0% to 0.15%, Nb in a content of from greater than 0% to 0.15%, and V in a content of from greater than 0% to 0.15%;
- (c) Cu in a content of from greater than 0% to 1% and/or Ni in a content of from greater than 0% to 1%;
- (d) B in a content of from greater than 0% to 0.005%;
- (e) at least one element selected from the group consisting of Ca in a content of from greater than 0% to 0.01%, Mg in a content of from greater than 0% to 0.01%, and a rare-earth element in a content of from greater than 0% to 0.01%. Reasons for specifying these ranges are as in the first high-strength steel sheet, and the explanation thereof is omitted here.

[0153] The second high-strength steel sheet according to the present invention has a tensile strength of 590 MPa or more and exhibits superior workability because of having a satisfactory elongation and good local formability. The second high-strength steel sheet is advantageously usable as materials for automotive structural parts, as with the first high-strength steel sheet.

[0154] The second high-strength steel sheet also has good warm workability and is advantageously usable as materials in warm forming. As used herein the term "warm working" (warm forming) refers to forming in a temperature range of from about 50°C to about 500°C.

[0155] The metal structure and the chemical composition of the second high-strength steel sheet according to the present invention have been described above.

[0156] Next, a method capable of manufacturing the second high-strength steel sheet will be illustrated. The second high-strength steel sheet can be manufactured by a method including the steps of heating a steel sheet to a temperature range of from $[Ac_1 \text{ point} + 20^\circ\text{C}]$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$ (two-phase temperature range), the steel sheet having a chemical composition within the above-specified ranges; holding the steel sheet in the temperature range for 50 seconds or longer; cooling the steel sheet down to an arbitrary temperature T at an average cooling rate of from 2°C to 50°C per second, the temperature T falling within a range specified by Expression (1); holding the steel sheet in the temperature range specified by Expression (1) for 10 to 100 seconds; and holding the steel sheet in a temperature range specified by Expression (2) for 200 seconds or longer, in this order. The respective steps will be illustrated in order below. Expressions (1) and (2) are expressed as follows:

$$400^\circ\text{C} \leq T1 (^\circ\text{C}) \leq 540^\circ\text{C} \quad (1)$$

$$200^\circ\text{C} \leq T2 (^\circ\text{C}) < 400^\circ\text{C} \quad (2)$$

[0157] Initially, a high-strength steel sheet is prepared by hot-rolling a slab according to a common procedure to give a hot-rolled steel sheet; and cold-rolling the hot-rolled steel sheet. This is prepared as a high-strength steel sheet to be heated to the two-phase temperature range [temperature range of from $[Ac_1 \text{ point} + 20^\circ\text{C}]$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$]. The hot rolling may be performed at a finishing mill delivery temperature of typically 800°C or higher and a coiling temperature of typically 700°C or lower. The cold rolling may be performed to a cold rolling reduction in the range of typically from 10% to 70%.

[0158] The cold-rolled steel sheet obtained after cold rolling is heated to the temperature range of from $[Ac_1 \text{ point} + 20^\circ\text{C}]$ to $[Ac_3 \text{ point} + 20^\circ\text{C}]$ and held within the temperature range for 50 seconds or longer for soaking in a continuous annealing line.

[0159] The heating to a temperature falling within the ferrite-austenite two-phase temperature range allows the formation of polygonal ferrite in a predetermined amount. Specifically, heating to an excessively high temperature may cause the steel sheet to have a temperature falling within the austenite single-phase range, thereby suppress the formation of polygonal ferrite, and cause the steel sheet to fail to have a higher elongation and better workability. To prevent this, the heating temperature is controlled to $[Ac_3 \text{ point} + 20^\circ\text{C}]$ or lower, preferably $[Ac_3 \text{ point} + 10^\circ\text{C}]$ or lower, and more preferably lower than the Ac_3 point. The steel sheet, when heated to a temperature equal to or higher than the Ac_3 point, has a temperature falling within the austenite single-phase temperature range. However, when heating is performed to a temperature of equal to or lower than $[Ac_3 \text{ point} + 20^\circ\text{C}]$, a small amount of polygonal ferrite can remain even after soaking (holding) for a duration on the order of the soaking time as specified in the present invention. Thus, a predetermined amount of polygonal ferrite can be formed by regulating the average cooling rate after soaking as mentioned later. In contrast, heating, if performed to a temperature of lower than $[Ac_1 \text{ point} + 20^\circ\text{C}]$, may cause the excessive formation of polygonal ferrite. This may cause the steel sheet to fail to contain predetermined amounts of the high-temperature-formed bainite, the low-temperature-formed bainite or the like, and the retained austenite, resulting in insufficient workability. To prevent this, the heating temperature is controlled to $[Ac_1 \text{ point} + 20^\circ\text{C}]$ or higher, preferably $[Ac_1 \text{ point} + 30^\circ\text{C}]$ or higher, and more preferably $[Ac_1 \text{ point} + 50^\circ\text{C}]$ or higher.

[0160] Soaking in the two-phase temperature range, if performed for a time of shorter than 50 seconds, may fail to heat the steel sheet uniformly, and this may impede the formation of the retained austenite and cause the steel sheet to have an elongation and local formability at insufficient levels and to exhibit unsatisfactory workability. To prevent this, the soaking time is controlled to 50 seconds or longer and preferably 100 seconds or longer. However, soaking, if performed for an excessively long time, may cause the austenite grains to have larger sizes, sequentially cause the polygonal ferrite grains to have larger sizes, and readily cause the steel sheet to have elongation and local formability at insufficient levels. To prevent this, the soaking time is preferably 500 seconds or shorter and more preferably 450 seconds or shorter.

[0161] The heating of the cold-rolled steel sheet to the two-phase temperature range may be performed at an average heating rate of typically 1°C or above per second.

[0162] The Ac_1 point and the Ac_3 point can be calculated from Expressions (a) and (b), which are described in "Leslie Tekko Zairyo Kagaku (in Japanese; translation of "The Physical Metallurgy of Steels" by Leslie)", Maruzen Co., Ltd., May 31, 1985, p. 273, as in the first high-strength steel sheet.

[0163] After being heated to the two-phase temperature range and held in the range for 50 seconds or longer for soaking, the steel sheet is cooled down to an arbitrary temperature T at an average cooling rate of from 2°C to 50°C per second. The temperature T falls within the range specified by Expression (1). Thus, the steel sheet is cooled at a predetermined average cooling rate or higher in a temperature range of from the two-phase temperature range down to the arbitrary temperature T falling within the range specified by Expression (1). This allows the formation of a predetermined amount of polygonal ferrite and the formation of both the high-temperature-formed bainite and the low-temperature-formed bainite or the like. Cooling in this temperature range, if performed at an average cooling rate of lower than 2°C per second, may cause pearlite transformation to form pearlite in excess, and this may cause the steel sheet to have an insufficient elongation and to exhibit unsatisfactory workability. The average cooling rate in this temperature range is preferably 5°C or above per second, and more preferably 10°C or above per second. However, cooling in the temperature range, if performed at an excessively high average cooling rate, may impede the formation of a predetermined amount of polygonal ferrite. To prevent this, the average cooling rate is controlled to 50°C or below per second, preferably 40°C or below per second, and more preferably 30°C or below per second.

[0164] After being cooled down to the arbitrary temperature T falling within the range specified by Expression (1), the steel sheet is held in the temperature range T_1 specified by Expression (1) for 10 to 100 seconds; and then held in the temperature range T_2 specified by Expression (2) for 200 seconds or longer. Suitable separate controls of the holding times in the temperature range T_1 and in the temperature range T_2 allow the formation of predetermined amounts of the high-temperature-formed bainite and the low-temperature-formed bainite or the like, respectively.

[0165] Specific conditions for holding in the temperature range T_1 and in the temperature range T_2 are as with the conditions described in the first high-strength steel sheet, and the description thereof is omitted here.

[0166] After being held in the temperature range T_2 for a predetermined time, the steel sheet is cooled down to room temperature and yields a second high-strength steel sheet according to the present invention.

[0167] The first high-strength steel sheet may bear a hot-dip galvanized layer or a hot-dip galvanized layer on a surface thereof, as with the first high-strength steel sheet.

[0168] The hot-dip galvanized layer or the hot-dip galvanized layer may be formed under any conditions not limited, such as known conditions. Specific conditions are as in the first high-strength steel sheet, and the description thereof is omitted here.

[0169] The technique according to the present invention is advantageously applicable particularly to thin steel sheets having a thickness of 3 mm or less.

[0170] The second high-strength steel sheet according to the present invention has been described above.

[0171] The present application is based on Japanese Patent Application No. 2011-080953 filed on March 31, 2011; Japanese Patent Application No. 2011-080954 filed on March 31, 2011; Japanese Patent Application No. 2011-197670 filed on September 9, 2011; and Japanese Patent Application No. 2011-197671 filed on September 9, 2011, the entire contents of which are incorporated herein by reference.

EXAMPLES

[0172] The present invention will be illustrated in further detail with reference to several experimental examples below. It should be noted, however, that the examples are by no means construed to limit the scope of the invention; and various changes and modifications without departing from the spirit and scope of the invention are possible and fall within the scope of the invention. Following Reference Experimental Example 1 is an experimental example relating to the first high-strength steel sheet; and Experimental Example 2 is an experimental example relating to the second high-strength steel sheet.

Reference EXPERIMENTAL EXAMPLE 1

[0173] Experimental slabs were prepared by subjecting steels having chemical compositions given in Tables 1 and 2 below (with the remainder consisting of iron and inevitable impurities other than P, S, N, and O) to vacuum ingot making. The rare-earth elements (REM) in Tables 1 and 2 employed a misch metal containing about 50% of La and about 30% of Ce.

[0174] The Ac_1 points and the Ac_3 points of the steels (slabs) were calculated based on the chemical compositions given in Tables 1 and 2 and on Expression (a) and Expression (b), respectively. The results are indicated in Tables 3 to 5 below.

[0175] The prepared experimental slabs were sequentially subjected to hot rolling, cold rolling, and continuous annealing and yielded specimens. Specific conditions are as follows.

[0176] The experimental slabs were heated to 1250°C and held at this temperature for 30 minutes, hot-rolled to a rolling reduction of about 90% at a finishing mill delivery temperature of 920°C, and cooled from this temperature down to a coiling temperature of 500°C at an average cooling rate of 30°C, and coiled. After being coiled, the works were held at the coiling temperature (500°C) for 30 minutes, then cooled down to room temperature through furnace cooling, and yielded hot-rolled steel sheets having a thickness of 2.6 mm.

[0177] The resulting hot-rolled steel sheets were subjected to acid wash to remove surface scales, cold-rolled to a cold rolling reduction of 46%, and yielded cold-rolled steel sheets having a thickness of 1.4 mm.

[0178] The resulting cold-rolled steel sheets were heated to temperatures (°C) given in Tables 3 to 5, held for durations given in Tables 3 to 5 for soaking, cooled according to any of the following four patterns, subjected to continuous annealing, and yielded the specimens.

Cooling Pattern i: corresponding to the pattern (i) in Fig. 3

[0179] After the soaking, a work was cooled down to a start temperature T (°C) given in Tables 3 to 5 at an average cooling rate (°C per second) given in Tables 3 to 5, held at this start temperature T (°C), then cooled down to a start temperature (°C) in the temperature range T2 given in Tables 3 to 5, and held at this start temperature. Tables 3 to 5 indicate a residence time (second) in the temperature range T1; and a residence time (second) in the temperature range T2. The tables also indicate a time (second) from the time point at which holding in the temperature range T1 was completed to the time point at which the work temperature reached the start temperature in the temperature range T2.

Cooling Pattern ii: corresponding to the pattern (ii) in Fig. 3

[0180] After the soaking, a work was cooled down to a start temperature T (°C) given in Tables 3 to 5 at an average cooling rate (°C per second) given in Tables 3 to 5, subsequently cooled down to an end temperature (°C) given in Tables 3 to 5, cooled down to a start temperature (°C) in the temperature range T2 given in Tables 3 to 5, and held at this start temperature for a duration (second) given in Tables 3 to 5. Tables 3 to 5 indicate a residence time (second) in the temperature range T1; and a residence time (second) in the temperature range T2. The tables also indicate a time (second) from the time point at which holding in the temperature range T1 was completed to the time point at which the work temperature reached the start temperature in the temperature range T2.

Cooling Pattern iii: corresponding to the pattern (iii) in Fig. 3

[0181] After the soaking, a work was cooled down to a start temperature T (°C) given in Tables 3 and 4 at an average cooling rate (°C per second) given in Tables 3 and 4, then cooled down to a start temperature (°C) in the temperature range T2 given in Tables 3 and 4, and held at this start temperature. Tables 3 and 4 indicate a residence time (second) in the temperature range T1; and a residence time (second) in the temperature range T2.

