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(54) **STEEL SHEET AND METHOD FOR PRODUCING SAME**

(57) Provided are a steel sheet having a predetermined chemical composition, and a microstructure comprising, by area%, martensite: 90.0% or more and retained austenite: 3.0% or less, wherein a mean particle

size of prior austenite grains is 30.0 μm or less, and a standard deviation in particle size of prior austenite grains is 4.0 μm or more, and a method of production of the same.

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Description

FIELD

5 **[0001]** The present invention relates to a steel sheet and a method of production of the same.

BACKGROUND

10 **[0002]** In recent years, to deal with environmental issues, lightening the weight of auto parts has been desired for the purpose of reduction of emission of CO₂ gas and improvement of fuel efficiency. On the other hand, there have been increasing social calls for improvement of collision safety. To achieve both lighter weight and improved collision safety, increasing the strength of steel materials is an effective means. However, usually, if increasing the strength of steel materials, the workability falls, and therefore steel materials simultaneously improved in strength and workability have been considered necessary.

15 **[0003]** Relating to improvement of strength and workability, for example, PTL 1 describes a high strength steel sheet containing C: 0.1 to 0.25%, Si: 0.1 to 0.5%, Mn: 0.5 to 2.0%, Cr: 0.1 to 1.5%, Mo: 0.1 to 0.5%, Ti: 0.01 to 0.05%, and Nb: 0.01 to 0.05%, additionally containing V: 0.01 to 0.05% and/or B: 0.0001 to 0.005%, and having a balance of iron and unavoidable impurities, having a mean particle size of prior austenite of 20 μm or less, and having a standard deviation (σ) of prior austenite grains size distribution of 5 μm or less. Further, PTL 1 teaches that, according to the above-mentioned
20 constitution, it is possible to refine the prior austenite particle size and reduce fluctuation in the same and possible to realize a high strength steel sheet maintaining a high strength of a tensile strength of 980 MPa or more while being improved in bendability.

[0004] PTL 2 describes high strength/high ductility fine-martensite structure steel material containing C: 0.075 to 0.3 wt%, Mn: 3 to 10 wt%, and Si: 0 to 2.5 wt% and having a balance of Fe and unavoidable impurities, having a prior γ particle
25 size of 2.0 μm or less, and having a structure of equiaxed martensite having single blocks. Further, PTL 2 teaches that according to this high strength/high ductility fine martensite structure steel material, a tensile strength of 1200 MPa or more and a total elongation of 10% or more can be achieved.

[0005] PTL 3 describes a high strength steel material with prior γ-grains of a spherical shape containing, by mass%, C: 0.06 to 0.19%, Si: 0.15 to 0.60%, Mn: 0.60 to 1.80%, Cr: 0.05 to 1.20%, and Mo: 0.05 to 1.00% and also containing one or
30 more of Nb: 0.005 to 0.10%, V: 0.005 to 0.10%, and Ti: 0.005 to 0.10%, having particle size 100 nm or less carbonitrides of Nb, Ti, or V in a volume ratio of 0.01 to 0.8%, and having prior γ-grains of a particle size number 7 or more and having, inside the prior γ-grains, a martensite structure or a mixed structure of martensite and bainite. Further, PTL 3 teaches that according to the above-mentioned constitution, it becomes possible to provide a high strength steel material excellent in
35 toughness, arrestability, and weldability, having a large uniform elongation of over 10%, and having good mass producibility.

[CITATION LIST]

[PATENT LITERATURE]

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[0006]

[PTL 1] Japanese Unexamined Patent Publication No. 2009-242832

[PTL 2] Japanese Unexamined Patent Publication No. 2019-143244

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[PTL 3] Japanese Unexamined Patent Publication No. 2002-088440

SUMMARY

[TECHNICAL PROBLEM]

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[0007] As explained above, along with an increase in strength, the workability of the steel material falls. As described in PTLs 1 to 3, it is known that aside from bendability, total elongation, and uniform elongation such as described in PTLs 1 to 3, the hole expandability and other properties fall. If the hole expandability falls, for example, in the transmission parts, etc., of automobiles, sometimes formation of the desired shapes is not possible. For this reason, in the development of a high
55 strength hot rolled steel sheet and other high strength steel sheet, it is important to secure a certain level or more of properties in accordance with the application while trying to increase the strength. Further, a steel sheet for automotive use is often press-formed to work it to the target part shape. For example, in the transmission parts of automobiles, there are parts having complicated shapes such as the lower arms and trailing arms. Usually, press-forming is performed divided

into several steps, and therefore, for example, there are a relatively large number of locations receiving primary deformation resulting in strain being stored inside the steel sheet and in that state receiving separate deformation (stretch flange deformation, etc.) However, if strain is introduced to a steel sheet, work hardening occurs resulting in higher strength, and therefore in the later steps, the workability generally falls. For this reason, a steel sheet is being asked to exhibit high formability by for example having excellent work hardening ability (performance of continuing to become harder) even in a state where a certain degree of strain is introduced.

[0008] The present invention was made in consideration of this actual situation and has as its object to provide, by a novel constitution, a steel sheet which, despite being high strength, is improved in hole expandability and work hardening ability, and a method of production of the same.

[SOLUTION TO PROBLEM]

[0009] The inventors engaged in studies focusing on the microstructure of a steel sheet, in particular a hot rolled steel sheet, to achieve the above object. As a result, the inventors discovered that by making the microstructure of a hot rolled steel sheet having a predetermined chemical composition a structure mainly comprised of martensite, it is possible to achieve higher strength and improved hole expandability and that by limiting the mean particle size of prior austenite grains in the microstructure to within a predetermined range while increasing the variation in particle size of the prior austenite grains, it is possible to remarkably improve the work hardening ability, and thereby completed the present invention.

[0010] The present invention able to achieve the above object is as follows:

(1) A steel sheet having a chemical composition comprising, by mass%,

C: 0.040 to 0.200%,

Si: 0.30 to 2.00%,

Mn: 1.00 to 4.00%,

sol. Al: 0.001 to 0.500%,

P: 0.100% or less,

S: 0.0300% or less,

N: 0.0070% or less,

O: 0.0100% or less,

Nb: 0.001 to 1.000%,

Ti: 0 to 0.200%,

V: 0 to 0.300%,

Cu: 0 to 0.40%,

Cr: 0 to 0.90%,

Mo: 0 to 0.12%,

Ni: 0 to 0.30%,

B: 0 to 0.0030%,

Ca: 0 to 0.0010%,

Mg: 0 to 0.0010%,

Bi: 0 to 0.010%,

Zr: 0 to 0.050%,

Co: 0 to 0.010%,

Zn: 0 to 0.010%,

W: 0 to 0.100%,

Sn: 0 to 0.040%,

As: 0 to 0.100%,

REM: 0 to 0.0100%, and

balance: Fe and impurities, and

a microstructure comprising, by area%,

martensite: 90.0% or more, and

retained austenite: 3.0% or less, wherein

a mean particle size of prior austenite grains is 30.0 μm or less, and

a standard deviation in particle size of prior austenite grains is 4.0 μm or more.

(2) The steel sheet according to the above (1), wherein the chemical composition comprises, by mass%, at least one of

Ti: 0.001 to 0.200%,

V: 0.001 to 0.300%,
 Cu: 0.001 to 0.40%,
 Cr: 0.001 to 0.90%,
 Mo: 0.001 to 0.12%,
 Ni: 0.001 to 0.30%,
 B: 0.0001 to 0.0030%,
 Ca: 0.0001 to 0.0010%,
 Mg: 0.0001 to 0.0010%,
 Bi: 0.001 to 0.010%,
 Zr: 0.001 to 0.050%,
 Co: 0.001 to 0.010%,
 Zn: 0.001 to 0.010%,
 W: 0.001 to 0.100%,
 Sn: 0.001 to 0.040%,
 As: 0.001 to 0.100%, and
 REM: 0.0001 to 0.0100%.

(3) The steel sheet according to the above (1) or (2), wherein the microstructure further comprises, by area%, at least one of

ferrite: 10.0% or less,
 bainite: 10.0% or less, and
 pearlite: 10.0% or less.

(4) The steel sheet according to any one of the above (1) to (3), wherein a sheet thickness is 1.0 to 7.0 mm.

(5) A part including the steel sheet according to any one of the above (1) to (4).

(6) A method of production of a steel sheet comprising

continuously casting of casting a slab having a chemical composition according to the above (1) or (2), wherein an average cooling speed at 600 to 900°C is controlled to 10 to 50°C/min and an average cooling speed gradient is controlled to 40°C/min² or less,
 heating the cast slab and holding it in a temperature region of 1100°C or more for 6000 seconds or more,
 hot rolling including finish rolling of the slab, wherein the finish rolling satisfies conditions of following (a) to (c):

- (a) a rolling reduction at each rolling pass at one stage before a last stage and at the last stage is 20 to 50%,
- (b) a total rolling reduction is 90% or more, and
- (c) a final rolling temperature is 960 to 1100°C,

starting cooling of the finish rolled steel sheet within 0.5 to 10.0 seconds after completion of the hot rolling, then cooling the steel sheet down to a temperature of 400°C or less within 20.0 seconds from the start of cooling, and coiling the cooled steel sheet in a temperature region of 400°C or less.

[ADVANTAGEOUS EFFECTS OF INVENTION]

[0011] According to the present invention, it is possible to provide a steel sheet, in particular a hot rolled steel sheet, which, despite being high strength, is improved in hole expandability and work hardening ability, and a method of production of same.

DESCRIPTION OF EMBODIMENTS

<Steel Sheet>

[0012] The steel sheet according to an embodiment of the present invention, in particular the hot rolled steel sheet, has a chemical composition comprising, by mass%,

C: 0.040 to 0.200%,
 Si: 0.30 to 2.00%,
 Mn: 1.00 to 4.00%,

sol. Al: 0.001 to 0.500%,
 P: 0.100% or less,
 S: 0.0300% or less,
 N: 0.0070% or less,
 5 O: 0.0100% or less,
 Nb: 0.001 to 1.000%,
 Ti: 0 to 0.200%,
 V: 0 to 0.300%,
 Cu: 0 to 0.40%,
 10 Cr: 0 to 0.90%,
 Mo: 0 to 0.12%,
 Ni: 0 to 0.30%,
 B: 0 to 0.0030%,
 Ca: 0 to 0.0010%,
 15 Mg: 0 to 0.0010%,
 Bi: 0 to 0.010%,
 Zr: 0 to 0.050%,
 Co: 0 to 0.010%,
 Zn: 0 to 0.010%,
 20 W: 0 to 0.100%,
 Sn: 0 to 0.040%,
 As: 0 to 0.100%,
 REM: 0 to 0.0100%, and
 balance: Fe and impurities, and
 25 a microstructure comprising, by area%,
 martensite: 90.0% or more, and
 retained austenite: 3.0% or less, wherein
 a mean particle size of prior austenite grains is 30.0 μm or less, and
 a standard deviation in particle size of prior austenite grains is 4.0 μm or more.

