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# (54) HIGH-STRENGTH STEEL SHEET AND PROCESS FOR PRODUCING SAME

(57) Provided are a high-strength steel sheet, excellent in formability, having a TS of 600 MPa to 700 MPa, an El of 25% or more, and a $\lambda$ of 80% or more and a method for producing the same. A high-strength steel sheet has a composition containing 0.10% to 0.18% C, more than 0.5% to 1.5% Si, 0.5% to 1.5% Mn, 0.05% or less P, 0.005% or less S, and 0.05% or less Al on a mass basis, the remainder being Fe and inevitable impurities and also has a microstructure containing ferrite and pearlite. The volume fraction of the ferrite is 70% to 97%. The volume fraction of the pearlite is 3% or more. The volume fraction of cementite present at grain boundaries of the ferrite is 2% or less. The sum of the volume fractions of phases other than the ferrite, the pearlite, and the cementite is less than 3%. The average grain size of the ferrite is 7 $\mu$m or less.



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## Description

### Technical Field

[0001] The present invention relates to high-strength steel sheets, having excellent formability, applicable to automotive parts and particularly relates to a high-strength steel sheet having a tensile strength TS of 600 MPa to 700 MPa, an elongation El of 25% or more (in the case of a JIS #5 test specimen with a thickness of 1.6 mm), and a hole expansion ratio $\lambda$ of 80% or more, the hole expansion ratio $\lambda$ being an indicator for stretch flangeability, and a method for producing the same.

### Background Art

[0002] In recent years, the improvement of automotive fuel efficiency by automotive weight reduction has become an important issue from the viewpoint of environmental conservation. Therefore, gauge reduction and weight reduction have been investigated by increasing the strength of steel sheets which are materials of automotive parts. However, the increase in strength of steel sheets generally causes the reduction in ductility thereof; hence, high-strength steel sheets having both high strength and good formability are strongly needed.

[0003] Hitherto, several proposals have been made for high-strength steel sheets having excellent formability.

[0004] Patent Literature 1 discloses a high-strength steel sheet, having an excellent strength-hole expansion ratio balance and excellent shape fixability, for forming. The steel sheet contains 0.02% to 0.16% C, 0.010% or less P, 0.003% or more S, 0.2% to 4% one or both of Si and Al in total, and 0.5% to 4% one or more of Mn, Ni, Cr, Mo, and Cu in total as chemical components on a mass basis, the remainder being Fe and inevitable impurities, C / (Si + Al + P) being 0.1 or less. The cross-sectional microstructure of the steel sheet contains one or both of martensite and retained austenite, the sum of the area fraction of martensite and the area fraction of retained austenite being less than 3%, and one or both of ferrite and bainite, the sum of the area fraction of ferrite and the area fraction of bainite being 80% or more, the remainder being pearlite. The maximum length of pearlite, martensite, and retained austenite is 10 microns or less. The number of inclusions, having a size of 20 microns or more, present in a cross section of the steel sheet is 0.3 or less per square millimeter.

[0005] Patent Literature 2 discloses a hot-rolled steel containing 0.05% to less than 0.15% C, 0.8% to 1.2% Mn, 0.02% to 2.0% Si, 0.002% to less than 0.05% sol. Al, and 0.001%% to less than 0.005% N on a mass basis, the remainder being Fe and impurities. Each of Ti, Nb, and V in the impurities is less than 0.005%. The hot-rolled steel has a microstructure containing ferrite with an average grain size of 1.1 μm to 5.0 μm as a primary phase and one or both of pearlite and cementite as a secondary phase and satisfies the inequality $Mn\theta$ / $Mon\alpha \leq 1$, where $Mn\theta$ is the content of Mn in cementite in pearlite containing cementite and $Mn\alpha$ is the content of Mn in ferrite.