Cooling Pattern iv

[0182] After the soaking, a work was cooled down to a start temperature (°C) in the temperature range T1 or to a start temperature (°C) in the temperature range T2, each as given in Table 3, and held at the start temperature in question. Specifically, Sample No. 8 in Table 3 was a sample, in which the work after the soaking was held at 420°C for 450 seconds and then cooled down to room temperature at an average cooling rate of 5°C per second without holding (without stopping). The residence time in the temperature range T2 of this sample indicated in Table 3 refers to a time necessary to pass through the temperature range T2. Sample No. 15 in Table 3 was a sample, in which the work after the soaking was held at 380°C for 450 seconds and then cooled down to room temperature at an average cooling rate of 5°C per second without holding (without stopping). The residence time in the temperature range T1 of this sample indicated in Table 3 refers to a time necessary to pass through the temperature range T1. Table 3 also indicates a residence time in the temperature range T1 (second) and a residence time in the temperature range T2 (second).

[0183] Of the start temperatures and the end temperatures in the temperature range T1; and of the start temperatures in the temperature range T2 given in Tables 3 to 5, each of the asterisked values was out of the temperature range T1 or the temperature range T2 as specified in the present invention, but was indicated as a temperature in each column for convenience of explanation of the heat pattern.

[0184] The prepared specimens were subjected to metal structure observation and mechanical properties evaluation according to the following procedures.

Metal Structure Observation

[0185] Of the metal structure, area percentages of the high-temperature-formed bainite, the low-temperature-formed bainite or the like (namely, the low-temperature-formed bainite and the tempered martensite), and the polygonal ferrite were calculated based on an observation with a scanning electron microscope (SEM); whereas a volume percentage of the retained austenite was determined by a saturation magnetization measurement.

(1) Area Percentages of High-temperature-formed Bainite, Low-temperature-formed Bainite and the Like, and Polygonal Ferrite

[0186] To determine these area percentages, a specimen cross section parallel to the rolling direction was surface-polished, further electropolished, etched with a Nital solution, and a position at a one-fourth depth the sheet thickness was observed in five view fields with a SEM at a 3000-fold magnification. One view field to be observed had a size of about 50 μm long by about 50 μm wide.

[0187] Next, average distances of retained austenite and carbide observed as white or pale gray microstructures in the observation view fields were measured according to the method mentioned above. a high-temperature-formed bainite and a low-temperature-formed bainite or the like were distinguished from each other by the average distance, whose area percentages were measured by point counting.

[0188] Tables 6 to 8 indicate an area percentage "a" (%) of the high-temperature-formed bainite, a total area percentage "b" (%) of the low-temperature-formed bainite and tempered martensite, and an area percentage "c" (%) of the polygonal ferrite. The tables also indicate a total area percentage (a+b+c) of the area percentage "a", the total area percentage "b", and the area percentage "c".

[0189] Equivalent circle diameters of polygonal ferrite grains observed in the observation view fields were measured and averaged. The results are indicated in Tables 6 to 8. In addition, a sample having an average equivalent circle diameter D of polygonal ferrite grains of 10 μm or less was evaluated as "○" (good), and one having an average equivalent circle diameter of greater than 10 μm was evaluated as "△" (fair). The evaluation results are indicated in Tables 6 to 8.

(2) Retained Austenite Volume Percentage

[0190] Of the metal structure, a volume percentage of the retained austenite was determined by a saturation magnetization measurement. Specifically, a saturation magnetization (I) of a specimen and a saturation magnetization (Is) of a standard specimen were measured, based on which a volume percentage (V_{γr}) of the retained austenite was determined

according to an expression below. The standard specimen had been subjected to a heat treatment at 400°C for 15 hours. The saturation magnetization measurement was performed at room temperature with a DC magnetization B-H curve automatic recorder "Model BHS-40" supplied by Riken Denshi Co., Ltd. with a maximum applied magnetization of 5000 (Oe). The expression is expressed as follows:

$$V_{Yr} = (1 - I/I_s) \times 100$$

[0191] Equivalent circle diameters "d" of martensite-austenite constituents including both retained austenite and as-quenched martensite in combination were measured by polishing a surface of a specimen cross section parallel to the rolling direction, and observing the polished surface in five view fields with an optical microscope at a 1000-fold magnification. A number percentage of martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm with respect to the total number of the entire martensite-austenite constituents in the observed cross-section was calculated. A specimen having a number percentage of less than 15% was evaluated as accepted (○), whereas a specimen having a number percentage of 15% or more was evaluated as rejected (×). The evaluation results are indicated in Tables 6 to 8.

Mechanical Properties Evaluation

[0192] Mechanical properties of each specimen were evaluated based on the tensile strength (TS), elongation (EL), bore expansion ratio (λ), critical bending radius (R), and Erichsen value.

[0193]

(1) The tensile strength (TS) and elongation (EL) were measured through a tensile test according to Japanese Industrial Standard (JIS) Z2241. As a test specimen, a JIS Z 2201 No. 5 test specimen was cut from the specimen so that a direction perpendicular to the specimen rolling direction be a longitudinal direction of the test specimen. The measurement results are indicated in Tables 6 to 8.

(2) Stretch flangeability was evaluated based on the bore expansion ratio. The bore expansion ratio (λ) was measured through a bore expanding test according to the Japan Iron and Steel Federation Standard (JFS) T1001. The measurement results are indicated in Tables 6 to 8.

(3) The critical bending radius (R) was measured through a V-bending test according to JIS Z 2248. As a test specimen, a JIS Z 2204 No. 1 test specimen (thickness: 1.4 mm) was cut from the specimen so that a direction perpendicular to the specimen rolling direction be a longitudinal direction of the test specimen (i.e., so that the bend line agree with the rolling direction). The V-bending test was performed after applying mechanical grinding to a longitudinal end face of the test specimen so as to prevent cracking.

The V-bending test was performed at an angle between a die and a punch of 90° and at a punch tip radius varying in units of 0.5 mm. A minimum punch tip radius at which the test specimen can be bent without cracking was determined as the critical bending radius (R). The measurement results are indicated in Tables 6 to 8. The presence/absence of cracking was observed with a magnifying glass, and a test specimen without the occurrence of hair crack was evaluated as suffering from no cracking.

(4) The Erichsen value was measured through an Erichsen test according to JIS Z 2247. A test specimen of a size of 90 mm long by 90 mm wide by 1.4 mm thick was prepared by cutting from the specimen. The Erichsen test was performed with a device having a punch diameter of 20 mm. The measurement results are indicated in Tables 6 to 8. The Erichsen test enables evaluations of both the total elongation properties and the local ductility of the steel sheet.

[0194] The mechanical properties of the specimen were evaluated based on criteria for the elongation (EL), bore expansion ratio (λ), critical bending radius (R), and Erichsen value varying depending on the tensile strength (TS). Specifically, required properties including EL, λ, R, and Erichsen value vary depending on the steel sheet tensile strength TS. Accordingly, the mechanical properties were evaluated in accordance with the following criteria that vary depending on the TS level.

[0195] Based on the criteria, a sample evaluated as satisfactory all in the properties of EL, λ, R, and Erichsen value were evaluated as accepted (○), whereas one evaluated as not satisfying the criteria in one or more of the properties was evaluated as rejected (×). The evaluation results are indicated in Tables 6 to 8.

(1) TS of 780 MPa grade

[0196]

TS: from 780 MPa to less than 980 MPa
 EL: 25% or more
 λ : 30% or more
 R: 1.0 mm or less
 Erichsen value: 10.4 mm or more

(2) TS of 980 MPa grade

[0197]

TS: from 980 MPa to less than 1180 MPa
 EL: 19% or more
 λ : 20% or more
 R: 3.0 mm or less
 Erichsen value: 10.0 mm or more

(3) TS of 1180 MPa grade

[0198]

TS: from 1180 MPa to less than 1270 MPa
 EL: 15% or more
 λ : 20% or more
 R: 4.5 mm or less
 Erichsen value: 9.6 mm or more

(4) TS of 1270 MPa grade

[0199]

TS: from 1270 MPa to less than 1370 MPa
 EL: 14% or more
 λ : 20% or more
 R: 5.5 mm or less
 Erichsen value: 9.4 mm or more

[0200] The first high-strength steel sheet is designed to be applied to steel sheets having a tensile strength TS of from 780 MPa to less than 1370 MPa. Samples having a tensile strength TS of less than 780 MPa, or of 1370 MPa or more were ineligible herein even when being satisfactory in EL, λ , R, and Erichsen value.

[0201] Tables 1 to 8 demonstrate as follows. Of Samples Nos. 1 to 70 indicated in Tables 6 to 8, Samples Nos. 4, 29, 31, 38, 55, 65, and 67 underwent cooling in Pattern i; Samples Nos. 7, 11, 14, and 33 underwent cooling in Pattern iii; Samples Nos. 8 and 15 underwent cooling in Pattern iv; and the other samples underwent cooling in Pattern ii.

[0202] Samples evaluated as "○" in the assessment (general evaluation) in Tables 6 to 8 were steel sheets satisfying the conditions specified in the present application and satisfying criteria values of the mechanical properties (EL, λ , R, and Erichsen value) determined according to the tensile strength TS. This demonstrates that high-strength steel sheets exhibited good workability in general.

[0203] By contrast, samples evaluated as "×" in the assessment (Samples Nos. 8, 13, 15, 29, 31, 34, 37, 41, 46, 48, 52, and 60 to 63 in Tables 6 to 8) were steel sheets not satisfying one or more of the conditions specified in the present application. Details thereof are as follows.

[0204] Sample No. 8 in Table 6 underwent holding in the temperature range T1 for an excessively long time and subsequent cooling without holding in the temperature range T2. This sample suffered from insufficient formation of the low-temperature-formed bainite or the like and heavy formation of coarse martensite-austenite constituents. The sample thereby had a low bore expansion ratio λ and failed to exhibit better workability. Sample No. 13 in Table 6 underwent, after being heated to and held in the two-phase temperature range, cooling down to an arbitrary temperature T falling within the range specified by Expression (1) at an excessively low average cooling rate. This sample suffered from pearlite transformation, failed to include a sufficient amount of retained austenite, had an insufficient elongation, and failed to exhibit better workability. Sample No. 15 in Table 6 underwent cooling down to the temperature range T2 after soaking without holding in the temperature range T1 (without stopping), and holding in the temperature range T2. This

sample suffered from little formation of the high-temperature-formed bainite because of being held only in the temperature range T2, had a low elongation and poor local formability (Erichsen value), and failed to exhibit better workability. Sample No. 29 in Table 6 underwent, after soaking, cooling down to the temperature range T2 without holding in the temperature range T1 (without stopping), and holding at two different temperatures in the temperature range T2. This sample suffered from little formation of the high-temperature-formed bainite because of being held only in the temperature range T2, had a low elongation, and failed to exhibit better workability.

[0205] Sample No. 31 in Table 6 underwent holding in the temperature range T1 for an excessively short time. This sample suffered from formation of an excessively small amount of the high-temperature-formed bainite, thereby had a low elongation, and failed to exhibit better workability. Sample No. 34 in Table 7 underwent holding in the temperature range T1 for an excessively long time without holding in the temperature range T2. This sample suffered from insufficient formation of the low-temperature-formed bainite or the like and heavy formation of coarse martensite-austenite constituents. The sample thereby had a low Erichsen value and poor local formability and failed to exhibit better workability. Sample No. 37 in Table 7 underwent heating at an excessively high temperature. This sample suffered from no formation of polygonal ferrite, had a low elongation, and failed to exhibit better steel sheet workability. Sample No. 41 in Table 7 underwent heating at an excessively low temperature, suffered from excessive formation of polygonal ferrite, and had an insufficient strength.

[0206] Sample No. 46 in Table 7 underwent holding in the two-phase temperature range for an excessively short time and suffered from insufficient formation of the retained austenite. This sample had a low elongation and a low Erichsen value to exhibit poor local formability, and failed to exhibit better steel sheet workability. Sample No. 48 in Table 7 underwent, after soaking, holding at a temperature higher than the temperature range T1 specified in the present invention, subsequently cooling down to the temperature range T2 without holding in the temperature range T1, and holding in the temperature range T2. This sample suffered from excessive formation of polygonal ferrite, insufficient formation of the high-temperature-formed bainite, thereby had a low elongation, and failed to exhibit better workability. Sample No. 52 in Table 7 underwent, after holding in the temperature range T1, cooling down to a temperature lower than the temperature range T2 without holding in the temperature range T2. This sample suffered from little formation of the low-temperature-formed bainite, included a large amount of coarse martensite-austenite constituents as identified through SEM observation, and include a large amount of as-quenched martensite. The sample thereby had an excessively high strength.