30 **[0013]** As explained previously, it is known that along with an increase in the strength of a steel material, the hole expandability and other properties fall. For example, to produce a part having a complicated shape such as a lower arm, trailing arm, etc., among the transmission parts of an automobile, a steel sheet securing a high strength, in particular high strength of a tensile strength of 980 MPa or more enabling reduction of weight, while having excellent hole expandability is being sought. From the viewpoint of raising the strength, the microstructure of the steel sheet is preferably made a structure
 35 mainly comprised of martensite. However, martensitic steel has a layered structure including packets, blocks, laths, and other substructures in the prior austenite grains. While excellent in strength, in general, there is a problem of a low workability. For this reason, in forming operations performed divided into several steps such as press-forming, due to the work hardening caused by strain introduced in the initial period of deformation, in the latter period of deformation, the workability generally falls. Therefore, a steel sheet able to realize both high strength and workability by exhibiting a high work hardening ability even in the latter period of deformation of press-forming is being sought.

[0014] Therefore, the inventors engaged in studies focusing in particular on the microstructure of the hot rolled steel sheet in addition to prescribing a suitable chemical composition of the steel sheet, in particular the hot rolled steel sheet. First, the inventors discovered that by making the microstructure of hot rolled steel sheet having a predetermined chemical composition a structure mainly comprised of martensite, more specifically, a structure containing, by area%, martensite:
 45 90.0% or more and retained austenite: 3.0% or less, it is possible to achieve high strength, for example, high strength of a tensile strength of 980 MPa or more, while remarkably improving the hole expandability of the hot rolled steel sheet. While not intending to be bound by any specific theory, it is believed that by making the microstructure a more uniform structure comprising martensite in an area% of 90.0% or more, it is possible to reduce the hardness difference in the microstructure compared with the case where other structures softer than martensite, for example, ferrite, etc., are contained in relatively
 50 large amounts and that due to such reduction of the hardness difference, the hole expandability can be improved. Further, retained austenite can become starting points for fracture during deformation in press-forming, etc., and therefore by limiting the retained austenite to an area% of 3.0% or less in addition to controlling the martensite to an area% of 90.0% or more, the hole expandability can be improved more remarkably.

55 **[0015]** Next, since it is believed prior austenite grain boundaries act as resistance against motion of dislocations and would be effective for improving work hardening ability, the inventors studied improvement of the work hardening ability from the viewpoint of making the particle size of the prior austenite grains in a microstructure mainly comprised of martensite a suitable one. More specifically, by making the prior austenite grains finer, it is possible to increase the density

of prior austenite grain boundaries. For this reason, it is possible to increase the obstacles to dislocation by making the prior austenite grains finer and therefore it becomes possible to raise the work hardening ability. However, if just making the prior austenite grains finer, for example, sometimes a sufficient work hardening ability cannot be exhibited in a latter period of deformation of a forming operation such as press-forming performed divided into several steps. Therefore, the inventors took note of control of the particle size distribution, more specifically control of the variation in particle size, in addition to control of the particle size in prior austenite grains, and studied the same. As a result, the inventors discovered that by making the prior austenite grains finer within a predetermined range, more specifically controlling the mean particle size of prior austenite grains to 30.0 μm or less, the work hardening ability of the hot rolled steel sheet as a whole is improved while by making the variation in particle size of the prior austenite grains greater, more specifically by controlling the standard deviation in the particle size of prior austenite grains to 4.0 μm or more, it is possible to achieve a high work hardening rate even in a state where a certain extent of strain is introduced such as at the latter period of press-forming.

[0016] While not intending to be bound by any specific theory, it is believed that by controlling the standard deviation in the particle size of prior austenite grains to 4.0 μm or more, it is possible to form a mixed grain structure of coarse grains and fine grains mixed together and that such a mixed grain structure contributes to a high work hardening rate in the latter period of press-forming and other deformation. More specifically, it is believed that by forming a mixed grain structure of coarse grains and fine grains mixed together, uneven deformation is induced during press-forming or other working and as a result a sufficient work hardening ability can be maintained even in the latter period of deformation and therefore it becomes possible to achieve a high work hardening rate. Due to this, for example, even at locations receiving primary deformation in press-forming, etc., and then again receiving separate deformation (stretch flange deformation, etc.) in a state with strain stored inside the steel sheet, if steel sheet according to an embodiment of the present invention, the high work hardening ability is maintained, and therefore stable forming becomes possible. The fact that in a microstructure mainly comprised of martensite, by increasing the variation in particle size of the prior austenite grains and forming a mixed grain structure of coarse grains and fine grains mixed together, it is possible to improve the work hardening ability of steel sheet had not been known in the past and was clarified by the inventors this time. As a result, according to the steel sheet according to an embodiment of the present invention, for example, despite the tensile strength being a high strength of 980 MPa or more, the hole expandability and work hardening ability can be remarkably improved. Therefore, the steel sheet according to an embodiment of the present invention can reliably achieve both the contradictory properties of high strength and excellent workability, and therefore is particularly useful in use in the automotive field where realization of both of these properties is sought.

[0017] Below, the steel sheet according to an embodiment of the present invention will be explained in more detail. In the following explanation, the "%" of the units of contents of the elements, unless otherwise indicated, means "mass%". Further, in this Description, the "to" showing a numerical range, unless otherwise indicated, is used in the sense of the numerical values described before and after the same being included as the lower limit value and the upper limit value.

[C: 0.040 to 0.200%]

[0018] C is an element effective for raising the strength of steel sheet. Further, C forms carbides and/or carbonitrides with Nb in the steel and contributes to refinement of the structure by the pinning effect of the precipitates formed. To sufficiently obtain these effects, the C content is 0.040% or more. The C content may also be 0.060% or more, 0.080% or more, 0.100% or more, or 0.120% or more. On the other hand, if excessively containing C, sometimes the workability falls. Therefore, the C content is 0.200% or less. The C content may also be 0.180% or less, 0.160% or less, 0.150% or less, or 0.140% or less.

[Si: 0.30 to 2.00%]

[0019] Si is an element effective for raising the strength as a solution strengthening element. To sufficiently obtain such an effect, the Si content is 0.30% or more. The Si content may also be 0.40% or more, more than 0.50%, 0.51% or more, 0.52% or more, 0.53% or more, 0.54% or more, 0.55% or more, more than 0.55%, 0.60% or more, 0.70% or more, 0.85% or more, 1.00% or more, or 1.20% or more. On the other hand, if excessively containing Si, the chemical convertability and workability fall and during hot rolling, slab cracking sometimes occurs. Therefore, the Si content is 2.00% or less. The Si content may also be 1.80% or less, 1.60% or less, 1.50% or less, or 1.40% or less.

[Mn: 1.00 to 4.00%]

[0020] Mn is an element effective for raising the hardenability and the strength as a solution strengthening element. To sufficiently obtain these effects, the Mn content is 1.00% or more. The Mn content may also be 1.20% or more, 1.50% or more, 1.80% or more, 2.00% or more, or 2.20% or more. On the other hand, if excessively containing Mn, the workability sometimes falls. Therefore, the Mn content is 4.00% or less. The Mn content may also be 3.80% or less, 3.50% or less,

3.20% or less, 3.00% or less, or 2.80% or less.

[sol. Al: 0.001 to 0.500%]

5 **[0021]** sol. Al is an element acting as a deoxidizer of molten steel. Further, sol. Al is an element suppressing the precipitation of the cementite so harmful to hole expandability. To obtain these effects, the sol. Al content is 0.001% or more. The sol. Al content may also be 0.010% or more, 0.020% or more, 0.030% or more, 0.050% or more, or 0.100% or more. On the other hand, even if excessively containing sol. Al, the effect becomes saturated and a rise in production costs is liable to be invited. Therefore, the sol. Al content is 0.500% or less. The sol. Al content may also be 0.400% or less,
10 0.300% or less, or 0.200% or less. "sol. Al" means acid soluble Al and indicates solid solution Al present in the steel in a solid solution state.

[P: 0.100% or Less]

15 **[0022]** If P is excessively contained, sometimes grain boundary segregation, etc., causes the workability to fall. Therefore, the P content is 0.100% or less. The P content may also be 0.050% or less, 0.030% or less, 0.020% or less, or 0.015% or less. The lower limit of the P content is not particularly prescribed and may also be 0%, but excessive reduction would invite a rise in costs. Therefore, the P content may also be 0.0001% or more, 0.001% or more, or 0.005% or more.

20 [S: 0.0300% or Less]

[0023] If S is excessively contained, sometimes MnS and other sulfides are formed in large amounts and the workability is made to fall. Therefore, the S content is 0.0300% or less. The S content may also be 0.0200% or less, 0.0100% or less, or
25 0.0050% or less. The lower limit of the S content is not particularly prescribed and may also be 0%, but excessive reduction would invite a rise in costs. Therefore, the S content may also be 0.0001% or more, 0.0010% or more, or 0.0030% or more.

[N: 0.0070% or Less]

30 **[0024]** If N is excessively contained, sometimes coarse nitrides are formed and the workability is made to fall. Therefore, the N content is 0.0070% or less. The N content may also be 0.0050% or less, 0.0040% or less, or 0.0030% or less. The lower limit of the N content is not particularly prescribed and may also be 0%, but excessive reduction would invite a rise in costs. Therefore, the N content may also be 0.0001% or more or 0.0005% or more.

35 [O: 0.0100% or Less]

[0025] O is an element entering in the production process. If excessively containing O, coarse inclusions are formed and the workability of the steel sheet is liable to fall. Therefore, the O content is 0.0100% or less. The O content may also be 0.0080% or less, 0.0060% or less, or 0.0040% or less. The lower limit of the O content is not particularly prescribed and
40 may also be 0%, but reduction to less than 0.0001% would require time for refining and invite a drop in productivity. Therefore, the O content may also be 0.0001% or more or 0.0005% or more.

[Nb: 0.001 to 1.000%]

45 **[0026]** Nb is an element forming carbides, nitrides, and/or carbonitrides in the steel and contributes to refinement of the prior austenite grains and in turn higher strength of the steel sheet by the pinning effect. To sufficiently obtain these effects, the Nb content is 0.001% or more. The Nb content may also be 0.005% or more, 0.010% or more, 0.050% or more, 0.100% or more, 0.200% or more, or 0.300% or more. On the other hand, if excessively containing Nb, coarse carbides, etc., are formed in the steel and the workability of the steel sheet sometimes falls. Therefore, the Nb content is 1.000% or less. The
50 Nb content may also be 0.800% or less, 0.600% or less, or 0.500% or less.

[0027] The basic chemical composition of the steel sheet according to an embodiment of the present invention is as explained above. Furthermore, the steel sheet may, according to need, further contain at least one of the following elements in place of part of the balance of Fe.