[0006] Patent Literature 3 discloses a method for producing a hot-rolled steel sheet in which the structural fraction of cementite with an equivalent circle radius of 0.1 μm or more is 0.1% or less and/or the structural fraction of martensite is 5% or less and which has a tensile strength of 50 $kgf/mm^2$ or more, stretch flangeability corresponding to a hole expansion ratio of 1.8 or more, and excellent ductility. The hot-rolled steel sheet is obtained in such a way that steel containing 0.07% to 0.18% C, 0.5% to 1.0% Si, 0.7% to 1.5% Mn, 0.02% or less P, 0.005% or less S, 0.0005% to 0.0050% Ca, and 0.01% to 0.10% Al on a weight basis, the remainder being Fe and inevitable impurities, is formed into a slab; the slab is heated to 1,000°C to 1,200°C and is hot-rolled; finish rolling is completed at a temperature of ($Ar_3$ transformation temperature + 60)°C to 950°C; cooling is performed at a rate of 50 °C/s or more within 3 seconds from the completion of finish rolling; quenching is completed within the range of not lower than (T - 70)°C to not higher than a temperature (T°C) calculated by the equation $T = 660 - 450 \times [\%C] + 40 \times [\%Si] - 60 \times [\%Mn] + 470 \times [\%P]$; air-cooling is performed; and coiling is then performed at higher than 350°C to 500°C.

### Citation List

#### Patent Literature

[0007]

PTL 1: Japanese Unexamined Patent Application Publication No. 2004-68095
PTL 2: Japanese Unexamined Patent Application Publication No. 2004-137564
PTL 3: Japanese Unexamined Patent Application Publication No. 4-88125

## Summary of Invention

### Technical Problem

[0008] However, in the high-strength steel sheet disclosed in Patent Literature 1 and the hot-rolled steel disclosed in Patent Literature 2, a TS of 600 MPa to 700 MPa is not achieved. In the high-strength hot-rolled steel sheet, an El of 25% or more is not achieved when the thickness thereof is 1.6 mm.

[0009] It is an object of the present invention to provide a high-strength steel sheet, excellent in formability, having a TS of 600 MPa to 700 MPa, an El of 25% or more (in the case of a JIS #5 test specimen with a thickness of 1.6 mm), and a $\lambda$ of 80% or more and a method for producing the same. Solution to Problem

[0010] The inventors have investigated a high-strength steel sheet targeted as described above and have found that it is effective to form a microstructure which contains ferrite and pearlite and in which the volume fraction of ferrite is 70% to 97%, the volume fraction of pearlite is 3% or more, the volume fraction of cementite present at ferrite grain boundaries is 2% or less, the sum of the volume fractions of the other phases is less than 3% or less, and the average grain size of ferrite is 7 $\mu$m or less.

[0011] The present invention has been made on the basis of this finding and provides a high-strength steel sheet having a composition containing 0.10% to 0.18% C, more than 0.5% to 1.5% Si, 0.5% to 1.5% Mn, 0.05% or less P, 0.005% or less S, and 0.05% or less Al on a mass basis, the remainder being Fe and inevitable impurities, and also having a microstructure containing ferrite and pearlite. The volume fraction of the ferrite is 70% to 97%. The volume fraction of the pearlite is 3% or more. The volume fraction of cementite present at grain boundaries of the ferrite is 2% or less. The sum of the volume fractions of phases other than the ferrite, the pearlite, and the cementite is less than 3%. The average grain size of the ferrite is 7 $\mu$m or less.

[0012] The high-strength steel sheet according to the present invention preferably further contains at least one selected from the group consisting of 0.01% to 1.0% Cr, 0.01% to 0.1% Ti, and 0.01% to 0.1% V on a mass basis.

[0013] The high-strength steel sheet according to the present invention preferably has a tensile strength TS of 600 MPa to 700 MPa. The high-strength steel sheet according to the present invention preferably has a hole expansion ratio $\lambda$ of 80% or more. In the high-strength steel sheet according to the present invention, the volume fraction of the ferrite is preferably 80% to 95%.

[0014] In the high-strength steel sheet according to the present invention, the volume fraction of the pearlite is preferably 3% to 30%. In the high-strength steel sheet according to the present invention, the volume fraction of the pearlite is preferably 5% to 28%.