[0207] Sample No. 60 in Table 8 had an excessively low carbon content. This sample suffered from formation of an excessively small amount of the retained austenite, had a low elongation and a low Erichsen value, and failed to exhibit better workability. Sample No. 61 in Table 8 had an excessively high Si content. This sample suffered from excessive formation of polygonal ferrite, suffered from insufficient formation of the high-temperature-formed bainite and the low-temperature-formed bainite or the like, and failed to have a strength surely at a desired level. Sample No. 62 in Table 8 had an excessively low Si content. This sample suffered from insufficient formation of the retained austenite, thereby had a low elongation, and failed to exhibit better workability. Sample No. 63 in Table 8 had an excessively low Mn content and underwent insufficient quenching. This sample suffered from excessive formation of polygonal ferrite, but insufficient formation of the low-temperature-formed bainite or the like during cooling. The sample had a low elongation, a small bore expansion ratio, and a low Erichsen value, and failed to exhibit better workability.

[0208] These results demonstrate that high-strength steel sheets having better workability can be produced.

[0209] Steel sheets having a tensile strength of 980 MPa grade are indicated in Tables 6 and 7. Among them, Samples Nos. 3 to 7, 9 to 12, 14, 16 to 27, 30, 32, 33, 35, 36, 38 to 40, and 42 satisfied the conditions specified in the present application. Relating to these samples, a relationship between the elongation (EL) and the tensile strength (TS) is illustrated in Fig. 4. In Fig. 4, data indicated by the symbol "●" (filled circle) are data of samples having an average equivalent circle diameter D of polygonal ferrite grains of 10 μm or less; and data indicated by the symbol "■" (filled square) are data of samples having an average equivalent circle diameter D of polygonal ferrite grains of greater than 10 μm .

[0210] Fig. 4 demonstrates that steel sheets could have a higher elongation (EL) and exhibit further better workability by controlling the average equivalent circle diameter D of polygonal ferrite grains to 10 μm or less, even when having a tensile strength (TS) at an equivalent level.

[Table 1]

Steel type	Chemical composition (in mass percent)																		
	C	Si	Mn	P	S	Al	Cr	Mo	Ti	Nb	V	Cu	Ni	B	Ca	Mg	REM	N	O
a	0.17	1.41	1.80	0.02	0.002	0.03	-	-	-	-	-	-	-	-	-	-	-	0.002	0.001
b	0.13	1.85	1.65	0.02	0.002	0.04	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
c	0.17	1.78	228	0.03	0.002	0.04	-	-	-	-	-	-	-	-	-	-	-	0.004	0.001
d	0.17	2.18	2.31	0.03	0.001	0.05	-	-	-	-	-	-	-	-	-	-	-	0.004	0.001
e	0.17	1.85	1.89	0.03	0.002	0.03	0.3	-	-	-	-	-	-	-	-	-	-	0.004	0.001
f	0.17	1.82	2.09	0.02	0.001	0.04	-	0.2	-	-	-	-	-	-	-	-	-	0.003	0.001
g	0.17	2.02	2.22	0.02	0.002	0.04	-	-	0.08	-	-	-	-	-	-	-	-	0.005	0.001
h	0.17	1.98	2.21	0.01	0.002	0.03	-	-	0.03	0.04	-	-	-	-	-	-	-	0.003	0.001
i	0.16	2.01	2.26	0.03	0.002	0.05	-	-	0.03	-	0.06	-	-	-	-	-	-	0.004	0.001
j	0.17	1.82	2.01	0.01	0.001	0.03	-	-	-	-	-	0.34	0.38	-	-	-	-	0.002	0.002
k	0.18	1.77	1.95	0.01	0.002	0.05	-	-	0.02	-	-	-	-	0.0022	-	-	-	0.004	0.001
l	0.15	1.95	2.34	0.02	0.002	0.03	-	-	-	-	-	-	-	-	0.0025	0.0013	0.0015	0.004	0.001
m	0.17	2.02	2.05	0.01	0.002	0.03	-	-	-	-	-	-	-	-	0.0035	-	0.0022	0.002	0.001
n	0.24	1.75	2.25	0.02	0.001	0.02	-	-	-	-	-	-	-	-	-	-	-	0.002	0.001
o	0.16	1.35	2.19	0.02	0.001	0.03	-	-	-	-	-	-	-	0.0005	-	-	-	0.003	0.001
p	0.13	2.15	2.50	0.01	0.002	0.03	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
q	0.28	1.15	1.80	0.01	0.002	0.33	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
r	0.12	2.78	2.54	0.02	0.001	0.04	-	-	-	-	-	-	-	-	-	-	-	0.004	0.001
s	0.17	1.38	1.67	0.03	0.001	0.04	0.5	0.2	-	-	-	-	-	-	-	-	-	0.003	0.001
t	0.23	2.31	2.26	0.02	0.002	0.05	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
u	0.25	1.76	2.47	0.02	0.001	0.04	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
v	0.19	2.01	2.63	0.01	0.001	0.03	-	-	0.02	-	-	-	-	-	-	-	-	0.003	0.001
w	0.28	1.55	2.33	0.01	0.002	0.03	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
x	0.17	2.65	2.85	0.02	0.002	0.04	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001

(continued)

Steel type	Chemical composition (in mass percent)																		
	C	Si	Mn	P	S	Al	Cr	Mo	Ti	Nb	V	Cu	Ni	B	Ca	Mg	REM	N	O
y	0.29	1.12	2.73	0.01	0.002	1.02	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
z	0.19	2.02	2.59	0.03	0.001	0.04	0.6	-	0.07	-	-	0.12	0.11	-	-	-	-	0.002	0.001

Chemical composition (in mass percent)

29

[Table 3]

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	$[(Ac_1+Ac_3)/2]+20$ (°C)	Ac ₃ +20 (°C)	Soaking		Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
						Heating temperature (°C)	Holding time (sec)		Start temperature T (°C)	End temperature (°C)		Start temperature (°C)	Temperature range T1	Temperature range T2	
1	a	745	861	823	881	850	70	60	450	420	4	380	29	263	ii
2	b	759	900	850	920	890	200	60	450	420	4	380	29	218	ii
3	c	750	874	832	894	870	200	30	420	400	4	350	29	484	ii
4	c	750	874	832	894	870	200	80	420	420	4	395	30	490	i
5	c	750	874	832	894	870	200	30	450	420	4	350	14	483	ii
6	c	750	874	832	894	870	200	30	450	420	20	380	93	496	ii
7	c	750	874	832	894	870	200	30	480	-	-	380	30	343	iii
8	c	750	874	832	894	870	200	30	420	420	-	-	458	40	iv
9	d	762	895	849	915	880	200	30	450	420	4	350	29	483	ii
10	d	762	895	849	915	890	480	15	450	420	4	350	32	483	ii
11	d	762	895	849	915	880	200	30	450	-	-	380	28	496	iii
12	d	762	895	849	915	880	200	10	450	420	4	350	35	483	ii
13	d	762	895	849	915	880	200	1	450	420	4	350	116	483	ii
14	d	762	895	849	915	880	200	30	450	-	-	390	86	505	iii
15	d	762	895	849	915	880	200	60	-	-	-	380	2	486	iv
16	e	762	883	842	903	880	200	95	450	420	4	350	42	833	ii
17	f	754	882	838	902	870	450	30	450	420	4	350	44	633	ii
18	g	758	912	855	932	900	200	30	450	420	4	350	44	633	ii
19	h	757	876	836	896	860	200	30	450	420	4	350	44	633	ii
20	i	757	910	854	930	900	200	30	450	420	4	350	44	633	ii
21	j	748	854	821	874	830	200	30	450	420	4	350	44	633	ii
22	k	754	879	837	899	870	200	30	450	420	4	350	44	633	ii

(continued)

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	[(Ac ₁ +Ac ₃)/2]+20 (°C)	Ac ₃ +20 (°C)	Soaking		Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
						Heating temperature (°C)	Holding time (sec)		Start temperature T (°C)	End temperature (°C)		Start temperature (°C)	Temperature range T1	Temperature range T2	
23	I	755	874	835	894	860	200	30	450	420	4	350	44	483	ii
24	I	755	874	835	894	860	200	10	480	450	4	350	33	482	ii
25	I	755	874	835	894	860	200	30	450	380※	4	350	32	495	ii
26	I	755	874	835	894	860	200	30	500	480	4	320	28	476	ii
27	I	755	874	835	894	860	200	30	410	400	4	380	29	490	ii
28	I	755	874	835	894	870	200	30	420	400	4	260	19	616	ii
29	I	755	874	835	894	860	200	60	380※	380※	4	230	2	1835	i
30	m	760	874	837	894	860	200	90	450	420	4	350	12	283	ii
31	m	760	874	837	894	860	200	60	420	420	1	350	3	481	i

[Table 4]

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	$[(Ac_1+Ac_3)/2]+2$ (°C)	AC ₃ +20 (°C)	Soaking		Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
						Heating temperature (°C)	Holding time (sec)		Start temperature T (°C)	End temperature (°C)		Start temperature (°C)	Temperature range T1	Temperature range T2	
32	n	750	843	817	863	830	200	30	450	420	4	350	84	483	ii
33	n	750	843	817	863	830	200	15	530	-	-	250	22	484	iii
34	n	750	843	817	863	830	200	30	480	450	4	420 ※	481	40	ii
35	o	739	849	814	869	840	200	30	520	490	4	350	28	481	ii
36	o	739	849	814	869	840	200	30	405	400	4	380	30	640	ii
37	o	739	849	814	869	930	200	90	450	420	4	380	28	638	ii
38	p	759	877	838	897	870	200	15	420	420	4	380	35	488	i
39	q	737	939	858	959	870	200	60	450	420	4	380	29	238	ii
40	r	777	918	867	938	910	460	30	450	420	4	350	29	483	ii
41	r	777	918	867	938	750	200	30	450	420	4	350	29	483	ii
42	s	754	877	835	897	870	200	15	450	420	4	380	53	638	ii
43	t	766	882	844	902	870	200	30	480	450	4	320	29	476	ii
44	t	766	882	844	902	870	200	30	450	420	4	230	28	610	ii
45	t	766	882	844	902	870	200	95	450	420	4	320	27	477	ii
46	t	766	882	844	902	850	20	30	450	420	4	350	29	483	ii
47	u	748	843	815	863	820	200	30	450	420	4	320	29	627	ii
48	u	748	843	815	863	820	200	30	650 ※	620 ※	4	380	4	636	ii
49	v	753	857	825	877	850	200	30	450	420	4	320	49	927	ii
50	v	753	857	825	877	850	200	5	450	420	4	320	64	927	ii
51	v	753	857	825	877	850	200	30	450	420	4	320	94	927	ii
52	v	753	857	825	877	850	200	30	480	250 ※	4	150 ※	23	43	ii
53	w	743	817	800	837	810	200	30	450	420	4	350	29	483	ii

(continued)

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	$[(Ac_1 + Ac_3)/2] + 20$ (°C)	Soaking	Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
							Start temperature T (°C)	End temperature (°C)			Temperature range T1	Temperature range T2	
54	x	770	889	849	Heating temperature (°C) 880	Holding time (sec) 60	480	450	4	320	64	1226	ii
55	x	770	889	849	880	200	420	420	4	320	50	1227	i
56	x	770	889	849	880	200	480	※ 450	4	225	66	1808	ii
57	y	726	1184	975	990	200	450	420	4	320	84	1827	ii
58	z	762	889	845	880	200	480	450	4	350	49	1232	ii

[Table 5]

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	[(Ac ₁ +Ac ₃)/2]+20 (°C)	Ac ₃ +20 (°C)	Soaking		Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
						Heating temperature (°C)	Holding time (sec)		Start temperature (°C)	End temperature (°C)		Start temperature (°C)	Temperature range T1	Temperature range T2	
59	α	764	886	845	906	880	200	30	480	450	4	320	64	1226	ii
60	β	754	899	847	919	890	200	30	450	420	4	380	30	638	ii
61	γ	793	941	887	961	900	200	30	450	420	4	380	30	638	ii
62	δ	712	801	777	821	780	200	30	450	420	4	380	30	638	ii
63	ε	762	891	847	911	880	200	30	450	420	4	380	30	638	ii
64	ζ	753	855	824	875	850	200	30	450	420	4	320	44	927	ii
65	η	755	867	831	887	850	200	30	420	420	4	320	45	927	i
66	ι	754	864	829	884	850	200	30	480	380 ※	4	320	50	940	ii
67	κ	744	852	818	872	850	200	30	450	450	4	320	45	926	i
68	λ	755	875	835	895	860	200	30	450	420	4	320	44	927	ii
69	μ	754	876	835	89G	860	200	30	450	420	4	320	44	927	ii
70	ν	754	856	825	876	840	200	30	450	420	4	320	44	927	ii

[Table 6]