55 [Cr: 0 to 0.90%]

[0028] Cr is an element raising the hardenability of steel and contributing to improvement of the strength and/or corrosion resistance. The Cr content may also be 0%, but to obtain these effects, the Cr content is preferably 0.001% or

more and may also be 0.01% or more, 0.05% or more, or 0.10% or more. On the other hand, even if excessively containing Cr, the effect becomes saturated and a rise in production costs is liable to be invited. Therefore, the Cr content is preferably 0.90% or less and may also be 0.70% or less, 0.50% or less, 0.40% or less, or 0.30% or less.

- 5 [Ti: 0 to 0.200%, V: 0 to 0.300%, Cu: 0 to 0.40%, Mo: 0 to 0.12%, Ni: 0 to 0.30%, B: 0 to 0.0030%, Ca: 0 to 0.0010%, Mg: 0 to 0.0010%, Bi: 0 to 0.010%, Zr: 0 to 0.050%, Co: 0 to 0.010%, Zn: 0 to 0.010%, W: 0 to 0.100%, Sn: 0 to 0.040%, As: 0 to 0.100%, and REM: 0 to 0.0100%]

- 10 **[0029]** Ti, V, Cu, Mo, Ni, B, Ca, Mg, Bi, Zr, Co, Zn, W, Sn, As, and REM may be contained in the steel sheet as optional elements or sometimes are present in the steel sheet as tramp elements. The contents of these elements may also be Ti: 0 to 0.200%, or 0.100%, V: 0 to 0.300%, or 0.200%, Cu: 0 to 0.40%, or 0.20%, Mo: 0 to 0.12%, 0.09%, 0.08%, 0.06%, or 0.04%, Ni: 0 to 0.30%, or 0.15%, B: 0 to 0.0030%, or 0.0015%, Ca: 0 to 0.0010%, or 0.0008%, Mg: 0 to 0.0010%, or 0.0008%, Bi: 0 to 0.010%, Zr: 0 to 0.050%, or 0.030%, Co: 0 to 0.010%, Zn: 0 to 0.010%, W: 0 to 0.100%, or 0.050%, Sn: 0 to 0.040%, or 0.020%, As: 0 to 0.100%, or 0.050%, and REM: 0 to 0.0100%, or 0.0050%. Regarding the lower limit values of
15 these elements, for example, the Ti, V, Cu, Mo, Ni, Bi, Zr, Co, Zn, W, Sn, and As contents may also be 0.001% or more, 0.005% or more, or 0.008% or more. Similarly, the B, Ca, Mg and REM content may also be 0.0001% or more, 0.0002% or more, or 0.0005% or more.

- [0030]** In the steel sheet according to an embodiment of the present invention, the balance besides the above-mentioned elements is comprised of Fe and impurities. The "impurities" are constituents, etc., entering from ore, scrap,
20 and other such starting materials due to various factors in the production process when, for example, industrially producing the steel sheet. They are allowed to be included in a range not affecting the effect of the present invention.

- [0031]** The chemical composition of the steel sheet according to an embodiment of the present invention may be measured by a general analysis method. For example, the chemical composition of the steel sheet may be measured by inductively coupled plasma-atomic emission spectrometry (ICP-AES). C and S can be measured using the combustion-
25 infrared absorption method, N using the inert gas melting-thermal conductivity method, and O using the inert gas melting-nondispersive type infrared absorption method.

[Microstructure]

- 30 [Martensite: 90.0% or More and Retained Austenite: 3.0% or Less]

- [0032]** The microstructure of the steel sheet according to an embodiment of the present invention includes, by area%, martensite: 90.0% or more and retained austenite: 3.0% or less. By configuring the microstructure of the steel sheet to include these structures, it is possible to achieve high strength, for example, high strength of a tensile strength of 980 MPa
35 or more, while remarkably improving the hole expandability of the obtained steel sheet. More specifically, by controlling the hard martensite to a range of, by area%, 90.0% or more to obtain a more uniform structure, not only is higher strength contributed to, but also the hardness difference in the microstructure can be reduced. Due to such reduction of the hardness difference, the hole expandability can be improved. If the area ratio of the martensite is less than 90.0%, the desired strength and hole expandability cannot be achieved. From the viewpoint of further higher strength and improved
40 hole expandability, the higher the area ratio of martensite, the more preferable. For example, it may be 92.0% or more, 94.0% or more, 96.0% or more, or 98.0% or more. The upper limit of the area ratio of martensite is not particularly prescribed and may also be 100.0%. For example, it may be 99.0% or less. On the other hand, retained austenite can form starting points for fracture during deformation in press-forming, etc., and therefore by controlling the martensite to an area% of 90.0% or more plus controlling the retained austenite to an area% of 3.0% or less, it becomes possible to more
45 remarkably improve the hole expandability. If the area ratio of the retained austenite is more than 3.0%, the grains form starting points for fracture during deformation and the hole expandability falls. From the viewpoint of further improving the hole expandability, the lower the area ratio of the retained austenite, the more preferable. For example, it may be 2.5% or less, 2.0% or less, 1.5% or less, or 1.0% or less. The lower limit of the area ratio of the retained austenite is not particularly limited and may be 0%. For example, it may be 0.5% or more.

- 50 [Balance Structure]

- [0033]** The balance structure besides the martensite and retained austenite may be an area% of 0%, but if there is a balance structure present, the balance structure may include at least one of ferrite: 10.0% or less, bainite: 10.0% or less,
55 and pearlite: 10.0% or less. If the area ratio of the at least one of ferrite, bainite, and pearlite is a total of more than 10.0%, the area ratio of martensite becomes less than 90.0%, and therefore as a result the desired strength and hole expandability can no longer be achieved. The lower limits of ferrite, bainite, and pearlite may respectively be 0%. For example, they may be respectively 0.1% or more, 0.5% or more, 1.0% or more, 2.0% or more, or 3.0% or more. Similarly, the upper limits of

ferrite, bainite, and pearlite may be respectively 8.0% or less, 6.0% or less, 5.0% or less, or 4.0% or less.

[Identification of Microstructure and Calculation of Area Ratios]

[0034] The microstructure in steel sheet is identified and the area ratios are calculated by examination under an optical microscope and X-ray diffraction after corrosion using a Nital reagent or LePera solution. The structure is examined under an optical microscope at a sheet thickness cross-section in a direction vertical to the sheet surface. Note that the sheet thickness cross-section is preferably parallel to the rolling direction. Specifically, first, a sample is taken from the steel sheet and examined surface of the sample is etched by Nital. Next, an optical microscope is used to photograph a $300\text{ }\mu\text{m} \times 300\text{ }\mu\text{m}$ field at the 1/4 depth position of sheet thickness. The obtained structural photograph is analyzed to calculate the total area of the martensite and bainite and the individual area ratios of ferrite and pearlite. Next, the sample with the examined surface corroded by the LePera solution is used and an optical microscope is similarly used to photograph a $300\text{ }\mu\text{m} \times 300\text{ }\mu\text{m}$ field at the 1/4 depth position of sheet thickness. The obtained structural photograph is analyzed to calculate the total area ratio of martensite and retained austenite. Next, a sample ground at its surface down to 1/4 depth of sheet thickness from the logarithmic direction of the rolled surface is used to calculate the volume ratio of the retained austenite by X-ray diffraction measurement. The volume ratio of retained austenite is equal to the area ratio, and therefore this is deemed the area ratio of the retained austenite. The obtained area ratio of retained austenite is subtracted from the total area ratio of martensite and retained austenite similarly calculated previously to calculate the area ratio of martensite. Finally, the obtained area ratio of martensite is subtracted from the total area ratio of martensite and bainite similarly calculated in advance to thereby calculate the area ratio of the bainite.

[Mean Particle Size of Prior Austenite Grains: $30.0\text{ }\mu\text{m}$ or Less]

[0035] In the steel sheet according to an embodiment of the present invention, the mean particle size of the prior austenite grains is $30.0\text{ }\mu\text{m}$ or less. As explained previously, prior austenite grain boundaries act as resistance to motion of dislocations and are believed effective for improvement of the work hardening ability. In relation to this, by refining the prior austenite grains, it is possible to increase the density of the prior austenite grain boundaries. For this reason, by refining the prior austenite grains to $30.0\text{ }\mu\text{m}$ or less, it is possible to increase the obstacles to dislocation and therefore possible to raise the work hardening ability of the obtained steel sheet. From the viewpoint of further raising the work hardening ability of the steel sheet, the smaller the mean particle size of the prior austenite grains, the more preferable. For example, it may be $28.0\text{ }\mu\text{m}$ or less, $25.0\text{ }\mu\text{m}$ or less, $22.0\text{ }\mu\text{m}$ or less, $20.0\text{ }\mu\text{m}$ or less, $18.0\text{ }\mu\text{m}$ or less, or $15.0\text{ }\mu\text{m}$ or less. The lower limit is not particularly prescribed, but the mean particle size of the prior austenite grains may be, for example, $4.0\text{ }\mu\text{m}$ or more, $4.1\text{ }\mu\text{m}$ or more, $4.2\text{ }\mu\text{m}$ or more, $4.5\text{ }\mu\text{m}$ or more, $4.7\text{ }\mu\text{m}$ or more, $5.0\text{ }\mu\text{m}$ or more, $8.0\text{ }\mu\text{m}$ or more, $10.0\text{ }\mu\text{m}$ or more, or $12.0\text{ }\mu\text{m}$ or more.

[Standard Deviation in Particle Size of Prior Austenite Grains: $4.0\text{ }\mu\text{m}$ or More]

[0036] In an embodiment of the present invention, the standard deviation in particle size of prior austenite grains is $4.0\text{ }\mu\text{m}$ or more. By limiting the mean particle size of the prior austenite grains $30.0\text{ }\mu\text{m}$ or less while making the standard deviation in particle size of the prior austenite grains $4.0\text{ }\mu\text{m}$ or more, i.e., by increasing the variation in particle size of the prior austenite grains, it is possible to form a mixed structure of coarse grains and fine grains mixed together. It is believed that by forming such a mixed grain structure, uneven deformation is induced during press-forming and other working. As a result, sufficient work hardening ability can be maintained even in a state where a certain extent of strain is introduced such as the latter period of deformation in press-forming. For this reason, a high work hardening rate can be achieved. From the viewpoint of further raising the work hardening ability of steel sheet, the greater the standard deviation in particle size of the prior austenite grains, i.e., the greater the variation, the more preferable. For example, it may be $4.5\text{ }\mu\text{m}$ or more, $5.0\text{ }\mu\text{m}$ or more, more than $5.0\text{ }\mu\text{m}$, $5.1\text{ }\mu\text{m}$ or more, $5.2\text{ }\mu\text{m}$ or more, $5.3\text{ }\mu\text{m}$ or more, $5.4\text{ }\mu\text{m}$ or more, $5.5\text{ }\mu\text{m}$ or more, $6.0\text{ }\mu\text{m}$ or more, $8.0\text{ }\mu\text{m}$ or more, or $10.0\text{ }\mu\text{m}$ or more. The upper limit is not particularly prescribed, but the mean particle size of the prior austenite grains is $30.0\text{ }\mu\text{m}$ or less, and therefore the upper limit of the standard deviation is self set and cannot become any value. The upper limit is not particularly prescribed, but the standard deviation in particle size of prior austenite grains may be, for example, $20.0\text{ }\mu\text{m}$ or less, $15.0\text{ }\mu\text{m}$ or less, $12.0\text{ }\mu\text{m}$ or less, $10.0\text{ }\mu\text{m}$ or less, or $8.0\text{ }\mu\text{m}$ or less.