[0015] A method for producing a high-strength steel sheet according to the present invention includes a step of preparing a steel slab having a chemical composition containing 0.10% to 0.18% C, more than 0.5% to 1.5% Si, 0.5% to 1.5% Mn, 0.05% or less P, 0.005% or less S, and 0.05% or less Al on a mass basis, the remainder being Fe and inevitable impurities; a step of hot-rolling the steel slab into a hot-rolled sheet; and a step of annealing the hot-rolled sheet in such a way that the hot-rolled sheet is heated to a two-phase temperature range between the $Ac_1$ transformation temperature and the $Ac_3$ transformation temperature, is cooled to a temperature range of 450°C to 600°C at an average cooling rate of 5 °C/s to 30 °C/s, and is then held at this temperature range for 100 s or more.

[0016] The steel slab preferably further contains at least one selected from the group consisting of 0.01% to 1.0% Cr, 0.01% to 0.1% Ti, and 0.01% to 0.1% V on a mass basis.

[0017] The annealing step preferably includes heating to the two-phase temperature range between the $Ac_1$ transformation temperature and the $Ac_3$ transformation temperature, cooling to a temperature range of 450°C to 600°C at an average cooling rate of 10 °C/s to 20 °C/s, and then holding at this temperature range for 100 s to 300 s.

### Advantageous Effects of Invention

[0018] According to the present invention, a high-strength steel sheet, excellent in formability, having a TS of 600 MPa to 700 MPa, an El of 25% or more, and a $\lambda$ of 80% or more can be produced.

## Description of Embodiments

[0019] Reasons for limiting a high-strength steel sheet according to the present invention and a method for producing the same are described below in detail.

### (1) Composition

[0020] The unit "%" for the content of an element component hereinafter refers to mass percent.

C: 0.10% to 0.18%

**[0021]** C forms a secondary phase such as pearlite, microstructure, or cementite to contribute to increasing the strength of the steel sheet. In order to achieve a TS of 600 MPa or more, the content of C needs to be 0.10% or more. However, when the C content is more than 0.18%, the amount of the secondary phase is too large; hence, TS exceeds 700 MPa or El or $\lambda$ is reduced. Therefore, the C content is 0.10% to 0.18%. The C content is preferably 0.12% to 0.16%.

Si: more than 0.5% to 1.5%

**[0022]** Si is an element contributing to solid solution hardening. In order to achieve a TS of 600 MPa or more, the content of Si needs to be more than 0.5%. However, when the Si content is more than 1.5%, surface properties of the steel sheet are impaired by scaling. Therefore, the Si content is more than 0.5% to 1.5%. The Si content is preferably 0.7% to 1.2%.

Mn: 0.5% to 1.5%

**[0023]** Mn is an element contributing to solid solution hardening. In order to achieve a TS of 600 MPa or more, the content of Mn needs to be 0.5% or more. However, when the Mn content is more than 1.5%, TS exceeds 700 MPa or a reduction in $\lambda$ is caused by segregation. Therefore, the Mn content is 0.5% to 1.5%. The Mn content is preferably 1.1% to 1.5%.

P: 0.05% or less

**[0024]** P is an element contributing to solid solution hardening. However, when the content of P is more than 0.05%, a reduction in El is caused by segregation. Therefore, the P content is 0.05% or less. The P content is preferably 0.03% or less.

S: 0.005% or less

**[0025]** When the content of S is more than 0.005%, S segregates at prior-austenite grain boundaries or Mn precipitates in the steel sheet to cause a reduction in $\lambda$. Therefore, the S content is 0.005% or less and is preferably low.

Al: 0.05% or less

**[0026]** Al is added to steel as a deoxidizer and is an element effective in enhancing the cleanliness of steel. However, when the content of Al is more than 0.05%, a large number of inclusions are caused, thereby causing surface defects of the steel sheet. Therefore, the Al content is 0.05% or less. The Al content is preferably 0.03% or less.