Composite microstructure																
No.	High-temperature-formed bainite "a" (in area percent)		Low-temperature-formed bainite "b" (in area percent)	Polygonal ferrite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number percentage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
						Grain size (μm)	Evaluation									
1	22		30	38	90	3	○	10	○	821	28	33	0.0	10.7	○	780 MPa grade
2	18		27	45	90	4	○	11	○	808	29	31	0.0	10.8	○	780 MPa grade
3	18		35	33	86	5	○	14	○	1012	23	28	1.5	10.4	○	980 MPa grade
4	27		37	15	79	4	○	15	○	997	25	23	2.0	10.5	○	980 MPa grade
5	14		38	34	86	5	○	13	○	1034	22	38	1.0	10.4	○	980 MPa grade
6	34		24	29	87	5	○	15	○	1001	24	27	2.0	10.5	○	980 MPa grade
7	22		33	31	86	4	○	14	○	1023	22	32	1.0	10.5	○	980 MPa grade
8	47		5	33	85	4	○	15	×	1045	21	14	4.0	10.1	×	980 MPa grade
9	20		32	36	88	3	○	14	○	999	25	32	2.0	10.6	○	980 MPa grade
10	19		34	37	90	13	Δ	14	○	983	23	27	2.5	10.3	○	980 MPa grade
11	18		37	35	90	4	○	14	○	1022	23	31	1.5	10.4	○	980 MPa grade
12	13		25	47	85	4	○	15	○	1001	24	27	2.0	10.5	○	980 MPa grade

(continued)

No.	Composite microstructure		Polygonal ferrite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in vol- ume per- cent)	Number percentage of MA con- stituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
	High-temper- ature-formed bainite "a" (in area percent)	Low-temper- ature-formed bainite "b" (in area percent)			Grain size (μm)	Evaluation									
13	0	0	67	67	5	○	0	○	856	17	34	0.0	10.7	×	780 MPa grade
14	27	22	34	83	4	○	16	○	1035	23	28	3.0	10.5	○	980 MPa grade
15	3	51	37	91	4	○	8	○	1072	17	47	3.0	9.8	×	980 MPa grade
16	35	41	14	90	5	○	15	○	986	24	47	0.0	10.6	○	980 MPa grade
17	23	35	27	85	12	△	14	○	1028	21	31	0.5	10.2	○	980 MPa grade
18	19	28	39	86	2	○	14	○	1046	22	28	2.0	10.4	○	980 MPa grade
19	21	23	42	86	3	○	15	○	1055	21	32	1.5	10.3	○	980 MPa grade
20	18	29	40	87	3	○	14	○	1027	23	30	1.5	10.4	○	980 MPa grade
21	20	23	43	86	3	○	16	○	1011	24	35	1.0	10.5	○	980 MPa grade
22	19	24	41	84	2	○	15	○	1012	23	27	2.0	10.4	○	980 MPa grade
23	18	32	39	89	4	○	14	○	1035	23	28	1.5	10.4	○	980 MPa grade
24	14	24	48	86	3	○	15	○	1027	24	26	2.0	10.5	○	980 MPa grade

(continued)

Composite microstructure																	
No.	High-temperature-formed bainite "a" (in area percent)		Low-temperature-formed bainite "b" (in area percent)	Polygonal ferrite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number percentage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks	
			Grain size (μm)			Evaluation											
25	23		26	37	86	4	○	14	○	1003	25	27	1.5	10.6	○	980 MPa grade	
26	24		28	38	90	4	○	15	○	992	25	28	1.5	10.6	○	980 MPa grade	
27	12		37	39	88	4	○	13	○	1024	22	38	0.5	10.4	○	980 MPa grade	
28	26		36	26	88	3	○	14	○	1203	18	32	3.5	10.1	○	1180 MPa grade	
29	5		53	33	91	3	○	9	○	1199	14	54	3.0	9.5	×	1180 MPa grade	
30	21		31	38	90	3	○	15	○	1032	23	32	2.0	10.4	○	980 MPa grade	
31	4		50	36	90	3	○	10	○	1144	13	42	0.5	10.1	×	980 MPa grade	

[Table 7]

No.			Polygonal ferrite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number per-centage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
	High-temperature-formed bainite "a" (in area percent)	Low-temperature-formed bainite "b" (in area percent)	Grain size (μm)	Evaluation											
32	40	17	31	88	4	○	15	○	998	25	26	2.5	10.7	○	980 MPa grade
33	34	15	39	88	4	○	15	○	1056	22	31	2.0	10.4	○	980 MPa grade
34	44	6	32	82	4	○	16	×	1116	19	20	3.0	9.5	×	980 MPa grade
35	38	24	28	90	4	○	15	○	986	24	27	2.5	10.6	○	980 MPa grade
36	26	32	29	87	8	○	14	○	1011	23	26	2.5	10.5	○	980 MPa grade
37	46	45	0	91	-	-	13	○	1025	18	62	0.0	10.3	×	980 MPa grade
38	39	37	12	88	4	○	13	○	985	24	35	1.5	10.5	○	980 MPa grade
39	32	30	25	87	4	○	16	○	1034	24	28	2.0	10.5	○	980 MPa grade
40	21	27	38	86	14	△	14	○	1022	21	34	0.0	10.2	○	980 MPa grade
41	0	0	87	87	22	△	0	○	689	22	34	0.0	10.6	×	-
42	28	37	26	91	5	○	14	○	1032	23	32	0.5	10.4	○	980 MPa grade
43	22	35	33	90	5	○	14	○	1223	17	29	3.0	10.2	○	1180 MPa grade
44	22	41	31	94	4	○	8	○	1295	15	31	4.0	9.8	○	1270 MPa grade

(continued)

No.	High-temperature-formed bainite "a" (in area percent)		Low-temperature-formed bainite "b" (in area percent)	Polygonal ferrite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number per-centage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
	Grain size (μm)	Evaluation														
45	21	41	25	87	3	○	13	○	1236	16	37	2.5	10.1	○		1180MPa grade
46	35	23	41	99	2	○	3	○	989	15	31	3.0	9.7	×		980 MPa grade
47	23	31	38	92	4	○	13	○	1188	18	36	3.0	10.2	○		1180MPa grade
48	4	29	63	96	15	△	8	○	994	16	39	2.5	10.2	×		980 MPa grade
49	26	43	22	91	2	○	12	○	1197	18	32	3.0	10.2	○		1180MPa grade
50	18	37	35	90	2	○	13	○	1191	19	29	3.5	10.3	○		1180MPa grade
51	37	28	24	89	2	○	13	○	1224	17	27	3.5	10.0	○		1180MPa grade
52	31	8	26	65	3	○	7	×	1489	9	16	6.0	9.1	×		-
53	25	32	33	90	4	○	14	○	1192	19	25	4.0	10.2	○		1180MPa grade
54	29	38	24	91	4	○	12	○	1242	16	32	3.5	9.9	○		1180MPa grade
55	16	53	22	91	3	○	10	○	1315	15	34	4.5	9.7	○		1270MPa grade
56	21	48	23	92	4	○	8	○	1336	14	36	4.0	9.8	○		1270MPa grade
57	18	29	47	94	8	○	9	○	1285	14	41	4.0	9.6	○		1270MPa grade

(continued)

No.	High-temperature-formed bainite "a" (in area percent)	Low-temperature-formed bainite "b" (in area percent)	Polygonal ferrite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number per-centage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
					Grain size (μm)	Evaluation									
58	28	41	24	93	3	○	11	○	1228	16	36	2.5	10.1	○	1180MPa grade

[Table 8]

No.	Composite microstructure		Polygonal ferrite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number percentage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
	High-temperature-formed bainite "a" (in area percent)	Low-temperature-formed bainite "b" (in area percent)			Grain size (μm)	Evaluation									
59	26	43	21	90	2	○	11	○	1289	15	32	4.5	9.9	○	1270 MPa grade
60	32	23	42	97	4	○	3	○	812	20	32	0.0	10.2	×	780 MPa grade
61	0	0	97	97	22	△	0	○	756	15	31	0.0	10.4	×	-
62	22	27	48	97	4	○	3	○	854	19	38	0.0	10.2	×	780 MPa grade
63	32	3	53	88	2	○	12	×	877	19	13	0.5	10.0	×	780 MPa-grade
64	28	33	28	89	2	○	13	○	1195	17	27	3.5	10.2	○	1180 MPa grade
65	22	35	32	89	3	○	12	○	1224	17	25	3.0	10.3	○	1180 MPa grade
66	24	33	34	91	5	○	13	○	1182	18	24	3.5	10.4	○	1180 MPa grade
67	27	38	22	87	5	○	14	○	1256	18	29	4.0	10.0	○	1180 MPa grade
68	23	38	28	89	5	○	13	○	1227	17	35	3.5	10.2	○	1180 MPa grade
69	22	35	31	88	5	○	12	○	1216	18	24	3.5	10.4	○	1180 MPa grade
70	25	36	29	90	4	○	13	○	1229	17	31	3.0	10.3	○	1180 MPa grade

EXPERIMENTAL EXAMPLE 2

[0211] Experimental slabs were prepared by subjecting steels having chemical compositions given in Table 9 below (with the remainder consisting of iron and inevitable impurities other than P, S, N, and O) to vacuum ingot making. The rare-earth elements (REM) in Table 9 employed a misch metal containing about 50% of La and about 30% of Ce.

[0212] The Ac_1 points and the Ac_3 points of the steels (slabs) were calculated based on the chemical compositions given in Table 9 and on Expression (a) and Expression (b), respectively. The results are indicated in Tables 10 and 11 below.

[0213] The prepared experimental slabs were sequentially subjected to hot rolling, cold rolling, and continuous annealing and yielded specimens. Specific conditions are as follows.

[0214] The experimental slabs were heated to 1250°C and held at this temperature for 30 minutes, hot-rolled to a rolling reduction of about 90% at a finishing mill delivery temperature of 920°C, and cooled from this temperature down to a coiling temperature of 500°C at an average cooling rate of 30°C per second, and coiled. After being coiled, the works were held at the coiling temperature (500°C) for 30 minutes, cooled down to room temperature through furnace cooling, and yielded hot-rolled steel sheets having a thickness of 2.6 mm.

[0215] The resulting hot-rolled steel sheets were subjected to acid wash to remove surface scales, cold-rolled to a cold rolling reduction of 46%, and yielded cold-rolled steel sheets having a thickness of 1.4 mm.

[0216] The resulting cold-rolled steel sheets were heated to temperatures (°C) given in Tables 10 and 11, held for durations given in Tables 10 and 11 for soaking, cooled according to any of the following four patterns, subjected to continuous annealing, and yielded specimens.

Cooling Pattern i: corresponding to the pattern (i) in Fig. 3

[0217] After the soaking, a work was cooled down to a start temperature T (°C) given in Tables 10 and 11 at an average cooling rate (°C per second) given in Tables 10 and 11, held at this start temperature T (°C), then cooled down to a start temperature (°C) in the temperature range T2 given in Tables 10 and 11, and held at this start temperature. Tables 10 and 11 indicate a residence time (second) in the temperature range T1; and a residence time (second) in the temperature range T2. The tables also indicate a time (second) from the time point at which holding in the temperature range T1 was completed to the time point at which the work temperature reached the start temperature in the temperature range T2.

Cooling Pattern ii: corresponding to the pattern (ii) in Fig. 3

[0218] After the soaking, a work was cooled down to a start temperature T (°C) given in Tables 10 and 11 at an average cooling rate (°C per second) given in Tables 10 and 11, subsequently cooled down to an end temperature (°C) given in Tables 10 and 11, cooled down to a start temperature (°C) in the temperature range T2 given in Tables 10 and 11, and held at this start temperature for a duration (second) given in Tables 10 and 11. Tables 10 and 11 indicate a residence time (second) in the temperature range T1; and a residence time (second) in the temperature range T2. The tables also indicate a time (second) from the time point at which holding in the temperature range T1 was completed to the time point at which the work temperature reached the start temperature in the temperature range T2.

Cooling Pattern iii: corresponding to the pattern (iii) in Fig. 3

[0219] After the soaking, a work was cooled down to a start temperature T (°C) given in Tables 10 and 11 at an average cooling rate (°C per second) given in Tables 10 and 11, then cooled down to a start temperature (°C) in the temperature range T2 given in Tables 10 and 11, and held at this start temperature. Tables 10 and 11 indicate a residence time (second) in the temperature range T1; and a residence time (second) in the temperature range T2.

Cooling Pattern iv

[0220] After the soaking, a work was cooled down to a start temperature (°C) in the temperature range T1 given in Table 10 and held at the start temperature. Specifically, Sample No. 19 in Table 10 was a sample, in which the work after the soaking was held at 420°C for 450 seconds and then cooled down to room temperature at an average cooling rate of 5°C per second without holding (without stopping). The residence time in the temperature range T2 of this sample in Table 10 refers to a time necessary to pass through the temperature range T2. Table 10 indicates a residence time in the temperature range T1 (second) and a residence time in the temperature range T2 (second).