[0037] In the present invention, to achieve the desired work hardening ability, limiting the mean particle size of the prior austenite grains in the microstructure to $30.0\text{ }\mu\text{m}$ or less while controlling the standard deviation in particle size of prior austenite grains to $4.0\text{ }\mu\text{m}$ or more is extremely important. That is to say, this is because if either of the features is not satisfied, at least one of the effect of improvement of the work hardening ability due to refinement of the prior austenite grains and the effect of improvement of the work hardening ability due to the mixed grain structure of coarse grains and fine grains becomes insufficient. In particular, in a microstructure mainly comprised of martensite, in general the particle size of the prior austenite grains becomes relatively uniform, i.e., the standard deviation in the particle size becomes a relatively

small value. For this reason, in a microstructure where martensite accounts for an area% of 90.0% or more, limiting the mean particle size of the prior austenite grains to a range of 30.0 μm or less while going to the trouble of raising the variation in particle size of the prior austenite grains is not general practice. Therefore, creating such a microstructure is extremely difficult. Such a method has not been conventionally known. This time, as explained later in detail in relation to the method of production of the steel sheet, the inventors learned that in particular by performing the slab continuous casting step, hot rolling step, and cooling step under suitable conditions, it is possible to refine the prior austenite grains while forming a microstructure comprised of coarse grains and fine grains mixed together and, furthermore, first discovered the effect of improvement of the work hardening ability due to such a microstructure. Therefore, according to the steel sheet according to an embodiment of the present invention, by making the microstructure one mainly comprised of martensite and having prior austenite grains which are refined and having coarse grains and fine grains mixed together, it is possible to improve the high strength and hole expandability while remarkably improving the work hardening ability.

[Average Aspect Ratio of Prior Austenite Grains: 3.0 or Less]

[0038] The average aspect ratio of the prior austenite grains is not particularly limited, but, for example, it may be 3.0 or less, 2.5 or less, 2.0 or less, 1.8 or less, 1.6 or less, or 1.4 or less. By reducing the average aspect ratio of the prior austenite grains, it is possible to reduce the anisotropy of the microstructure. The lower limit is not particularly prescribed, but, for example, the average aspect ratio of the prior austenite grains may be 0.6 or more, 0.7 or more, or 0.8 or more. The present invention, as explained above, has as its object the provision of sheet steel which is high strength, yet despite this, is improved in hole expandability and work hardening ability. The above-mentioned object is achieved by forming the microstructure of steel sheet having a predetermined chemical composition by a structure mainly comprised of martensite and by limiting the mean particle size of the prior austenite grains in the microstructure to within a predetermined range while increasing the variation in particle size of the prior austenite grains. Therefore, it is clear that the average aspect ratio of the prior austenite grains is not a technical feature essential in achieving the object of the present invention.

[Methods of Determination of Mean Particle Size of Prior Austenite Grains, Standard Deviation in Particle Size of Prior Austenite Grains, and Average Aspect Ratio of Prior Austenite Grains]

[0039] The mean particle size of prior austenite grains, standard deviation in particle size of prior austenite grains, and average aspect ratio of prior austenite grains are determined in the following way. First, a sample is cut out from any position 50 mm or more away from the end faces of the steel sheet (if not possible to take a sample from that position, a position avoiding the end parts) so that a vertical sheet thickness cross-section can be examined. The sheet thickness cross-section is preferably parallel to the rolling direction. The size of the sample, while depending on the measurement device, is made a size enabling examination of about 10 mm in the direction vertical to the sheet thickness direction. The cross-section of the sample is polished using #600 to #1500 silicon carbide paper, then is finished to a mirror surface using particle size 1 to 6 μm diamond powder made to disperse in alcohol or other diluent or pure water. Next, electrolytic polishing is used to finish the examined surface. At the 1/4 depth position of sheet thickness in the longitudinal direction of the sample cross-section, a length 50 μm and sheet thickness direction 50 μm region is measured by electron backscatter diffraction at 0.1 μm measurement intervals to obtain crystal orientation information. For the measurement, an EBSD analysis apparatus comprised of a thermal field emission type scan electron microscope and EBSD detector may be used. For example, an EBSD analysis apparatus comprised of a JSM-7001F made by JEOL and a DVC5 type detector made by TSL may be used. At that time, the vacuum degree inside the EBSD analysis apparatus may be 9.6×10^{-5} Pa or less, the acceleration voltage may be 15 kV, and the probe current level may be 13. The obtained crystal orientation information is used to calculate the crystal orientation of the prior austenite grains from the crystal orientation relationship of general prior austenite grains and crystal grains having a body centered structure after transformation. For the method of calculating the crystal orientation of prior austenite grains, the following method is used. First, the method described in Acta Materialia, 58(2010), 6393-6403 is used to prepare a crystal orientation map of the prior austenite grains. At one of the prior austenite grains contained in the examined field, the average value of the shortest diameter and the longest diameter is calculated. The average value is made the particle size of the prior austenite grains. The above operation is performed for all of the prior austenite grains except for the prior austenite grains not contained in the photographed field in the entirety of the crystal grains such as at the end parts of the photographed field. The particle size of all of the prior austenite grains in the photographed field is sought. By calculating the mean particle size and standard deviation from the particle sizes of all of the prior austenite grains obtained, the mean particle size and standard deviation of the particle size of the prior austenite grains are determined.

[0040] Next, at one of the prior austenite grains contained in the examined field, the ratio of the diameter in the sheet thickness direction and diameter in the rolling direction (rolling direction diameter/sheet thickness direction diameter) is calculated and that value is used as the aspect ratio of the prior austenite grains. If the rolling direction is unclear, the cross-section is examined at a direction of 0°, 45°, 90°, and 135° with respect to any direction, the cross-section with the highest

aspect ratio among them is deemed the cross-section parallel to the rolling direction, and the ratio of the diameter in the sheet thickness direction and diameter in the rolling direction (rolling direction diameter/sheet thickness direction diameter) is calculated. The above operation is performed for all of the prior austenite grains except for the prior austenite grains not contained in the photographed field in the entirety of the crystal grains such as at the end parts of the photographed field. The aspect ratio of all of the prior austenite grains in the photographed field is sought. By arithmetically averaging the aspect ratios of all of the prior austenite grains obtained, the average aspect ratio of the prior austenite grains is determined.

[Sheet Thickness]

[0041] The steel sheet according to an embodiment of the present invention is not particularly limited, but in general it has a 1.0 to 8.0 mm sheet thickness. For example, the sheet thickness may also be 1.2 mm or more, 1.6 mm or more, or 2.0 mm or more and/or may also be 7.0 mm or less, 6.0 mm or less, 5.5 mm or less, 5.0 mm or less, 4.4 mm or less, 4.2 mm or less, or 4.0 mm or less.

[0042] The steel sheet according to an embodiment of the present invention can reliably realize the contradictory properties of high strength and excellent workability and is useful for use for parts in technical fields in which achievement of both of these properties is sought, etc. In particular, it is useful for use for parts in the automotive field, etc. For this reason, in a preferred embodiment, an auto part including steel sheet according to an embodiment of the present invention, in particular, a transmission of an automobile, is provided. As examples of transmission parts of automobiles, a lower arm, trailing arm, etc., may be mentioned. These auto parts, in particular transmission parts of automobiles, need only contain the steel sheet according to an embodiment of the present invention in at least portions of these parts. For this reason, at least portions of these parts satisfy the above features of the chemical composition and structure. At portions of the steel sheet with relatively low degrees of working in press-forming and other forming, the features of the steel sheet do not particularly change before and after forming. Portions of the steel sheet with relatively low degrees of working are judged by being flat in shape without being bent or otherwise deformed, by being small in rate of change of sheet thickness, and other features.

[Mechanical Properties]

[Tensile Strength: TS]

[0043] According to the steel sheet having the above-mentioned chemical composition and microstructure, in particular hot rolled steel sheet, it is possible to achieve a high tensile strength, specifically a tensile strength of 980 MPa or more. The tensile strength is preferably 1000 MPa or more, 1080 MPa or more, or 1180 MPa or more. According to the steel sheet according to an embodiment of the present invention, despite having such an extremely high tensile strength, it is possible to realize excellent hole expandability and work hardening ability by a specific combination of the chemical composition and microstructure explained above. The upper limit of the tensile strength is not particularly prescribed, but, for example, the tensile strength of the steel sheet is 1780 MPa or less, 1700 MPa or less, or 1600 MPa or less. The tensile strength is measured by taking a JIS No. 5 test piece from an orientation (C direction) where the longitudinal direction of the test piece becomes parallel to the rolling perpendicular direction of the steel sheet and performing a tensile test based on JIS Z 2241: 2011. For example, if it is difficult to obtain a JIS No. 5 test piece due to dimensional restrictions, it is possible to use another test piece described in JIS Z 2241: 2011. However, if the sheet thickness is less than 0.5 mm, 0.5 mm is made the lower limit for performing suitable evaluation. For example, if it is difficult to obtain a JIS No. 5 test piece due to dimensional restrictions and it is also difficult to use another test piece described in JIS Z 2241: 2011, it is possible to perform a micro Vickers test based on JIS Z 2244-1: 2020 and use the value obtained by converting that hardness (HV) to tensile strength. The sample used for the micro Vickers test can be prepared by the same method as the sample for evaluation of the mean particle size and aspect ratio of the prior austenite grains. The micro Vickers test may be performed by measuring 30 points at the sheet thickness 1/4 position by a load of 500 gf and using the average value. The conversion can be performed by the following formula:

$$\text{Tensile strength [MPa]} = 3.12 \times \text{Vickers hardness [HV]} + 16$$

[Hole Expansion Rate: λ]

[0044] According to the steel sheet having the above-mentioned chemical composition and microstructure, it is possible to obtain a high hole expandability, specifically a hole expansion rate of 45% or more. The hole expansion rate may be preferably 50% or more, more preferably 60% or more or 70% or more. The upper limit of the hole expansion rate is not

particularly prescribed, but, for example, the hole expansion rate may be 150% or less, 120% or less, or 100% or less. The hole expansion rate is determined in the following way: First, a width 100 mm×length 100 mm test piece is taken from the steel sheet and a punch hole (initial hole: hole diameter $d_0=10$ mm) is prepared using a punch tool with a punch diameter of 10 mm and die diameter of 10.25 to 11.5 mm (clearance 12.5%). Next, while set so that the burr became the die side, a 60° conical punch is used to expand the initial hole until a crack passing through the sheet thickness is formed. The hole diameter d_1 mm is measured at the time of cracking and the hole expansion rate λ (%) of each test piece is found by the following formula. This hole expansion test is conducted three times and the average value of the same is determined as the hole expansion rate λ .

$$\lambda=100\times\{(d_1-d_0)/d_0\}$$

<Method of Production of Steel Sheet>

[0045] Next, a preferable method of production of steel sheet according to an embodiment of the present invention will be explained. The following explanation is intended to illustrate the characteristic method for producing the steel sheet according to an embodiment of the present invention and is not intended to limit the steel sheet to one produced by the method of production such as explained below. More specifically, below, production of hot rolled steel sheet will be specifically shown, but the steel sheet according to an embodiment of the present invention encompasses any steel sheet having the above explained chemical composition and microstructure, i.e., not only hot rolled steel sheet, but also cold rolled steel sheet, plated steel sheet, etc. Therefore, the following description just simply explains a preferable method of production when the steel sheet according to an embodiment of the present invention is hot rolled steel sheet.