**[0027]** The remainder is Fe and inevitable impurities. At least one selected from the group consisting of 0.01% to 1.0% Cr, 0.01% to 0.1% Ti, and 0.01% to 0.1% V may be contained. This is because Cr, Ti, and V have a function of suppressing the recrystallization and recovery of austenite in a hot-rolling temperature range, promoting the grain refining of ferrite, forming a carbide, or strengthening ferrite in a solid solution state. Incidentally, Nb is an element for achieving a similar effect. The addition of these elements does not significantly reduce the elongation (El) as compared to the addition of the same amount of Nb. It is preferred that C is 0.02% to 0.5%, Ti is 0.02% to 0.05%, and V is 0.02% to 0.05%.

**[0028]** Incidentally, the inevitable impurities are, for example, O, which is 0.003% or less, Cu, Ni, Sn, and Sb, which are 0.05% or less.

(2) Microstructure

**[0029]** In order to increase the strength and formability of the steel sheet, a microstructure containing ferrite and pearlite is formed.

Volume fraction of ferrite: 70% to 97%

**[0030]** When the volume fraction of ferrite in the microstructure is less than 70%, TS exceeds 700 MPa or a $\lambda$ of 80% or more is not achieved. In contrast, when the volume fraction thereof is more than 97%, a TS of 600 MPa is not achieved because the amount of pearlite is reduced. Therefore, the volume fraction of ferrite is 70% to 97%.

**[0031]** The volume fraction of ferrite is preferably 95% or less and more preferably 80% to 90%.

Volume fraction of pearlite: 3% or more

**[0032]** When the volume fraction of pearlite is 3% or more, λ is increased. The volume fraction of pearlite is preferably 5% or more. This is probably because pearlite is soft as compared to cementite, martensite, and retained austenite and therefore the number of voids caused at the interface between ferrite and pearlite is small as compared to the number of voids caused at the interface between ferrite and martensite and the interface between ferrite and retained austenite after forming.

Volume fraction of cementite present at ferrite grain boundaries: 2% or less

**[0033]** The steel sheet according to the present invention may possibly contain cementite, martensite, and the like in addition to ferrite and pearlite. When the volume fraction of cementite, particularly cementite present at ferrite grain boundaries, in the microstructure is more than 2%, the number of voids caused at the interface between ferrite and cementite during hole expansion is increased and therefore a reduction in λ is caused. Thus, the volume fraction of the cementite present at the ferrite grain boundaries is 2% or less. Incidentally, the volume fraction thereof may be 0%.

Volume fractions of phases other than ferrite, pearlite, and the cementite present at ferrite grain boundaries: less than 3% in total

**[0034]** Phases other than ferrite, pearlite, and the cementite present at the ferrite grain boundaries are martensite, retained austenite, and the like. When the sum of the volume fractions of these phases in the microstructure is less than 3%, required properties of the steel sheet are not significantly affected. Therefore, the sum of the volume fractions of the phases other than ferrite, pearlite, and the cementite present at the ferrite grain boundaries is less than 3%. The sum thereof is preferably 2.5% or less and may be 0%.

Average grain size of ferrite: 7 μm or less

**[0035]** When the average grain size of ferrite is more than 7 μm, a reduction in strength is caused and therefore a TS of 600 MPa or more is not achieved. Therefore, the average grain size of ferrite is 7 μm or less. The average grain size of ferrite is preferably 5 μm or less.

**[0036]** Herein, the volume fraction of each of ferrite, pearlite, cementite, martensite, and retained austenite in the microstructure is determined in such a way that a thickness-wise cross-section of the steel sheet that is parallel to the rolling direction of the steel sheet is polished and is subsequently corroded with nital, three fields of view are photographed at 1,000 times magnification using an optical microscope, and the types of structures are identified by image processing. Furthermore, the average grain size of ferrite is also calculated by an intercept method. Herein, in the determination of the average grain size of ferrite, orthogonal line segments are drawn so as to longitudinally divide an image (corresponding to 84 μm in the rolling direction and 65 μm in the thickness direction) photographed at 1,000 times magnification using the optical microscope into 20 parts and so as to laterally divide the image into 20 parts, a value obtained by dividing the sum of the lengths of ferrite grains cut by one of the line segments by the number of the ferrite grains is defined as the cut length, and the average intercept length L is calculated for each line segment. The average grain size d is determined by the following equation:

$$d = 1.13 \times L.$$

**[0037]** The volume fraction of the cementite present at the ferrite grain boundaries in the microstructure is determined in such a way that three fields of view are photographed at 3,000 times magnification using a scanning electron microscope and the cementite present at the ferrite grain boundaries is extracted by image processing.