[0221] Of the start temperatures and the end temperatures in the temperature range T1; and of the start temperatures in the temperature range T2 given in Table 10, each of the asterisked values was out of the temperature range T1 or the temperature range T2 as specified in the present invention, but was indicated as a temperature in each column for

convenience of explanation of the heat pattern.

[0222] The prepared specimens were subjected to metal structure observation and mechanical properties evaluation according to the following procedures.

5 Metal Structure Observation

[0223] Of the metal structure, area percentages of the polygonal ferrite, the high-temperature-formed bainite, and the low-temperature-formed bainite or the like (namely, the low-temperature-formed bainite and the tempered martensite) were calculated based on an observation with a scanning electron microscope (SEM); whereas a volume percentage of the retained austenite was determined by a saturation magnetization measurement.

(1) Area Percentages of Polygonal Ferrite, High-temperature-formed Bainite, and Low-temperature-formed Bainite and the Like

[0224] To determine these area percentages, a specimen cross section parallel to the rolling direction was surface-polished, further electropolished, etched with a Nital solution, and a position at a one-fourth depth the sheet thickness was observed in five view fields with a SEM at a 3000-fold magnification. One view field to be observed had a size of about 50 μm long by about 50 μm wide.

[0225] Next, average distances of retained austenite and carbides observed as white or pale gray microstructures in the observation view fields were measured according to the method mentioned above. The high-temperature-formed bainite and the low-temperature-formed bainite or the like were distinguished from each other by the average distance, whose area percentages were measured by point counting.

[0226] Tables 12 and 13 indicate an area percentage "a" (%) of the polygonal ferrite, an area percentage "b" (%) of the high-temperature-formed bainite, and a total area percentage "c" (%) of the low-temperature-formed bainite and the tempered martensite. The tables also indicate a total area percentage (a+b+c) of the area percentage "a", the area percentage "b", and the total area percentage "c".

[0227] Equivalent circle diameters of polygonal ferrite grains observed in the observation view fields were measured and averaged. The results are indicated in Tables 12 and 13. In addition, a sample having an average equivalent circle diameter D of polygonal ferrite grains of 10 μm or less was evaluated as "○" (good), and one having an average equivalent circle diameter of greater than 10 μm was evaluated as "△" (fair). The evaluation results are indicated in Tables 12 and 13.

(2) Retained Austenite Volume Percentage

[0228] Of the metal structure, a volume percentage of the retained austenite was determined by a saturation magnetization measurement. Specifically, a saturation magnetization (I) of a specimen and a saturation magnetization (I_s) of a standard specimen were measured, based on which a volume percentage (V_{Yr}) of the retained austenite was determined according to an expression below. The standard specimen had been subjected to a heat treatment at 400°C for 15 hours. The saturation magnetization measurement was performed at room temperature with a DC magnetization B-H curve automatic recorder "Model BHS-40" supplied by Riken Denshi, Co., Ltd. with a maximum applied magnetization of 5000 (Oe). The expression is expressed as follows:

$$V_{Yr} = (1 - I/I_s) \times 100$$

[0229] Equivalent circle diameters "d" of martensite-austenite constituents including both retained austenite and as-quenched martensite in combination were measured by polishing a surface of a specimen cross section parallel to the rolling direction, and observing the polished surface in five view fields with an optical microscope at a 1000-fold observation magnification. A number percentage of martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm with respect to the total number of the entire martensite-austenite constituents in the observed cross-section was calculated. A specimen having a number percentage of less than 15% was evaluated as accepted (○), whereas a specimen having a number percentage of 15% or more was evaluated as rejected (×). The evaluation results are indicated in Tables 12 and 13.

55 Mechanical Properties Evaluation

[0230] Mechanical properties of each specimen were evaluated based on the tensile strength (TS), elongation (EL), bore expansion ratio (λ), critical bending radius (R), and Erichsen value.

[0231]

(1) The tensile strength (TS) and elongation (EL) were measured through a tensile test according to JIS Z 2241. As a test specimen, a JIS Z 2201 No. 5 test specimen was cut from the specimen so that a direction perpendicular to the specimen rolling direction be a longitudinal direction of the test specimen. The measurement results are indicated in Tables 12 and 13.

(2) Stretch flangeability was evaluated based on the bore expansion ratio. The bore expansion ratio (λ) was measured through a bore expanding test according to the Japan Iron and Steel Federation Standard (JFS) T 1001. The measurement results are indicated in Tables 12 and 13.

(3) The critical bending radius (R) was measured through a V-bending test according to JIS Z 2248. As a test specimen, a JIS Z 2204 No. 1 test specimen (thickness: 1.4 mm) was cut from the specimen so that a direction perpendicular to the specimen rolling direction be a longitudinal direction of the test specimen (i.e., so that the bend line agree with the rolling direction). The V-bending test was performed after applying mechanical grinding to a longitudinal end face of the test specimen so as to prevent cracking.

The V-bending test was performed at an angle between a die and a punch of 90° and at a punch tip radius varying in units of 0.5 mm. A minimum punch tip radius at which the test specimen can be bent without cracking was determined as the critical bending radius (R). The measurement results are indicated in Tables 12 and 13. The presence/absence of cracking was observed with a magnifying glass, and a test specimen without the occurrence of hair crack was evaluated as suffering from no cracking.

(4) The Erichsen value was measured through an Erichsen test according to JIS Z 2247. A test specimen of a size of 90 mm long by 90 mm wide by 1.4 mm thick was prepared by cutting from the specimen. The Erichsen test was performed with a device having a punch diameter of 20 mm. The measurement results are indicated in Tables 12 and 13. The Erichsen test enables evaluations of both the total elongation properties and the local ductility of the steel sheet.

[0232] The mechanical properties of the specimen were evaluated based on criteria for the elongation (EL), bore expansion ratio (λ), critical bending radius (R), and Erichsen value varying depending on the tensile strength (TS). Specifically, required properties including EL, λ , R, and Erichsen value vary depending on the steel sheet tensile strength TS. Accordingly, the mechanical properties were evaluated in accordance with the following criteria that vary depending on the TS level.

[0233] Based on the criteria, a sample evaluated as satisfactory all in the properties of EL, λ , R, and Erichsen value were evaluated as accepted (○), whereas a sample having one or more properties lower than the criteria was evaluated as rejected (×). The evaluation results are indicated in Tables 12 and 13.

(1) TS of 590 MPa grade

[0234]

TS: from 590 MPa to less than 780 MPa

EL: 34% or more

λ : 30% or more

R: 0.5 mm or less

Erichsen value: 10.8 mm or more

(2) TS of 780 MPa grade

[0235]

TS: from 780 MPa to less than 980 MPa

EL: 25% or more

λ : 30% or more

R: 1.0 mm or less

Erichsen value: 10.4 mm or more

(3) TS of 980 MPa grade

[0236]

TS: from 980 MPa to less than 1180 MPa

EL: 19% or more

A: 20% or more

R: 3.0 mm or less

Erichsen value: 10.0 mm or more

(4) TS of 1180 MPa grade

[0237]

TS: from 1180 MPa to less than 1270 MPa

EL: 15% or more

λ : 20% or more

R: 4.5 mm or less

Erichsen value: 9.6 mm or more

[0238] The second high-strength steel sheet is designed to be applied to steel sheets having a tensile strength TS of from 590 MPa to less than 1270 MPa. Samples having a tensile strength TS of less than 590 MPa, or of 1270 MPa or more were ineligible herein even when being satisfactory in EL, λ , R, and Erichsen value.

[0239] Tables 9 to 13 demonstrate as follows. Of Samples Nos. 1 to 43 in Tables 12 and 13, Samples Nos. 1, 3, 4, 11, 14, 15, 20, and 28 underwent cooling in Pattern i; Samples Nos. 2 and 6 underwent cooling in Pattern iii; Sample No. 19 underwent cooling in Pattern iv; and the other samples underwent cooling in Pattern ii.

[0240] Samples evaluated as "○" in the assessment in Tables 12 and 13 were steel sheets satisfying the conditions specified in the present invention and satisfying criteria values of the mechanical properties (EL, λ , R, and Erichsen value) determined according to the tensile strength TS. This demonstrates that high-strength steel sheets according to the present invention had a high elongation and satisfactory local formability and exhibited good workability in general.

[0241] By contrast, samples evaluated as "×" in the assessment (Samples Nos. 4, 8, 9, 12, 15, 18 to 20, 31, and 34 to 36 in Tables 12 and 13) were steel sheets not satisfying one or more of the conditions specified in the present invention. Details thereof are as follows.

[0242] Sample No. 4 in Table 12 underwent, after being heated to and held in the two-phase temperature range, cooling down to an arbitrary temperature T falling within the range specified by Expression (1) at an excessively low average cooling rate. This sample suffered from pearlite transformation, failed to include a desired amount of the retained austenite, and thereby had an insufficient strength. Sample No. 8 in Table 12 underwent holding in the two-phase temperature range for an excessively short time. This sample failed to include a sufficient amount of the retained austenite and had an insufficient strength. Sample No. 9 in Table 12 underwent, after the soaking, holding at a temperature higher than the temperature range T1 specified in the present invention, subsequently cooling down to the temperature range T2 without holding in the temperature range T1, and holding in the temperature range T2. This sample suffered from heavy formation of polygonal ferrite and suffered from formation of insufficient amounts of the high-temperature-formed bainite and the retained austenite. The sample had an elongation and a Erichsen value at low levels and failed to exhibit better workability.

[0243] Sample No. 12 in Table 12 underwent, after holding in the temperature range T1, cooling down to a temperature lower than the temperature range T2 without holding in the temperature range T2. This sample suffered from little formation of the low-temperature-formed bainite, included a large amount of coarse martensite-austenite constituents as identified through SEM observation, and included a large amount of as-quenched martensite. The sample satisfied none of the specified acceptance criteria in elongation, bore expansion ratio, critical bending radius, and Erichsen value and failed to exhibit better workability. Sample No. 15 in Table 12 underwent holding in the temperature range T1 for an excessively long time without holding in the temperature range T2. This sample suffered from insufficient formation of the low-temperature-formed bainite or the like and heavy formation of coarse martensite-austenite constituents. The sample therefore have a low bore expansion ratio, a small critical bending radius, and a low Erichsen value to have poor local formability and failed to exhibit better steel sheet workability.

[0244] Sample No. 18 in Table 12 underwent heating at an excessively high temperature, thereby suffered from little formation of polygonal ferrite and excessive formation of the high-temperature-formed bainite and the low-temperature-formed bainite or the like. This sample had a low elongation and failed to exhibit better steel sheet workability. Sample No. 19 in Table 12 underwent holding in the temperature range T1 for an excessively long time, and cooling without holding in the temperature range T2. This sample suffered from insufficient formation of the low-temperature-formed bainite or the like and heavy formation of coarse martensite-austenite constituents. The sample had a low bore expansion ratio and a low Erichsen value to have poor local formability and failed to exhibit better workability. Sample No. 20 in Table 12 underwent, after the soaking, cooling down to the temperature range T2 without holding in the temperature

range T1 (without stopping), and holding at two different temperatures in the temperature range T2. This sample suffered from little formation of the high-temperature-formed bainite and little formation of the retained austenite because of being held only in the temperature range T2. The sample had an elongation and an Erichsen value at low levels and failed to exhibit better workability. Sample No. 31 in Table 13 underwent heating at an excessively low temperature. This sample suffered from heavy formation of polygonal ferrite and no formation of the high-temperature-formed bainite, the low-temperature-formed bainite or the like, and the retained austenite. The sample had a low elongation and failed to exhibit better workability.

[0245] Sample No. 34 in Table 13 had an excessively low carbon content. This sample suffered from insufficient formation of the retained austenite, had an elongation and an Erichsen value at low levels, and failed to exhibit better workability. Sample No. 35 in Table 13 had an excessively low Si content. This sample suffered from insufficient formation of the retained austenite, had a low elongation, and failed to exhibit better workability. Sample No. 36 in Table 13 had an excessively low Mn content and underwent insufficient quenching. This sample underwent accelerated formation of polygonal ferrite during cooling, but suffered from insufficient formation of the low-temperature-formed bainite or the like. The sample had an elongation, a bore expansion ratio, and a critical bending radius at low levels and failed to exhibit better workability.

[0246] These results demonstrate that the present invention can provide high-strength steel sheets exhibiting better workability.