[0046] The method of production of the steel sheet according to an embodiment of the present invention comprises

continuously casting of casting a slab having a chemical composition explained above in relation to the steel sheet, wherein an average cooling speed at 600 to 900°C is controlled to 10 to 50°C/min and an average cooling speed gradient is controlled to 40°C/min² or less,

heating the cast slab and holding it in a temperature region of 1100°C or more for 6000 seconds or more,

hot rolling including finish rolling of the slab, wherein the finish rolling satisfies conditions of following (a) to (c):

- (a) a rolling reduction at each rolling pass at one stage before a last stage and at the last stage is 20 to 50%,
- (b) a total rolling reduction is 90% or more, and
- (c) a final rolling temperature is 960 to 1100°C,

starting cooling of the finish rolled steel sheet within 0.5 to 10.0 seconds after completion of the hot rolling, then cooling the steel sheet down to a temperature of 400°C or less within 20.0 seconds from the start of cooling, and coiling the cooled steel sheet in a temperature region of 400°C or less.

[0047] In the above-mentioned method of production, the temperatures described for the slab and steel sheet respectively mean the surface temperature of the slab and the surface temperature of the steel sheet. Below, the steps will be explained in detail.

[Continuous Casting Step]

[0048] First, a slab having the chemical composition explained in relation to the steel sheet is cast in the continuous casting step. The temperature history at the time of solidification is suitably controlled, more specifically is controlled so that the average cooling speed at 600 to 900°C becomes 10 to 50°C/min and the average cooling speed gradient becomes 40°C/min² or less. By controlling the continuous casting step so that the average cooling speed at 600 to 900°C becomes 10 to 50°C/min and the average cooling speed gradient becomes 40°C/min² or less, it becomes possible to achieve the desired mean particle size and standard deviation in particle size of the prior austenite grains in the microstructure of the finally obtained steel sheet.

[0049] If the average cooling speed at 600 to 900°C is less than 10°C/min, since the average cooling speed is slow, the crystal grains formed by transformation to body centered cubic structures (bcc structures) at the time of solidification become coarser and the mean particle size of the prior austenite grains in the finally obtained microstructure becomes greater than 30.0 μm . In this case, it becomes no longer possible to achieve a sufficient work hardening ability in the obtained steel sheet. On the other hand, if the average cooling speed at 600 to 900°C is more than 50°C/min, since the average cooling speed is fast, the crystal grains become fine and uniform in the process of transformation of the solidified structure. The mean particle size of the prior austenite grains in the finally obtained microstructure becomes smaller, but it

is not possible to increase the variation in the particle size. That is, the standard deviation in particle size of the prior austenite grains becomes smaller than $4.0\text{ }\mu\text{m}$ and similarly sufficient work hardening ability can no longer be achieved.

[0050] In the present method of production, the "average cooling speed gradient at 600 to 900°C" means the average of the rate of change of the cooling speed per unit time in 600 to 900°C. For example, in the case where a cooling speed changes to 50°C/min from 10°C/min, the average cooling speed gradient in the present method of production becomes $40^\circ\text{C}/\text{min}^2$. Conversely, even in the case where the cooling speed changes from 50°C/min to 10°C/min, the average cooling speed gradient in the present method of production becomes $40^\circ\text{C}/\text{min}^2$. If the average cooling speed gradient at 600 to 900°C becomes more than $40^\circ\text{C}/\text{min}^2$, the fluctuation of the cooling speed becomes too great, and therefore uneven cooling occurs. In such a case, a phenomenon arises where just specific crystal grains abnormally grow in the process of transformation of the solidified structure and it becomes no longer possible to obtain the desired mean particle size and/or the standard deviation in particle size of the prior austenite grains. As a result, in the finally obtained steel sheet, it becomes no longer possible to achieve a sufficient work hardening ability. The average cooling speed gradient at 600 to 900°C is preferably $30^\circ\text{C}/\text{min}^2$ or less. The lower limit is not particularly prescribed, but the average cooling speed gradient at 600 to 900°C may also be $2^\circ\text{C}/\text{min}^2$ or more or $3^\circ\text{C}/\text{min}^2$ or more.

[Heating Step]

[0051] The cast slab is heated at the next heating step and is held in the temperature region of 1100°C or more for 6000 seconds or more. In the present method of production, "holding at the temperature region of 1100°C or more" includes not only the case of holding the temperature of the slab at a 1100°C or more fixed temperature but encompasses the case of holding the temperature of the slab while fluctuating in the temperature region of 1100°C or more. By holding the slab at the temperature region of 1100°C or more for 6000 seconds or more, it is possible to make the coarse carbides present in the structure completely dissolve and possible to eliminate starting points of cracking. If the holding time is less than 1100°C or the holding time is less than 6000 seconds, the coarse carbides become incompletely dissolved. If the coarse carbides are incompletely dissolved, in the cooling step explained later, due to the occurrence of ferrite or bainite transformation starting from such carbides, the area ratio of martensite becomes less than 90.0% and as a result it becomes no longer possible to obtain the desired strength and/or hole expandability. The upper limit of the heating temperature of the slab is preferably 1300°C or less or 1200°C or less. Similarly, the upper limit of the holding time at the temperature region of 1100°C or more is preferably 10000 seconds or less.

[Hot Rolling Step]

[Rough Rolling]

[0052] In the present method of production, for example, the heated slab may be rough rolled before the finish rolling so as to adjust the sheet thickness, etc. The rough rolling need only be able to secure the desired sheet bar dimensions. The conditions are not particularly limited.

[(a) Rolling Reduction in Rolling Passes of One Stage Before Last Stage and the Last Stage: 20 to 50%]

[0053] The heated slab or the slab additionally rough rolled in accordance with need is next finish rolled. In the present method of production, the finish rolling is performed using a tandem rolling mill comprised of several rolling stands, for example, five or more rolling stands. In the present method of production, in the finish rolling performed on the heated slab, the rolling reduction at each rolling pass at the last two stages, i.e., one stage before the last stage and the last stage, is controlled to 20 to 50%. At each rolling pass at one stage before the last stage and the last stage, by rolling by such a relatively high rolling reduction, recrystallization is promoted and the microstructure can be made finer and in addition the average aspect ratio of the prior austenite grains can be reduced. If the rolling reduction at each rolling pass at one stage before the last stage and the last stage is less than 20%, recrystallization either is not completed or is not sufficiently promoted and in the microstructure of the finally obtained steel sheet, the desired mean particle size of the prior austenite grains sometimes cannot be reached and/or the average aspect ratio of the prior austenite grains sometimes becomes a relatively large value. If the desired mean particle size of the prior austenite grains cannot be achieved, sufficient work hardening ability no longer can be obtained. On the other hand, if the rolling reduction at each rolling pass of one stage before the last stage and/or the last stage is too high, the rolling load becomes excessive and the burden of the rolling mill and other facilities becomes higher. For this reason, the rolling reduction at each rolling pass of one stage before the last stage and the last stage is 50% or less. Preferably the rolling reduction at each rolling pass of one stage before the last stage and the last stage is 45% or less.

[(b) Overall Rolling Reduction: 90% or More]

[0054] In the present method of production, the total rolling reduction in the final rolling is controlled to 90% or more. The Mn contained in the steel is an element causing a drop in the fracture energy of the grain boundaries, and therefore if there are regions where Mn is locally concentrated, sometimes occurrence of cracking is promoted at the time of plastic deformation in the press-forming, etc. There, from the viewpoint of further improving the hole expandability, suppressing or reducing local concentration of Mn would be effective. By controlling the total rolling reduction in finish rolling to 90% or more, it is possible to make the Mn disperse in the steel and in turn suppress or reduce the variation in Mn concentration in the steel, i.e., suppress or reduce the local concentration of Mn. If the total rolling reduction in the finish rolling is less than 90%, the variation in Mn concentration becomes relatively high and locally, Mn concentrates and growth of regions with reduced fracture energy sometimes cannot be sufficiently suppressed. The upper limit of the total rolling reduction in the finish rolling may be, for example, 99% or less or 98% or less. Here, the total rolling reduction in the finish rolling is calculated by the following formula:

Total rolling reduction (%) = (sheet thickness before finish rolling - sheet thickness after finish rolling) / sheet thickness before finish rolling × 100

[(c) Final Rolling Temperature: 960 to 1100°C]

[0055] In the present method of production, in addition to control of the rolling reduction at each rolling pass of the last two stages of the finish rolling, the final rolling temperature (end temperature of finish rolling) is also extremely important in controlling the microstructure of the steel sheet. If the final rolling temperature is less than 960°C, recrystallization either is not completed or is not sufficiently promoted and in the microstructure of the finally obtained steel sheet, the desired mean particle size of the prior austenite grains sometimes cannot be reached and/or the average aspect ratio of the prior austenite grains sometimes becomes a relatively large value. If not possible to achieve the desired mean particle size of the prior austenite grains, it becomes no longer possible to obtain sufficient work hardening ability. On the other hand, if the final rolling temperature is more than 1100°C, the prior austenite grains become coarser overall and sometimes it is not possible to achieve the desired mean particle size of the prior austenite grains and/or standard deviation in particle size of the prior austenite grains. In this case as well, only naturally, it becomes no longer possible to obtain a sufficient work hardening ability.

[Cooling Step]

[Time From After Completion of Hot Rolling Step to Start of Cooling: 0.5 to 10.0 Seconds]

[Time From Start of Cooling to Becoming 400°C or Less: 20.0 Seconds or Less]

[0056] The finish rolled steel sheet starts to be cooled in the next cooling step within 0.5 to 10.0 seconds after the completion of the hot rolling step, then is cooled down to a temperature of 400°C or less within 20.0 seconds from the start of cooling. By performing such cooling control, in the microstructure of the finally obtained steel sheet, it is possible to achieve the desired mean particle size and standard deviation in particle size of the prior austenite grains.