(3) Production method

**[0038]** Steel slab: A steel slab used is preferably produced by a continuous casting process for the purpose of preventing the macro-segregation of components of molten steel, produced by a known process using a converter or the like, having the above composition and may be produced by a ingot-casting process.

**[0039]** Hot rolling: The steel slab produced as described above is reheated in a furnace after being cooled to room temperature or without being cooled to room temperature or is held at high temperature without being fed through a furnace and is then hot-rolled. Hot-rolling conditions are not particularly limited. It is preferred that after the steel slab is heated to a temperature of 1,100°C to 1,300°C, hot rolling (finish rolling) is completed at 850°C to 950°C and the steel slab is coiled at 720°C or lower. This is due to reasons below. That is, when the heating temperature is lower than 1,100°C, the deformation resistance of steel is high and therefore hot rolling may possibly be difficult. When the heating temperature is higher than 1,300°C, crystal grains become coarse and therefore TS may possibly be reduced. When the finishing delivery temperature is lower than 850°C, ferrite is produced during rolling; hence, extended ferrite is formed and a reduction in λ may possibly be caused. When the finishing delivery temperature is higher than 950°C, crystal grains become coarse and therefore TS may possibly be reduced. Furthermore, the coiling temperature is higher than 720°C, the formation of an internal oxidation layer is significant and therefore chemical treatability and post-painting corrosion resistance may possibly be deteriorated.

**[0040]** After hot rolling, a hot-rolled sheet is pickled for the purpose of removing scale formed on the surface of the steel sheet.

**[0041]** Annealing: The pickled hot-rolled sheet is annealed in such a way that the hot-rolled sheet is heated to a two-phase temperature range between the $Ac_1$ transformation temperature and the $Ac_3$ transformation temperature, is cooled to a temperature range of 450°C to 600°C at an average cooling rate of 5 °C/s to 30 °C/s, and is then held at this temperature range for 100 s or more. The reason for heating the hot-rolled sheet to the two-phase temperature range between the $Ac_1$ transformation temperature and the $Ac_3$ transformation temperature is to form the microstructure containing ferrite and pearlite is formed. Furthermore, the reason for cooling the hot-rolled sheet to a temperature range of 450°C to 600°C at an average cooling rate of 5 °C/s to 30 °C/s is as follows: when the cooling temperature is higher than 600°C, the volume fraction of the cementite present at the ferrite grain boundaries exceeds 2% and therefore target λ is not achieved; when the cooling temperature is lower than 450°C, the amount of martensite is increased and therefore TS exceeds 700 MPa or λ is reduced; when the average cooling rate is less than 5 °C/s, the ferrite grains become coarse and therefore a TS of 600 MPa is not achieved; and when the average cooling rate is more than 30 °C/s, the volume fraction of the cementite present at the ferrite grain boundaries exceeds 2% and therefore a λ of 80% or more is not achieved. Incidentally, the average cooling rate is preferably 10 °C/s to 20 °C/s. The reason for holding the hot-rolled sheet at a temperature of 450°C to 600°C for 100 s or more is that when the residence time is less than 100 s, the amount of pearlite is reduced and therefore λ is reduced. The residence time is more preferably 150 s or more. Incidentally, the residence time is preferably 300 s or less from the viewpoint of production efficiency because an effect due to residence for an excessively long time is saturated. Annealing can be performed using a continuous annealing line.