[0247] Steel sheets having a tensile strength of 780 MPa grade are indicated in Tables 12 and 13. Among them, Samples Nos. 3, 5 to 7, 11, 14, 16, 17, 23 to 26, 30, 32, and 37 to 43 satisfied the conditions specified in the present invention. Relating to these samples, a relationship between the elongation (EL) and the tensile strength (TS) is illustrated in Fig. 5. In Fig. 5, data indicated by the symbol "●" (filled circle) are data of samples having an average equivalent circle diameter D of polygonal ferrite grains of 10 μm or less; and data indicated by the symbol "■" (filled square) are data of samples having an average equivalent circle diameter D of polygonal ferrite grains of greater than 10 μm .

[0248] Fig. 5 demonstrates that steel sheets could have a higher elongation (EL) and exhibit further better workability by controlling the average equivalent circle diameter D of polygonal ferrite grains to 10 μm or less, even when having a tensile strength (TS) at an equivalent level.

[Table 9]

Steel type	Chemical composition (in mass percent)																		
	C	Si	Mn	P	S	Al	Cr	Mo	Ti	Nb	V	Cu	Ni	B	Ca	Mg	REM	N	O
A	0.11	1.32	1.57	0.02	0.002	0.02	-	-	-	-	-	-	-	-	-	-	-	0.002	0.001
B	0.14	1.82	2.29	0.02	0.001	0.04	-	-	-	-	-	-	-	-	-	-	-	0.004	0.001
C	0.10	1.13	2.05	0.01	0.002	0.05	-	-	-	-	-	-	-	-	-	-	-	0.002	0.002
D	0.19	2.54	2.38	0.03	0.001	0.04	-	-	-	-	-	-	-	-	-	-	-	0.005	0.002
E	0.18	1.54	2.01	0.01	0.002	0.05	-	-	-	-	-	-	-	-	-	-	-	0.004	0.002
F	0.16	1.55	1.63	0.03	0.001	0.02	0.4	-	-	-	-	-	-	-	-	-	-	0.003	0.002
G	0.16	1.58	1.66	0.03	0.001	0.04	-	0.3	-	-	-	-	-	-	-	-	-	0.004	0.001
H	0.16	1.54	1.87	0.02	0.001	0.03	-	-	0.07	-	-	-	-	-	-	-	-	0.005	0.002
I	0.17	1.56	1.88	0.02	0.002	0.03	-	-	0.02	0.04	-	-	-	-	-	-	-	0.005	0.001
J	0.16	1.17	1.85	0.02	0.001	0.45	-	-	-	-	0.08	-	-	-	-	-	-	0.003	0.001
K	0.27	1.88	2.04	0.02	0.002	0.03	-	-	-	-	-	0.24	0.28	-	-	-	-	0.002	0.002
L	0.15	2.48	1.91	0.02	0.002	0.02	-	-	0.02	-	-	-	-	0.0025	-	-	-	0.005	0.002
M	0.23	1.18	2.47	0.02	0.002	1.03	-	-	-	-	-	-	-	-	-	-	-	0.002	0.002
N	0.20	2.05	2.25	0.01	0.001	0.02	-	-	-	-	-	-	-	-	0.0021	0.0012	0.0018	0.003	0.002
O	0.07	1.54	2.08	0.01	0.001	0.05	-	-	-	-	-	-	-	-	-	-	-	0.003	0.002
P	0.18	0.56	1.87	0.02	0.002	0.04	-	-	-	-	-	-	-	-	-	-	-	0.003	0.001
Q	0.18	1.84	0.84	0.02	0.001	0.05	-	-	-	-	-	-	-	-	-	-	-	0.002	0.001
R	0.16	1.60	1.87	0.02	0.001	0.02	-	-	-	0.06	-	-	-	-	-	-	-	0.002	0.002
S	0.16	1.56	1.89	0.02	0.001	0.05	-	-	-	-	-	0.06	-	-	-	-	-	0.003	0.002
T	0.16	1.58	1.85	0.02	0.001	0.04	-	-	-	-	-	-	0.47	-	-	-	-	0.002	0.001
U	0.16	1.58	1.86	0.03	0.001	0.03	-	-	-	-	-	-	-	0.0006	-	-	-	0.003	0.001
V	0.16	1.57	1.86	0.01	0.001	0.02	-	-	-	-	-	-	-	-	0.0022	-	-	0.004	0.001
W	0.16	1.58	1.86	0.01	0.001	0.03	-	-	-	-	-	-	-	-	-	0.0019	-	0.003	0.002
X	0.17	1.59	1.88	0.01	0.001	0.05	-	-	-	-	-	-	-	-	-	-	0.0024	0.002	0.001

[Table 10]

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	Ac ₁ +20 (°C)	Ac ₃ +20 (°C)	Soaking		Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
						Heating temperature (°C)	Holding time (sec)								
1	A	745	878	765	898	860	200	15	420	420	4	380	75	488	i
2	A	745	878	765	898	860	60	15	420	-	-	380	33	515	iii
3	A	745	878	765	898	860	200	45	420	420	4	350	29	483	i
4	A	745	878	765	898	860	200	1	420	420	4	350	146	483	i
5	B	751	877	771	897	840	200	15	450	420	4	350	32	483	ii
6	B	751	877	771	897	840	200	5	450	-	-	320	28	493	iii
7	B	751	877	771	897	840	200	15	520	490	4	350	29	481	ii
8	B	751	877	771	897	860	20	10	450	420	4	380	36	488	ii
9	B	751	877	771	897	860	200	15	650 ※	620 ※	4	380	4	486	ii
10	C	734	861	754	881	820	200	15	450	420	4	380	33	488	ii
11	C	734	861	754	881	820	200	15	410	410	4	320	34	478	i
12	C	734	861	754	881	840	200	10	450	380 ※	4	150 ※	27	11	ii
13	D	771	901	791	921	860	200	15	450	420	4	290	12	471	ii
14	D	771	901	791	921	890	490	10	480	480	4	380	34	487	i
15	D	771	901	791	921	860	200	15	480	480	4	420 ※	483	40	i
16	E	746	860	766	880	840	200	15	450	420	4	320	32	477	ii
17	E	746	860	766	880	840	200	15	450	420	20	230	33	1824	ii
18	E	746	860	766	880	900	200	45	450	420	4	380	29	488	ii
19	E	746	860	766	880	820	200	15	420	420	-	-	462	40	iv
20	E	746	860	766	880	820	200	20	380 ※	380 ※	4	350	7	510	i

[Table 11]

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	Ac ₁ +20 (°C)	Ac ₃ +20 (°C)	Soaking		Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
						Heating temperature (°C)	Holding time (sec)		Start temperature T (°C)	End temperature (°C)			Temperature range T1	Temperature range T2	
21	F	757	874	777	894	840	200	15	450	420	4	350	32	483	ii
22	G	751	897	771	917	840	200	15	450	420	4	380	33	488	ii
23	H	748	895	768	915	860	200	15	450	420	4	350	32	483	ii
24	H	748	895	768	915	860	200	15	450	420	4	350	32	233	ii
25	I	748	875	768	895	860	200	15	450	420	4	350	32	483	ii
26	J	737	1027	757	1047	840	200	15	450	420	4	350	32	483	ii
27	K	751	844	771	864	780	200	15	450	420	4	230	31	910	ii
28	K	751	844	771	864	820	200	30	420	420	4	380	86	938	i
29	L	775	912	795	932	880	200	15	450	420	4	320	32	477	ii
30	L	775	912	795	932	910	480	10	480	450	4	380	34	487	ii
31	L	775	912	795	932	750	200	15	450	420	4	320	32	477	ii
32	M	731	1218	751	1238	820	200	15	450	420	4	350	32	1233	ii
33	N	759	858	779	878	820	200	15	450	420	4	320	32	477	ii
34	O	746	891	766	911	840	200	15	450	420	4	350	32	483	ii
35	P	719	824	739	844	800	200	15	450	420	4	350	32	483	ii
36	Q	768	915	788	935	840	200	15	450	420	4	350	32	483	ii
37	R	750	867	770	887	840	200	15	450	420	4	350	32	483	ii
38	S	748	875	768	895	840	200	15	450	420	4	350	32	483	ii
39	T	741	868	761	888	840	200	15	450	420	4	350	32	483	ii
40	U	749	877	769	897	840	200	15	450	420	4	350	32	483	ii
41	V	749	859	769	879	840	200	15	450	420	4	350	32	483	ii
42	W	749	862	769	882	840	200	15	450	420	4	350	32	483	ii

(continued)

No.	Steel type	Ac ₁ (°C)	Ac ₃ (°C)	Ac ₁ +20 (°C)	Ac ₃ +20 (°C)	Soaking	Average cooling rate (°C/sec)	Temperature range T1		Time from T1 to T2 (sec)	Temperature range T2	Residence time (sec)		Cooling pattern
						Heating temperature (°C)		Start temperature T (°C)	End temperature (°C)		Start temperature (°C)	Temperature range T1	Temperature range T2	
43	X	749	869	769	889	840	15	450	420	4	350	32	483	ii

[Table 12]

No.	Polygonal ferrite "a" (in area percent)	High-temperature-formed bainite "b" (in area percent)	Low-temperature-formed bainite "c" (in area percent)	Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number percentage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
					Grain size (μm)	Evaluation									
1	81	6	10	97	5	○	6	○	626	36	54	0.0	11.3	○	590 MPa grade
2	68	11	16	95	4	○	7	○	654	35	45	0.0	11.2	○	590 MPa grade
3	63	12	17	92	5	○	10	○	835	29	45	0.0	10.7	○	780 MPa grade
4	78	0	0	78	5	○	0	○	559	23	46	0.0	10.1	×	-
5	65	11	18	94	4	○	11	○	822	31	37	0.5	10.9	○	780 MPa grade
6	75	7	10	92	4	○	12	○	808	31	39	0.0	11.0	○	780 MPa grade
7	66	14	13	93	5	○	11	○	818	30	41	0.5	10.8	○	780 MPa grade
8	75	15	8	98	5	○	2	○	562	25	36	0.0	10.2	×	-
9	72	3	21	96	15	△	4	○	615	31	44	0.0	10.5	×	590 MPa grade
10	74	8	12	94	4	○	7	○	638	36	56	0.0	11.4	○	590 MPa grade
11	78	11	8	97	4	○	6	○	801	31	45	0.0	11.0	○	780 MPa grade
12	68	7	3	78	5	○	5	×	937	17	26	1.5	10.1	×	780 MPa grade
13	62	7	22	91	5	○	15	○	1035	22	26	1.5	10.4	○	980 MPa grade
14	64	11	18	93	14	△	10	○	822	28	41	0.5	10.7	○	780 MPa grade

(continued)

No.	Polygonal ferrite "a" (in area percent)	High-temperature-formed bainite "b" (in area percent)		Low-temperature-formed bainite "c" (in area percent)		Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number percentage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
							Grain size (μm)	Evaluation									
15	61	18		3		82	5	○	9	×	908	25	20	1.5	10.1	×	780 MPa grade
16	71	9		13		93	4	○	10	○	785	32	38	0.0	11.0	○	780 MPa grade
17	74	7		15		96	5	○	9	○	848	28	35	0.5	10.8	○	780 MPa grade
18	6	45		41		92	4	○	10	○	1001	17	63	0.0	10.7	×	980 MPa grade
19	73	11		2		86	4	○	14	×	996	23	17	2.5	9.8	×	980 MPa grade
20	62	4		33		99	4	○	3	○	1139	16	52	1.5	9.9	×	980 MPa grade

[Table 13]

No.	Polygonal ferrite "a" (in area percent)	Composite microstructure		Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number percentage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
		High-temperature-formed bainite "b" (in area percent)	Low-temperature-formed bainite "c" (in area percent)		Grain size (μm)	Evaluation									
21	57	8	22	87	5	○	15	○	1004	23	34	2.0	10.6	○	980 MPa grade
22	69	6	14	89	4	○	11	○	1028	23	28	1.5	10.5	○	980 MPa grade
23	76	7	9	92	2	○	11	○	834	29	43	0.0	10.9	○	780 MPa grade
24	75	7	11	93	2	○	10	○	842	29	35	0.5	10.8	○	780 MPa grade
25	65	15	13	93	2	○	9	○	854	28	36	0.0	10.7	○	780 MPa grade
26	73	12	9	94	3	○	10	○	797	31	44	0.0	11.0	○	780 MPa grade
27	55	8	27	90	3	○	11	○	1194	18	33	1.0	10.0	○	1180 MPa grade
2B	56	13	10	79	5	○	12	○	1032	22	23	2.0	10.2	○	980 MPa grade
29	59	15	14	88	5	○	13	○	1027	22	25	2.0	10.5	○	980 MPa grade
30	65	13	14	92	12	△	9	○	792	30	44	0.0	10.7	○	780 MPa grade
31	88	0	0	88	22	△	0	○	626	23	48	0.0	11.0	×	590 MPa grade
32	69	7	12	88	5	○	16	○	854	28	35	0.5	10.8	○	780 MPa grade
33	53	10	23	86	5	○	16	○	1024	22	26	2.0	10.5	○	980 MPa grade