[0057] If the time from the completion of the hot rolling step to the start of cooling is less than 0.5 second, grain growth does not sufficiently proceed and it becomes no longer possible to obtain the desired standard deviation in particle size of the prior austenite grains. Further, if the time from the completion of the hot rolling step to the start of cooling is more than 10.0 seconds, overall, grain growth proceeds too much and it becomes no longer possible to obtain the desired mean particle size of the prior austenite grains and/or standard deviation in particle size of the prior austenite grains. As a result, in each case, it becomes no longer possible to achieve sufficient work hardening ability in the steel sheet. On the other hand, if the cooling time from the start of cooling down to 400°C or less is more than 20.0 seconds or if the cooling stop temperature is more than 400°C, the area ratio of the martensite becomes less than 90.0% and as a result it becomes no longer possible to obtain the desired strength and/or hole expandability.

[Coiling Step]

[0058] Finally, the cooled steel sheet is coiled up at a temperature region of 400°C or less whereby the steel sheet is produced. If the coiling temperature is more than 400°C, in the same way as the case of the cooling step, the area ratio of the martensite becomes less than 90.0% and as a result it becomes no longer possible to obtain the desired strength and/or hole expandability.

[0059] According to the steel sheet produced by above-mentioned method of production, by configuring the micro-

structure by a more uniform structure containing, by area%, martensite: 90.0% or more and retained austenite: 3.0% or less, it is possible to achieve a high strength, for example, a high strength of a tensile strength of 980 MPa or more, while remarkably improving the hole expandability due to the reduction of the hardness difference, etc. Furthermore, by controlling the mean particle size of the prior austenite grains in the microstructure to 30.0 μm or less, it becomes possible to improve the work hardening ability of the steel sheet as a whole while by controlling the standard deviation in the particle size of the prior austenite grains to 4.0 μm or more, it becomes possible to achieve a high work hardening rate even in a state where a certain extent of strain is introduced such as in the latter period of deformation in press-forming. Therefore, the steel sheet produced according to the above-mentioned method of production can reliably achieve both the contradictory properties of high strength and excellent workability, and therefore is particularly useful in use in the automotive field where realization of both of these properties is sought.

[0060] Below, examples will be used to explain the present invention in more detail, but the present invention is not limited to these examples in any way.

EXAMPLES

[0061] In the following examples, steel sheets according to an embodiment of the present invention, in particular hot rolled steel sheets, were produced under various conditions and investigated for the tensile strength (TS), hole expansion rate (λ), and work hardening rate (WHR) of the obtained steel sheets.

[0062] First, molten steels were cast by the continuous casting method under the conditions shown in Table 3 to form slabs having the various chemical compositions shown in Tables 1 and 2. These slabs were heated to 1100 to 1200°C in temperature and held over the time periods shown in Table 3, then were hot rolled. The hot rolling was performed by rough rolling and finish rolling. More specifically, the rough rolling was performed under the same conditions in all of the examples and comparative examples while the finish rolling was performed under the conditions shown in Table 3 using a tandem rolling mill comprised of five rolling stands. Finally, the finish rolled steel sheets were cooled and coiled under the conditions shown in Table 3 to obtain steel sheets having the sheet thicknesses shown in Table 4.

[Table 1]

[0063]

Table 1

Steel no.	Chemical composition (mass%), balance of Fe and impurities									Remarks
	C	Si	Mn	sol.Al	P	s	N	O	Nb	
A	0.070	0.71	2.47	0.028	0.002	0.0008	0.0013	0.0038	0.021	Inv. steel
B	0.044	1.73	2.36	0.059	0.023	0.0057	0.0009	0.0012	0.052	Inv. steel
C	0.182	1.55	3.21	0.067	0.004	0.0039	0.0024	0.0059	0.067	Inv. steel
D	0.067	0.32	2.12	0.017	0.002	0.0041	0.0068	0.0022	0.034	Inv. steel
E	0.059	1.87	2.21	0.077	0.028	0.0022	0.0044	0.0018	0.041	Inv. steel
F	0.103	1.13	1.22	0.073	0.022	0.0040	0.0042	0.0014	0.035	Inv. steel
G	0.063	1.51	3.75	0.048	0.005	0.0022	0.0027	0.0068	0.072	Inv. steel
H	0.096	1.62	3.24	0.003	0.019	0.0020	0.0002	0.0045	0.054	Inv. steel
I	0.063	1.77	1.76	0.468	0.011	0.0043	0.0060	0.0027	0.068	Inv. steel
J	0.147	1.76	1.63	0.033	0.003	0.0018	0.0043	0.0035	0.002	Inv. steel
K	0.137	1.67	2.59	0.005	0.015	0.0055	0.0063	0.0022	0.896	Inv. steel
L	0.180	1.28	2.99	0.023	0.018	0.0038	0.0038	0.0021	0.035	Inv. steel
M	0.094	1.16	2.68	0.027	0.005	0.0051	0.0015	0.0028	0.074	Inv. steel
N	0.162	1.52	1.93	0.071	0.025	0.0024	0.0030	0.0045	0.033	Inv. steel
O	0.138	0.83	2.06	0.032	0.026	0.0041	0.0062	0.0022	0.078	Inv. steel
P	0.068	0.88	3.00	0.054	0.022	0.0044	0.0029	0.0036	0.071	Inv. steel
Q	0.054	0.96	1.68	0.043	0.027	0.0022	0.0052	0.0069	0.056	Inv. steel

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(continued)

Steel no.	Chemical composition (mass%), balance of Fe and impurities									Remarks
	C	Si	Mn	sol.Al	P	s	N	O	Nb	
R	0.113	1.78	2.71	0.059	0.019	0.0029	0.0025	0.0024	0.073	Inv. steel
S	0.073	0.65	1.56	0.016	0.019	0.0059	0.0009	0.0012	0.073	Inv. steel
T	0.149	1.72	2.50	0.035	0.010	0.0051	0.0060	0.0056	0.053	Inv. steel
U	0.077	1.79	1.55	0.027	0.019	0.0031	0.0018	0.0048	0.077	Inv. steel
V	<u>0.036</u>	1.72	1.58	0.012	0.023	0.0039	0.0058	0.0024	0.049	Comp. steel
W	<u>0.239</u>	1.07	2.38	0.034	0.005	0.0001	0.0037	0.0032	0.051	Comp. steel
X	0.070	<u>0.28</u>	2.55	0.028	0.001	0.0005	0.0011	0.0036	0.022	Comp. steel
Y	0.071	<u>2.21</u>	3.61	0.029	0.003	0.0050	0.0066	0.0028	0.046	Comp. steel
Z	0.137	1.54	<u>0.86</u>	0.013	0.030	0.0025	0.0008	0.0013	0.051	Comp. steel
AA	0.083	1.72	<u>4.31</u>	0.063	0.028	0.0007	0.0022	0.0024	0.048	Comp. steel
AB	0.173	0.96	2.80	<u>0.000</u>	0.007	0.0010	0.0005	0.0029	0.060	Comp. steel
AC	0.138	1.45	2.51	0.044	0.029	0.0021	0.0015	0.0071	<u>0.000</u>	Comp. steel
AD	0.071	0.93	1.31	0.014	0.015	0.0023	0.0035	0.0069	<u>1.135</u>	Comp. steel
Underlines indicate outside scope of present invention.										

[Table 2]

[0064]

Table 2

Steel no.	Chemical composition (mass%), balance of Fe and impurities																Remarks	
	Ti	V	Cu	Cr	Mo	Ni	B	Ca	Mg	Bi	Zr	Co	Zn	W	Sn	As		REM
A																		Inv. steel
B																		Inv. steel
C																		Inv. steel
D																		Inv. steel
E																		Inv. steel
F																		Inv. steel
G																		Inv. steel
H																		Inv. steel
I																		Inv. steel
J																		Inv. steel
K																		Inv. steel
L								0.0006	0.0007									Inv. steel
M																	0.0082	Inv. steel
N										0.007				0.078				Inv. steel
O											0.047					0.070		Inv. steel
P	0.173	0.166																Inv. steel
Q			0.28									0.008						Inv. steel
R				0.63														Inv. steel
S					0.09										0.030			Inv. steel
T						0.23												Inv. steel
U							0.0024						0.008					Inv. steel
V																		Comp. steel
W																		Comp. steel
X																		Comp. steel

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(continued)

Steel no.	Chemical composition (mass%), balance of Fe and impurities																Remarks	
	Ti	V	Cu	Cr	Mo	Ni	B	Ca	Mg	Bi	Zr	Co	Zn	W	Sn	As		REM
Y																		Comp. steel
Z																		Comp. steel
AA																		Comp. steel
AB																		Comp. steel
AC																		Comp. steel
AD																		Comp. steel

[Table 3]

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[0065]

Table 3

Production no.	Steel no.	Continuous casting step		Heating step	Hot rolling step				Cooling step		Remarks	
		600~900℃			Rolling reduction of one stage before last stage	Final stand rolling reduction	Total rolling reduction	Final rolling temperature	Time until cooling start	Time from cooling start to 400℃ or less		
		Average cooling speed	Average cooling speed gradient									
												°C/min
1	A	32	10	8760	41	40	94	1005	0.5	6.3	26	Inv. ex.
2	A	13	3	6624	22	45	98	996	3.0	5.6	382	Inv. ex.
3	A	47	11	9657	33	30	95	983	2.5	16.2	18	Inv. ex.
4	A	8	3	8164	26	25	96	990	1.3	8.8	33	Comp. ex.
5	A	53	14	7356	40	42	96	978	1.0	9.6	262	Comp. ex.
6	A	48	43	7651	33	33	97	1022	1.3	10.1	35	Comp. ex.
7	A	45	23	5822	27	25	98	1053	1.2	12.3	28	Comp. ex.
8	A	16	8	7358	16	32	96	992	5.1	18.2	27	Comp. ex.
9	A	24	5	7982	34	18	97	1039	1.6	7.6	27	Comp. ex.
10	A	44	18	8654	40	32	98	948	1.0	10.5	29	Comp. ex.
11	A	40	12	8423	35	33	97	1132	1.8	8.3	25	Comp. ex.
12	A	34	20	7877	28	29	95	1027	0.3	9.3	31	Comp. ex.
13	A	17	2	6385	26	30	91	989	14.2	11.6	25	Comp. ex.
14	A	25	5	9275	33	30	93	1062	3.2	23.8	23	Comp. ex.
15	A	32	10	7914	34	28	92	1005	1.7	10.3	435	Comp. ex.
16	B	25	15	9312	30	28	96	1051	9.3	8.6	12	Inv. ex.
17	C	33	13	9450	31	36	96	991	2.8	16.7	17	Inv. ex.
18	D	26	8	7256	26	35	95	978	1.5	7.8	16	Inv. ex.
19	E	30	9	9380	35	38	91	984	2.3	15.9	11	Inv. ex.

(continued)

Production no.	Steel no.	Continuous casting step		Heating step	Hot rolling step				Cooling step		Coiling step	Remarks
		600~900℃			Rolling reduction of one stage before last stage	Final stand rolling reduction	Total rolling reduction	Final rolling temperature	Time until cooling start	Time from cooling start to 400℃ or less		
		Average cooling speed	Average cooling speed gradient									
		℃/min	℃/min ²	Holding time at 1100℃ or more	%	%	%	℃	s	s	℃	
20	F	24	7	7737	27	27	93	999	5.4	18.1	15	Inv. ex.
21	G	35	4	7354	38	36	94	1068	1.0	9.2	15	Inv. ex.
22	H	31	6	8433	37	29	95	1013	4.3	19.1	15	Inv. ex.
23	I	42	4	8157	32	27	96	1065	2.8	8.6	14	Inv. ex.
24	J	34	16	8643	25	25	94	1068	5.2	14.3	25	Inv. ex.
25	K	26	8	9010	30	24	93	1036	3.8	8.1	13	Inv. ex.
26	L	15	6	6968	34	30	93	1013	1.5	10.4	22	Inv. ex.
27	M	15	3	7416	27	28	97	973	3.0	12.5	25	Inv. ex.
28	N	15	9	6940	29	36	95	974	4.7	10.8	24	Inv. ex.
29	O	37	15	7712	25	24	95	1041	7.2	9.1	25	Inv. ex.
30	P	28	6	6981	25	35	93	1063	6.8	9.0	17	Inv. ex.
31	Q	18	9	8295	28	37	93	1013	2.9	15.6	19	Inv. ex.
32	R	26	16	8078	34	34	95	1022	4.1	7.4	12	Inv. ex.
33	S	33	3	8589	31	28	92	1045	7.3	11.3	17	Inv. ex.
34	T	34	20	6814	25	33	97	1027	4.8	18.8	17	Inv. ex.
35	U	44	4	8548	24	29	91	994	4.4	9.7	14	Inv. ex.
36	V	42	21	7960	31	28	97	1061	2.5	13.1	22	Comp. ex.
37	W	28	8	8502	24	24	94	1032	6.8	12.6	19	Comp. ex.
38	X	15	6	6375	33	24	96	995	2.7	8.9	19	Comp. ex.
39	Y	31	12	9230	36	26	94	1044	7.4	10.5	26	Comp. ex.

(continued)

Production no.	Steel no.	Continuous casting step		Heating step	Hot rolling step				Cooling step		Remarks	
		600~900°C			Rolling reduction of one stage before last stage	Final stand rolling reduction	Total rolling reduction	Final rolling temperature	Time until cooling start	Time from cooling start to 400°C or less		
		Average cooling speed	Average cooling speed gradient									
40	Z	32	6	s	%	%	%	°C	s	s	°C	Comp. ex.
41	AA	41	16	8755	37	29	93	984	7.3	6.5	19	Comp. ex.
42	AB	41	8	8785	28	37	94	1021	3.4	16.9	16	Comp. ex.
43	AC	22	4	8865	37	26	92	982	2.8	13.3	13	Comp. ex.
44	AD	22	11	9471	27	30	96	1026	7.3	16.2	20	Comp. ex.
44	AD	22	11	8104	28	33	94	1042	3.7	17.5	23	Comp. ex.
Underlines indicate production conditions not preferable.												

[0066] The properties of the obtained steel sheets were measured and evaluated by the following methods:

[Tensile Strength (TS)]

5 **[0067]** The tensile strength (TS) was measured by taking a JIS No. 5 test piece from an orientation (C direction) where the longitudinal direction of the test piece became parallel with a rolling perpendicular direction of each steel sheet and performing a tensile test based on JIS Z 2241: 2011.

[Hole Expansion Rate (λ)]

10 **[0068]** The hole expansion rate was determined in the following way: First, a width 100 mm $\times$ length 100 mm test piece was taken from each steel sheet and a punch hole (initial hole: hole diameter $d_0=10$ mm) was prepared using a punch tool with a punch diameter of 10 mm and die diameter of 10.25 to 11.5 mm (clearance 12.5%). Next, while set so that the burr became the die side, a 60° conical punch was used to expand the initial hole until a crack passing through the sheet
15 thickness was formed. The hole diameter d_1 mm was measured at the time of cracking and the hole expansion rate λ (%) of each test piece was found by the following formula. This hole expansion test was conducted three times and the average value of the same was determined as the hole expansion rate λ :

$$20 \quad \lambda = 100 \times \{(d_1 - d_0) / d_0\}$$

[Work Hardening Ability]

25 **[0069]** The work hardening ability was evaluated by finding the work hardening rate (WHR) from a tensile test. Specifically, a state where the region where the strain (true strain) during tensile deformation when performing a tensile test the same as the case of measurement of TS became 0.04 or more was deemed as simulating the state of the latter period of deformation in press-forming, and the maximum value of the work hardening rate (WHR) in that region was found by the following formula:

$$30 \quad \text{WHR (MPa)} = d\sigma / d\varepsilon$$

where, σ is the true stress and ε is the true strain.

35 **[0070]** Cases where the tensile strength (TS) of the steel sheet was 980 MPa or more, the hole expansion rate (λ) was 45% or more, and a maximum value of the work hardening rate (WHR) in a region of true strain of 0.04 or more became 1000 MPa or more despite the high strength were evaluated as steel sheet improved in hole expandability and work hardening ability regardless of being high strength. The results are shown in Table 4.

[Table 4]

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[0071]

Table 4

Production no.	Steel no	Sheet thickness	Microstructure							Mechanical properties			Remarks	
			Martensite	Retained γ	Ferrite	Bainite	Pearlite	Prior austenite grains			TS	λ		Maximum work hardening rate at true strain ≥ 0.04
								Mean particle size	Standard deviation	Mean aspect ratio				
		mm	Area%	Area%	Area%	Area%	Area%	μm	μm	-	MPa	%	MPa	
1	A	3.2	98.6	0.1	0.0	1.3	0.0	14.1	4.1	1.3	1198	81	1036	Inv. ex.
2	A	3.2	97.8	0.7	0.0	1.5	0.0	28.6	5.2	1.0	1182	88	1626	Inv. ex.
3	A	2.9	95.5	1.0	0.0	3.5	0.0	17.7	4.2	1.4	1201	76	1154	Inv. ex.
4	A	3.3	95.7	0.8	0.0	3.5	0.0	38.8	4.2	1.0	1187	46	862	Comp. ex.
5	A	3.0	92.3	0.4	3.2	4.1	0.0	12.5	2.3	1.7	1211	53	793	Comp. ex.
6	A	3.5	95.5	0.6	0.0	3.9	0.0	32.5	3.7	1.4	1108	68	963	Comp. ex.
7	A	3.0	74.4	2.7	8.2	3.4	11.3	18.8	5.8	1.4	1269	28	1296	Comp. ex.
8	A	4.4	98.9	0.1	0.0	1.0	0.0	42.1	6.4	2.8	1210	49	978	Comp. ex.
9	A	3.5	94.2	1.9	0.0	3.9	0.0	48.6	5.3	3.3	1116	48	975	Comp. ex.
10	A	2.8	95.8	1.0	0.0	3.2	0.0	60.2	6.3	5.6	1185	46	942	Comp. ex.
11	A	2.6	97.8	0.8	0.0	1.4	0.0	34.2	3.8	1.0	1043	59	835	Comp. ex.
12	A	2.9	97.0	1.4	0.0	1.6	0.0	16.9	3.6	1.3	1285	97	766	Comp. ex.
13	A	4.4	95.9	0.0	0.0	4.1	0.0	33.9	3.8	1.6	1241	60	957	Comp. ex.
14	A	3.1	83.6	0.1	12.4	2.7	1.2	22.1	5.4	1.3	1294	25	1113	Comp. ex.
15	A	2.7	84.5	1.8	0.0	13.7	0.0	23.5	4.7	0.9	1074	29	1057	Comp. ex.
16	B	4.4	95.7	1.4	0.0	2.9	0.0	23.4	4.6	0.8	986	83	1562	Inv. ex.
17	C	1.5	93.7	1.4	0.0	4.9	0.0	22.5	7.0	1.1	1539	97	1452	Inv. ex.
18	D	3.0	94.0	1.0	0.0	5.0	0.0	22.3	6.8	1.6	983	92	1323	Inv. ex.
19	E	3.6	95.7	2.8	0.0	1.5	0.0	20.2	7.5	1.8	1286	96	1679	Inv. ex.
20	F	3.4	90.6	0.6	8.1	0.7	0.0	24.4	6.6	0.8	992	78	1155	Inv. ex.

(continued)

Production no.	Steel no	Sheet thickness	Microstructure							Mechanical properties			Remarks	
			Martensite	Retained γ	Ferrite	Bainite	Pearlite	Prior austenite grains			TS	λ		Maximum work hardening rate at true strain $\geq$ 0.04
								Mean particle size	Standard deviation	Mean aspect ratio				
		mm	Area%	Area%	Area%	Area%	Area%	μm	μm	-	MPa	%	MPa	
21	G	4.3	94.4	1.5	0.0	4.1	0.0	15.0	5.8	1.4	1482	72	1131	Inv. ex.
22	H	3.2	90.8	1.3	0.0	7.9	0.0	19.3	5.8	1.3	1200	73	1522	Inv. ex.
23	I	4.1	95.0	0.1	0.0	4.9	0.0	16.3	5.2	1.2	1124	61	1397	Inv. ex.
24	J	6.5	97.9	0.2	0.0	1.9	0.0	22.4	5.8	1.3	999	59	1356	Inv. ex.
25	K	3.6	97.2	0.5	0.0	2.3	0.0	14.9	5.9	1.8	1187	65	1437	Inv. ex.
26	L	4.3	96.8	1.0	0.0	2.2	0.0	25.1	6.6	1.1	1030	95	1415	Inv. ex.
27	M	2.7	96.7	2.2	0.0	1.1	0.0	16.2	5.1	0.9	1177	98	1528	Inv. ex.
28	N	3.3	96.3	2.1	0.0	1.6	0.0	13.4	4.3	1.1	1063	89	1464	Inv. ex.
29	O	2.5	97.0	1.2	0.0	1.8	0.0	26.4	6.8	1.6	1290	58	1211	Inv. ex.
30	P	3.5	97.8	0.8	0.0	1.4	0.0	14.6	5.4	1.5	1286	60	1442	Inv. ex.
31	Q	3.8	94.2	1.7	0.0	4.1	0.0	20.5	7.4	1.4	1003	54	1638	Inv. ex.
32	R	3.0	97.8	1.4	0.0	0.8	0.0	14.2	7.5	1.5	1037	60	1582	Inv. ex.
33	s	4.3	96.6	0.6	0.0	2.8	0.0	16.0	6.3	1.1	1041	87	1377	Inv. ex.
34	T	3.4	90.6	0.2	0.0	1.1	8.1	25.7	5.3	0.8	1237	81	1260	Inv. ex.
35	U	2.9	95.3	0.5	0.0	4.2	0.0	18.0	4.3	0.8	1281	94	1147	Inv. ex.
36	v	3.7	94.8	1.8	0.0	3.4	0.0	24.5	6.0	0.8	968	83	1175	Comp. ex.
37	w	3.5	96.1	3.3	0.0	0.6	0.0	19.4	5.5	1.0	1642	38	1562	Comp. ex.
38	X	3.1	96.3	2.6	0.0	1.1	0.0	20.7	5.2	1.7	963	96	1224	Comp. ex.
39	Y	2.7	94.8	3.7	0.0	1.5	0.0	16.0	4.4	1.2	1308	39	1175	Comp. ex.
40	z	3.7	83.4	2.2	8.6	3.7	2.1	22.6	6.3	1.3	958	30	1228	Comp. ex.
41	AA	4.1	95.5	0.0	0.0	4.5	0.0	24.1	4.5	1.2	1537	35	1684	Comp. ex.