(continued)

No.	Polygonal ferrite "a" (in area percent)	Composite microstructure		Total area percentage (a+b+c)	Polygonal ferrite		Retained austenite (in volume percent)	Number per-centage of MA constituent	TS (MPa)	EL (%)	λ (%)	R (mm)	Erichsen value (mm)	Assessment	Remarks
		High-temperature-formed bainite "b" (in area percent)	Low-temperature-formed bainite "c" (in area percent)		Grain size (μm)	Evaluation									
34	75	5	15	95	4	○	2	○	634	31	43	0.0	10.7	×	590 MPa grade
35	66	8	24	98	22	△	3	○	831	21	41	0.0	10.4	×	780 MPa grade
36	82	14	2	98	5	○	7	○	756	28	13	1.0	11.0	×	590 MPa grade
37	71	8	12	91	4	○	11	○	838	29	38	0.0	10.6	○	780 MPa grade
38	75	9	9	93	5	○	10	○	821	30	35	0.0	10.7	○	780 MPa grade
39	68	6	17	91	5	○	12	○	856	29	45	0.5	10.9	○	780 MPa grade
40	72	6	14	92	4	○	12	○	823	30	38	0.0	10.7	○	780 MPa grade
41	71	7	13	91	5	○	10	○	810	30	46	0.0	10.7	○	780 MPa grade
42	74	9	11	94	5	○	11	○	801	31	38	0.5	10.8	○	780 MPa grade
43	72	7	12	91	4	○	10	○	822	29	41	0.0	10.9	○	780 MPa grade

Claims

1. A high-strength steel sheet having excellent workability, comprising:

C in a content of from 0.10% to 0.3%;
Si in a content of from 1.0% to 3%;
Mn in a content of from 1.0% to 2.5%;
Al in a content of from 0.005% to 3%;
P in a content controlled to 0.1% or less; and
S in a content controlled to 0.05% or less,

optionally further comprising:

Cr in a content of from greater than 0% to 1%; and/or
Mo in a content of from greater than 0% to 1%,

optionally further comprising:

at least one element selected from the group consisting of:

Ti in a content of from greater than 0% to 0.15%;
Nb in a content of from greater than 0% to 0.15%; and
V in a content of from greater than 0% to 0.15%,

optionally further comprising:

Cu in a content of from greater than 0% to 1%; and/or
Ni in a content of from greater than 0% to 1%,

optionally further comprising:

B in a content of from greater than 0% to 0.005%, and

optionally further comprising:

at least one element selected from the group consisting of:

Ca in a content of from greater than 0% to 0.01%;
Mg in a content of from greater than 0% to 0.01%; and
a rare-earth element in a content of from greater than 0% to 0.01%,

in mass percent, with the remainder consisting of iron and inevitable impurities, wherein:

the steel sheet has a metal structure comprising polygonal ferrite, bainite, tempered martensite, and retained austenite;

(1) when the metal structure is observed with a scanning electron microscope,
(1a) the polygonal ferrite is present in an area percentage "a" of greater than 50% of the entire metal structure,
(1b) the bainite has a composite microstructure comprising:

a high-temperature-formed bainite having an average distance between adjacent regions of retained austenite and/or carbide of 1 μm or more; and
a low-temperature-formed bainite having an average distance between adjacent regions of retained austenite and/or carbide of less than 1 μm ,
the high-temperature-formed bainite is present in an area percentage "b" of from 5% to 40% of the entire metal structure; and
the low-temperature-formed bainite and the tempered martensite are present in a total area

percentage "c" of from 5% to 40% of the entire metal structure; and

(2) the retained austenite is present in a volume percentage of 5% or more of the entire metal structure as determined by a saturation magnetization measurement.

2. The high-strength steel sheet of claim 1, wherein, when martensite-austenite constituents comprising both as-quenched martensite and retained austenite are found upon observation at a cross-section of the metal structure with an optical microscope, martensite-austenite constituents each having an equivalent circle diameter "d" of greater than 7 μm are present in a number percentage of from 0% to less than 15% of a total number of entire martensite-austenite constituents at the observed cross-section.
3. The high-strength steel sheet of one of claims 1 and 2, wherein grains of the polygonal ferrite have an average equivalent circle diameter D of from greater than 0 μm to 10 μm .
4. The high-strength steel sheet of claim 1, comprising a hot-dip galvanized layer or a hot-dip galvanized layer on a surface thereof.
5. The high-strength steel sheet of claim 1, wherein the polygonal ferrite is present in an area percentage "a" of 55% or more of the entire metal structure.
6. The high-strength steel sheet of claim 5, wherein the polygonal ferrite is present in an area percentage "a" of 60% or more of the entire metal structure.

Patentansprüche

1. Hochfestes Stahlblech mit ausgezeichneter Bearbeitbarkeit, das umfasst:

C mit einem Gehalt von 0,10 % bis 0,3 %;
 Si mit einem Gehalt von 1,0 % bis 3 %;
 Mn mit einem Gehalt von 1,0 % bis 2,5 %;
 Al mit einem Gehalt von 0,005 % bis 3 %;
 P mit einem kontrollierten Gehalt bis 0,1 % oder weniger; und
 S mit einem kontrollierten Gehalt bis 0,05 % oder weniger,

des Weiteren wahlweise umfassend:

Cr mit einem Gehalt größer als 0 % bis 1 %; und/oder
 Mo mit einem Gehalt größer als 0 % bis 1 %,

des Weiteren wahlweise umfassend:

mindestens ein Element, das aus der Gruppe ausgewählt wird, die besteht aus:

Ti mit einem Gehalt größer als 0 % bis 0,15 %;
 Nb mit einem Gehalt größer als 0 % bis 0,15 %; und
 V mit einem Gehalt größer als 0 % bis 0,15 %,

des Weiteren wahlweise umfassend:

Cu mit einem Gehalt größer als 0 % bis 1 %; und/oder
 Ni mit einem Gehalt größer als 0 % bis 1 %,

des Weiteren wahlweise umfassend:

B mit einem Gehalt größer als 0 % bis 0,005 %, und

des Weiteren wahlweise umfassend:

mindestens ein Element, das aus der Gruppe ausgewählt wird, die besteht aus:

Ca mit einem Gehalt größer als 0 % bis 0,01 %;
Mg mit einem Gehalt größer als 0 % bis 0,01 %; und
einem Element der Seltenen Erden mit einem Gehalt größer als 0 % bis 0,01 %,

in Massenprozent, mit dem Rest, der aus Eisen und unvermeidlichen Verunreinigungen besteht, wobei:

das Stahlblech eine Metallstruktur hat, die polygonalen Ferrit, Bainit, getemperten Martensit und Restaustenit umfasst;

(1) wenn die Metallstruktur mit einem Rasterelektronenmikroskop betrachtet wird,
(1a) der polygonale Ferrit in einem Flächenprozentatz "a" größer als 50 % der gesamten Metallstruktur vorhanden ist,

(1b) der Bainit eine Verbundmikrostruktur hat, die umfasst:

einen durch Hochtemperatur gebildeten Bainit mit einem mittleren Abstand von 1 μm oder mehr zwischen angrenzenden Bereichen von Restaustenit und/oder Karbid; und
einen durch Niedrigtemperatur gebildeten Bainit mit einem mittleren Abstand von weniger als 1 μm zwischen angrenzenden Bereichen von Restaustenit und/oder Karbid;
der durch Hochtemperatur gebildete Bainit ist in einem Flächenprozentatz "b" von 5 % bis 40 % der gesamten Metallstruktur vorhanden; und
der durch Niedrigtemperatur gebildete Bainit und der getemperte Martensit sind in einem Gesamtflächenprozentatz "c" von 5 % bis 40 % der gesamten Metallstruktur vorhanden; und

(2) der Restaustenit ist in einem Volumenprozentatz von 5 % oder mehr der gesamten Metallstruktur vorhanden, wie durch eine Sättigungsmagnetisierungsmessung bestimmt wird.

2. Hochfestes Stahlblech nach Anspruch 1, wobei, wenn Martensit-Austenit-Bestandteile, die sowohl abgeschreckten Martensit als auch Restaustenit umfassen, durch Beobachtung mit einem optischen Mikroskop bei einem Querschnitt der Metallstruktur gefunden werden, Martensit-Austenit-Bestandteile jeder mit einem äquivalenten Kreisdurchmesser "d" größer als 7 μm in einem Anzahlprozentatz von 0 % bis weniger als 15 % einer Gesamtanzahl der gesamten Martensit-Austenit-Bestandteile bei dem betrachteten Querschnitt vorhanden sind.

3. Hochfestes Stahlblech nach einem der Ansprüche 1 und 2, wobei die Körnigkeit des polygonalen Ferrits einen mittleren äquivalenten Kreisdurchmesser D größer als 0 μm bis 10 μm hat.

4. Hochfestes Stahlblech nach Anspruch 1, das eine feuerverzinkte Schicht oder eine feuerverzinkte wärmebehandelte Schicht auf einer Oberfläche desselben umfasst.

5. Hochfestes Stahlblech nach Anspruch 1, wobei der polygonale Ferrit in einem Flächenprozentatz "a" von 55 % oder mehr der gesamten Metallstruktur vorhanden ist.

6. Hochfestes Stahlblech nach Anspruch 5, wobei der polygonale Ferrit in einem Flächenprozentatz "a" von 60 % oder mehr der gesamten Metallstruktur vorhanden ist.

Revendications

1. Feuillard en acier à haute résistance ayant une excellente aptitude à l'usage, comprenant :

C dans une teneur comprise entre 0,10 % et 0,3 % ;
Si dans une teneur comprise entre 1,0 % et 3 % ;
Mn dans une teneur comprise entre 1,0 % et 2,5 % ;
Al dans une teneur comprise entre 0,005 % et 3 % ;
P dans une teneur contrôlée inférieure ou égale à 0,1 % ; et
S dans une teneur contrôlée inférieure ou égale à 0,05 %,

éventuellement comprenant en outre :

Cr dans une teneur supérieure à 0 % jusqu'à 1 % ; et/ou
Mo dans une teneur supérieure à 0 % jusqu'à 1 %,

éventuellement comprenant en outre :

au moins un élément sélectionné parmi le groupe composé de :

Ti dans une teneur supérieure à 0 % jusqu'à 0,15 % ;
Nb dans une teneur supérieure à 0 % jusqu'à 0,15 % ; et
V dans une teneur supérieure à 0 % jusqu'à 0,15 %,

éventuellement comprenant en outre :

Cu dans une teneur supérieure à 0 % jusqu'à 1 % ; et/ou
Ni dans une teneur supérieure à 0 % jusqu'à 1 %,

éventuellement comprenant en outre :

B dans une teneur supérieure à 0 % jusqu'à 0,005 %, et

éventuellement comprenant en outre :

au moins un élément sélectionné parmi le groupe composé de :

Ca dans une teneur supérieure à 0 % jusqu'à 0,01 % ;
Mg dans une teneur supérieure à 0 % jusqu'à 0,01 % ; et
un élément de terres rares dans une teneur supérieure à 0 % jusqu'à 0,01 %,

en pourcentage de masse, le reste étant composé de fer et d'inévitables impuretés,
où:

le feuillard en acier possède une structure de métal comprenant de la ferrite polygonale, de la bainite,
de la martensite trempée et de l'austénite retenue ;

(1) lorsque l'on observe la structure de métal avec un microscope à balayage électronique,

(1a) la ferrite polygonale est présente dans un pourcentage de surface « a » supérieur à 50
% de toute la structure de métal,

(1b) la bainite possède une microstructure composite comprenant :

une bainite formée à haute température ayant une distance moyenne entre des zones
adjacentes d'austénite retenue et/ou de carbure supérieure ou égale à 1 μm ; et
une bainite formée à basse température ayant une distance moyenne entre des zones
adjacentes d'austénite retenue et/ou de carbure inférieure à 1 μm ,
la bainite formée à haute température est présente dans un pourcentage de surface « b »
de 5 % à 40 % de toute la structure de métal ; et
la bainite formée à basse température et la martensite trempée sont présentes dans un
pourcentage de surface total « c » de 5 % à 40 % de toute la structure de métal ; et

(2) l'austénite retenue est présente dans un pourcentage en volume supérieur ou égal à 5 % de
toute la structure de métal comme cela est déterminé par une mesure d'aimantation à saturation.