(continued)

Production no.	Steel no	Sheet thickness	Microstructure						Mechanical properties			Remarks		
			Martensite	Retained γ	Ferrite	Bainite	Pearlite	Prior austenite grains			TS		λ	Maximum work hardening rate at true strain $\geq$ 0.04
								Mean particle size	Standard deviation	Mean aspect ratio				
		mm	Area%	Area%	Area%	Area%	Area%	μm	μm	-	MPa	%	MPa	
42	AB	3.7	98.5	0.3	0.0	1.2	0.0	23.0	7.5	1.4	1073	38	1530	Comp. ex.
43	AC	2.3	97.1	1.7	0.0	1.2	0.0	36.1	4.6	1.2	1157	93	953	Comp. ex.
44	AD	2.8	95.3	0.1	0.0	4.6	0.0	23.9	6.7	1.8	1130	42	1314	Comp. ex.
Underlines indicate outside scope of present invention or not preferable properties.														

[0072] Referring to Tables 1 to 4, in Comparative Example 4, the average cooling speed at 600 to 900°C in the continuous casting step was slow, and therefore it is believed the crystal grains became coarser. As a result, the mean particle size of the prior austenite grains in the finally obtained microstructure became larger and the work hardening ability of the steel sheet fell. In Comparative Example 5, the average cooling speed at 600 to 900°C in the continuous casting step was fast, and therefore it is believed that crystal grains became fine and uniform in the process of transformation of the solidified structure. As a result, the standard deviation in the particle size of the prior austenite grains in the finally obtained microstructure became smaller and the work hardening ability of the steel sheet fell. In Comparative Example 6, the average cooling speed gradient at 600 to 900°C in the continuous casting step was large, and therefore it is believed the cooling speed fluctuated too much and uneven cooling resulted. As a result, the desired mean particle size and the standard deviation in the particle size of the prior austenite grains could not be obtained and the work hardening ability of the steel sheet fell. In Comparative Example 7, the holding time at the temperature region of 1100°C or more in the heating step was short, and therefore it is believed the coarse carbides incompletely dissolved and in the subsequent cooling step, the carbides became starting points for ferrite or bainite transformation, etc. As a result, the area ratio of martensite became less than 90.0% and λ fell. In each of Comparative Examples 8 and 9, the rolling reduction in the rolling pass of one stage before the last stage and in the last stage of the finish rolling was low, and therefore it is believed the recrystallization was not completed or was not sufficiently promoted. As a result, the mean particle size of the prior austenite grains in the finally obtained microstructure became greater and the work hardening ability of the steel sheet fell. In Comparative Example 10, the final rolling temperature at the finish rolling was low, and therefore it is believed the recrystallization was not completed or was not sufficiently promoted. As a result, the mean particle size of the prior austenite grains in the finally obtained microstructure became greater and the work hardening ability of the steel sheet fell. In Comparative Example 11, the final rolling temperature in the finish rolling was high, and therefore it is believed the prior austenite grains became coarser overall. As a result, the mean particle size and particle size of the prior austenite grains in the finally obtained microstructure became greater and the work hardening ability of the steel sheet fell. In Comparative Example 12, the time from after completion of the hot rolling step to the start of the cooling step was short, and therefore it is believed grain growth did not sufficiently proceed. As a result, the desired standard deviation in the particle size of the prior austenite grains could not be obtained and the work hardening ability of the steel sheet fell. In Comparative Example 13, the time from after completion of the hot rolling step to the start of the cooling step was long, and therefore it is believed that overall grain growth proceeded too much. As a result, the desired mean particle size and standard deviation of the particle size of the prior austenite grains in the finally obtained microstructure could not be obtained and the work hardening ability of the steel sheet fell. In Comparative Example 14, the time from the start of cooling in the cooling step until becoming 400°C or less was long, and therefore the area ratio of martensite became less than 90.0% and λ fell. In Comparative Example 15, the coiling temperature was high, and therefore similarly the area ratio of martensite became less than 90.0% and λ fell.

[0073] In each of Comparative Examples 36 and 38, the C and Si contents were low, and therefore the TS fell. On the other hand, in each of Comparative Example 37 and Comparative Example 39, the C and Si contents were high, and therefore retained austenite was formed in a relatively large amount and λ fell. In Comparative Example 40, the Mn content was low, and therefore the hardenability fell and as a result the area ratio of martensite became low and the TS and λ fell. In Comparative Example 41, the Mn content was high, and therefore λ fell. In Comparative Example 42, the sol. Al content was low, and therefore it is believed precipitation of cementite could not be sufficiently suppressed. As a result, λ fell. In Comparative Example 43, the Nb content was low, and therefore it is believed refinement of the prior austenite grains by the pinning effect could not be sufficiently promoted. As a result, the mean particle size of the prior austenite grains in the finally obtained microstructure became larger and the work hardening ability of the steel sheet fell. In Comparative Example 44, the Nb content was high, and therefore it is believed coarse carbides, etc., were formed in the steel. As a result, λ fell.

[0074] In contrast to this, in the steel sheets according to all of the invention examples, by having a predetermined chemical composition and, furthermore, by suitably controlling the conditions in the method of production, it was possible to obtain steel sheet having a microstructure containing, by area%, martensite: 90.0% or more and retained austenite: 3.0% or less, having a mean particle size of prior austenite grains of 30.0 μm or less, and having a standard deviation in particle size of prior austenite grains of 4.0 μm or more. Further, as a result, regardless of being a high strength of a tensile strength of 980 MPa or more, it was possible to remarkably improve the hole expandability and work hardening ability.

Claims

1. A steel sheet having a chemical composition comprising, by mass%,

C: 0.040 to 0.200%,

Si: 0.30 to 2.00%,

Mn: 1.00 to 4.00%,

sol. Al: 0.001 to 0.500%,

P: 0.100% or less,

S: 0.0300% or less,

N: 0.0070% or less,

O: 0.0100% or less,

Nb: 0.001 to 1.000%,

Ti: 0 to 0.200%,

V: 0 to 0.300%,

Cu: 0 to 0.40%,

Cr: 0 to 0.90%,

Mo: 0 to 0.12%,

Ni: 0 to 0.30%,

B: 0 to 0.0030%,

Ca: 0 to 0.0010%,

Mg: 0 to 0.0010%,

Bi: 0 to 0.010%,

Zr: 0 to 0.050%,

Co: 0 to 0.010%,

Zn: 0 to 0.010%,

W: 0 to 0.100%,

Sn: 0 to 0.040%,

As: 0 to 0.100%,

REM: 0 to 0.0100%, and

balance: Fe and impurities, and

a microstructure comprising, by area%,

martensite: 90.0% or more, and

retained austenite: 3.0% or less, wherein

a mean particle size of prior austenite grains is 30.0 μm or less, and

a standard deviation in particle size of prior austenite grains is 4.0 μm or more.

2. The steel sheet according to claim 1, wherein the chemical composition comprises, by mass%, at least one of

Ti: 0.001 to 0.200%,

V: 0.001 to 0.300%,

Cu: 0.001 to 0.40%,

Cr: 0.001 to 0.90%,

Mo: 0.001 to 0.12%,

Ni: 0.001 to 0.30%,

B: 0.0001 to 0.0030%,

Ca: 0.0001 to 0.0010%,

Mg: 0.0001 to 0.0010%,

Bi: 0.001 to 0.010%,

Zr: 0.001 to 0.050%,

Co: 0.001 to 0.010%,

Zn: 0.001 to 0.010%,

W: 0.001 to 0.100%,

Sn: 0.001 to 0.040%,

As: 0.001 to 0.100%, and

REM: 0.0001 to 0.0100%.

3. The steel sheet according to claim 1 or 2, wherein the microstructure further comprises, by area%, at least one of

ferrite: 10.0% or less,

bainite: 10.0% or less, and

pearlite: 10.0% or less.

4. The steel sheet according to any one of claims 1 to 3, wherein a sheet thickness is 1.0 to 7.0 mm.

5. A part including the steel sheet according to any one of claims 1 to 4.

6. A method of production of a steel sheet comprising

5 continuously casting of casting a slab having a chemical composition according to claim 1 or 2, wherein an average cooling speed at 600 to 900°C is controlled to 10 to 50°C/min and an average cooling speed gradient is controlled to 40°C/min² or less,
heating the cast slab and holding it in a temperature region of 1100°C or more for 6000 seconds or more,
hot rolling including finish rolling of the slab, wherein the finish rolling satisfies conditions of following (a) to (c):

10 (a) a rolling reduction at each rolling pass at one stage before a last stage and at the last stage is 20 to 50%,
(b) a total rolling reduction is 90% or more, and
(c) a final rolling temperature is 960 to 1100°C,

15 starting cooling of the finish rolled steel sheet within 0.5 to 10.0 seconds after completion of the hot rolling, then cooling the steel sheet down to a temperature of 400°C or less within 20.0 seconds from the start of cooling, and coiling the cooled steel sheet in a temperature region of 400°C or less.

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2024/009480

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; *C21D 9/46*(2006.01)i; *C22C 38/58*(2006.01)i
FI: C22C38/00 301W; C22C38/58; C21D9/46 T

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2024
Registered utility model specifications of Japan 1996-2024
Published registered utility model applications of Japan 1994-2024

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

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A		6
A	WO 2019/216269 A1 (NIPPON STEEL CORPORATION) 14 November 2019 (2019-11-14) entire text	1-6
A	WO 2018/151273 A1 (NIPPON STEEL & SUMITOMO METAL CORPORATION) 23 August 2018 (2018-08-23) entire text	1-6
A	WO 2023/008003 A1 (JFE STEEL CORPORATION) 02 February 2023 (2023-02-02) entire text	1-6
A	WO 2016/031165 A1 (JFE STEEL CORPORATION) 03 March 2016 (2016-03-03) entire text	1-6



Further documents are listed in the continuation of Box C.



See patent family annex.

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“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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“&” document member of the same patent family

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International application No.

PCT/JP2024/009480

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2022/180146 A1 (SALZGITTER FLACHSTAHL GMBH) 01 September 2022 (2022-09-01) entire text, all drawings	1-6

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/JP2024/009480

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Form PCT/ISA/210 (patent family annex) (July 2022)

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