2. Feuillard en acier à haute résistance selon la revendication 1, où, lorsque l'on trouve des éléments constitutifs martensite-austénite à la fois sous forme de martensite trempée et d'austénite retenue en observant une coupe transversale de la structure de métal avec un microscopie optique, les éléments constitutifs martensite-austénite ayant chacun un diamètre de cercle équivalent « d » supérieur à 7 μm sont présents dans un pourcentage numérique

EP 2 942 416 B1

de 0 % à moins de 15 % d'un nombre total d'éléments constitutifs martensite-austénite au niveau de la coupe transversale observée.

- 5 **3.** Feuillard en acier à haute résistance selon l'une des revendications 1 et 2, où les grains de la ferrite polygonale ont un diamètre de cercle équivalent D supérieur à 0 μm jusqu'à 10 μm .
- 4.** Feuillard en acier à haute résistance selon la revendication 1, comprenant une couche galvanisée par immersion à chaud ou bien une couche recuite par galvanisation par immersion à chaud à la surface dudit feuillard.
- 10 **5.** Feuillard en acier à haute résistance selon la revendication 1, où la ferrite polygonale est présente dans un pourcentage de surface « a » supérieur ou égal à 55 % de toute la structure de métal.
- 6.** Feuillard en acier à haute résistance selon la revendication 5, où la ferrite polygonale est présente dans un pourcentage de surface « a » supérieur ou égal à 60 % de toute la structure de métal.
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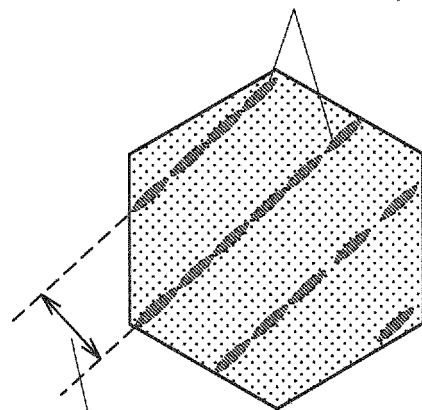
45

50

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FIG. 1

RETAINED AUSTENITE AND/OR CARBIDE



CENTER-TO-CENTER DISTANCE

FIG. 2

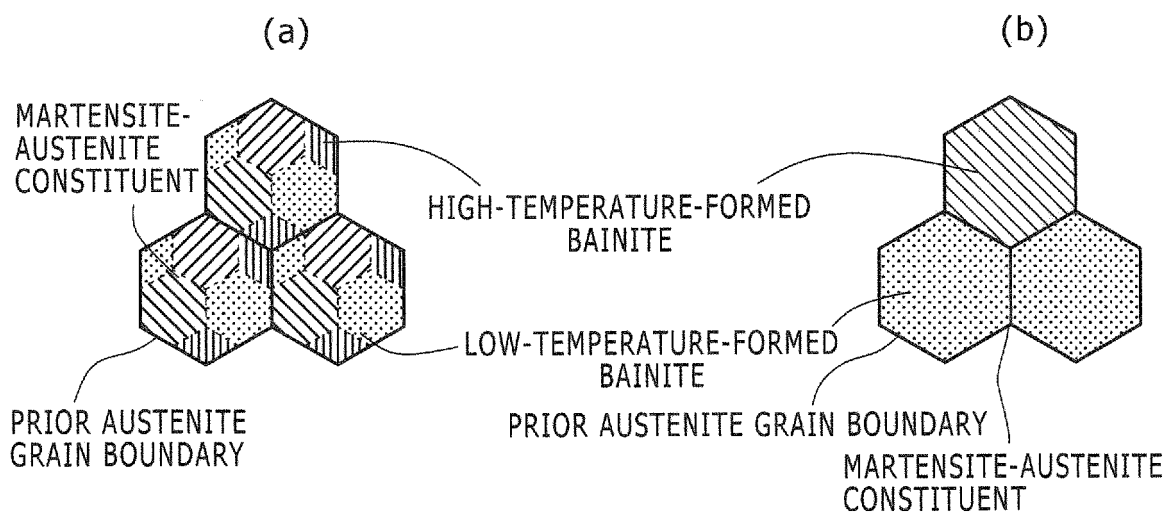


FIG. 3

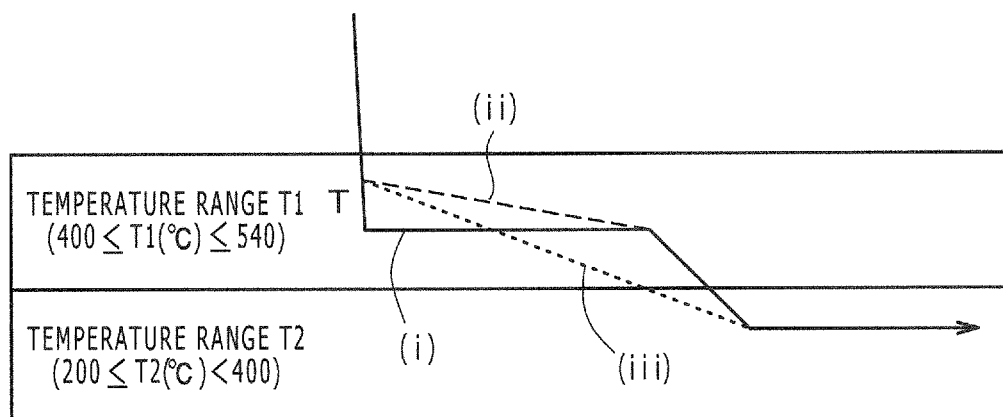


FIG. 4

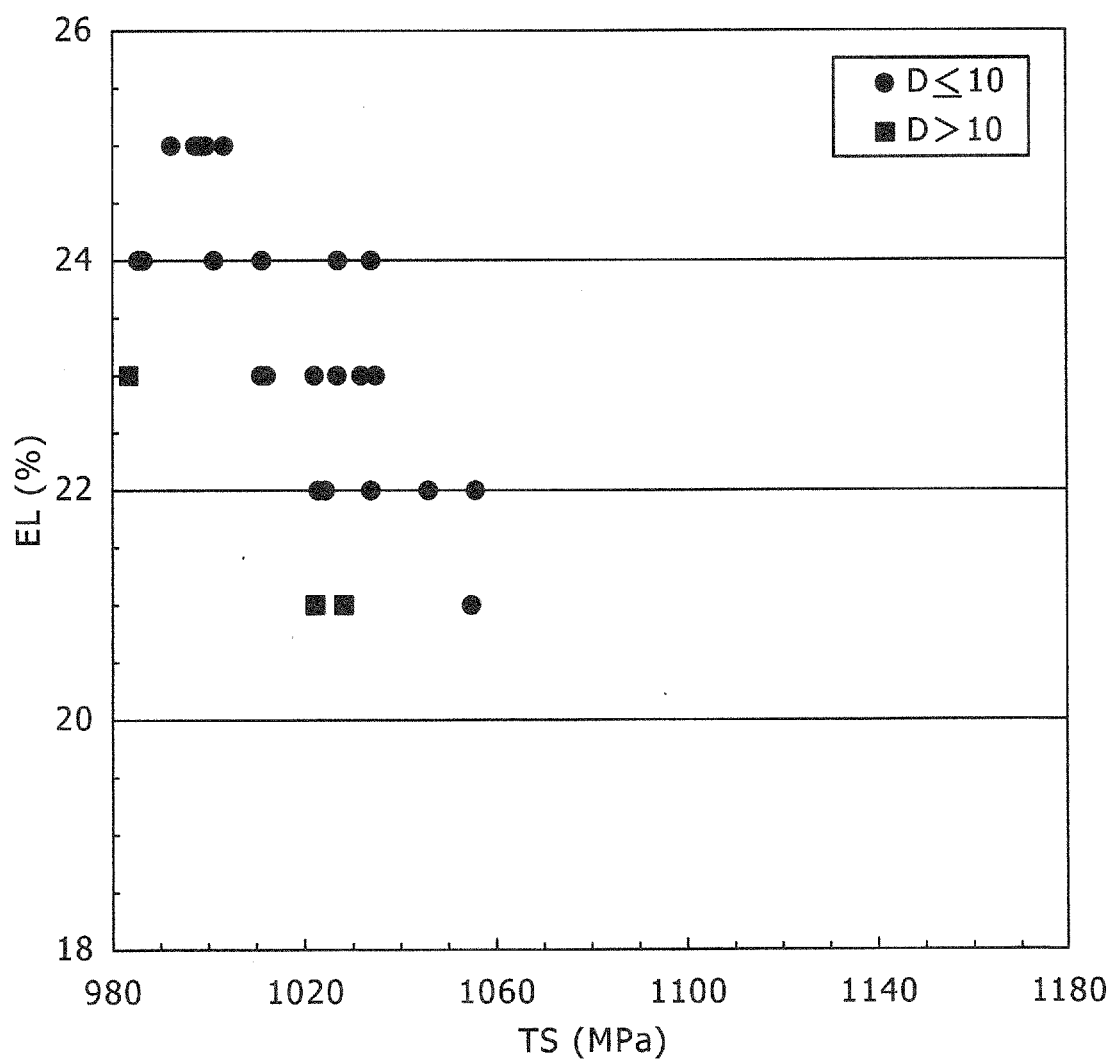
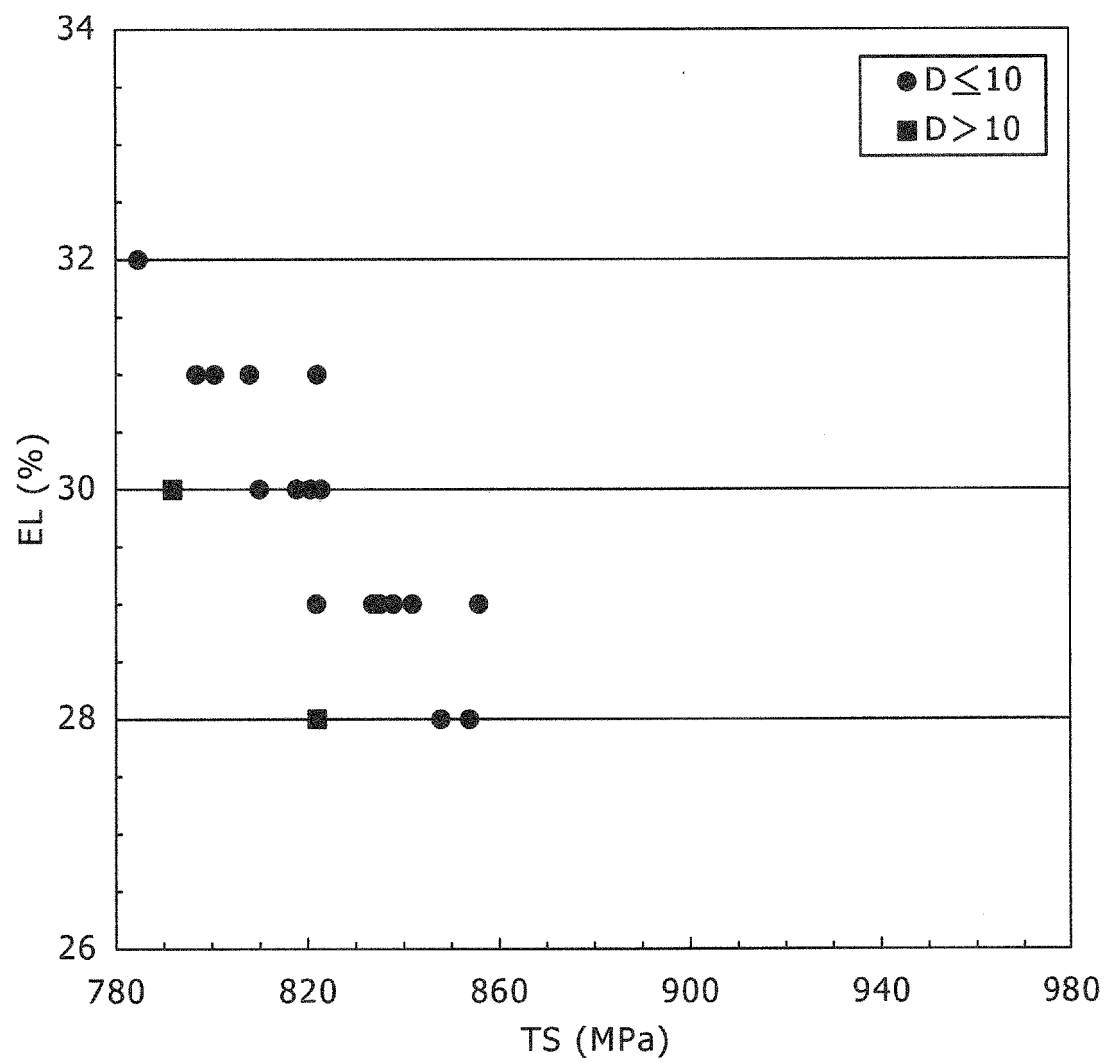


FIG. 5



REFERENCES CITED IN THE DESCRIPTION

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