EXAMPLES

**[0042]** Steels having a composition shown in Table 1 were produced and were then formed into slabs. Each slab was heated to 1,200°C, was hot-rolled at a finishing delivery temperature of 890°C, and was then coiled at 600°C, whereby a hot-rolled sheet with a thickness of 1.6 mm was obtained. After being pickled, the hot-rolled sheet was annealed in a continuous annealing line under annealing conditions shown in Table 2. Incidentally, the $Ac_1$ transformation temperature and $Ac_3$ transformation temperature of each steel shown in Table 1 were calculated by the following equations:

$$Ac_1 \text{ transformation temperature } (^\circ C) = 723 + 29.1(\%Si) - 10.7(\%Mn) + 16.9(\%Cr)$$

and

$$Ac_3 \text{ transformation temperature } (^\circ C) = 910 - 203(\%C)^{1/2} + 44.7(\%Si) - 30(\%Mn) + 700(\%P) + 400(\%Al) - 11(\%Cr) + 104(\%V) + 400(\%Ti)$$

where (%M) represents the mass percent of an element M.

**[0043]** The steel sheet obtained as described above was investigated for microstructure by the above-mentioned method and was subjected to a tensile test using a JIS #5 test specimen in accordance with JIS Z 2241, whereby TS and El were determined. Furthermore, a hole expansion test was performed using a 100 mm square test specimen in accordance with The Japan Iron and Steel Federation standard JFST 1001-1996, whereby λ was determined.

**[0044]** Results are shown in Table 3.

**[0045]** It is clear that steel sheets of examples of the present invention all have a TS of 600 MPa to 700 MPa, an El of 25% or more, a λ of 80% or more and are high-strength steel sheets with excellent formability. However, steel sheets of comparative examples do not have a target TS or λ.

[Table 1]

(mass percent)

| Steel No. | C | Si | Mn | P | S | Al | Others | $Ac_3$ transformation temperature (°C) | $Ac_1$ transformation temperature (°C) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 0.140 | 1.00 | 1.30 | 0.030 | 0.0020 | 0.035 | - | 875 | 738 | Within the scope of the present invention |
| B | 0.105 | 1.05 | 1.15 | 0.020 | 0.0015 | 0.040 | - | 887 | 741 | Within the scope of the present invention |
| C | 0.175 | 0.95 | 0.85 | 0.020 | 0.0035 | 0.030 | - | 868 | 742 | Within the scope of the present invention |
| D | 0.125 | 0.65 | 1.25 | 0.045 | 0.0010 | 0.025 | - | 871 | 729 | Within the scope of the present invention |
| E | 0.155 | 1.45 | 0.95 | 0.020 | 0.0025 | 0.035 | - | 894 | 755 | Within the scope of the present invention |
| F | 0.165 | 0.70 | 0.55 | 0.010 | 0.0008 | 0.040 | - | 865 | 737 | Within the scope of the present invention |
| G | 0.115 | 1.35 | 1.45 | 0.020 | 0.0040 | 0.035 | - | 886 | 747 | Within the scope of the present invention |
| H | <u>0.185</u> | 1.05 | 0.85 | 0.020 | 0.0035 | 0.030 | - | 870 | 744 | Outside the scope of the present invention |
| I | <u>0.085</u> | 1.05 | 0.85 | 0.020 | 0.0035 | 0.030 | - | 895 | 744 | Outside the scope of the present invention |
| J | 0.105 | <u>0.40</u> | 1.15 | 0.020 | 0.0015 | 0.040 | - | 860 | 724 | Outside the scope ot the present invention |
| K | 0.105 | 1.05 | <u>0.40</u> | 0.020 | 0.0015 | 0.040 | - | 908 | 749 | Outside the scope of the present invention |
| L | 0.120 | 1.40 | 0.85 | 0.020 | 0.0015 | 0.040 | Cr:0.04 | 907 | 755 | Within the scope of the present invention |
| M | 0.105 | 0.80 | 1.20 | 0.021 | 0.0016 | 0.041 | Ti:0.04 | 875 | 733 | Within the scope of the present invention |
| N | 0.110 | 0.90 | 1.30 | 0.021 | 0.0016 | 0.041 | V:0.03 | 875 | 735 | Within the scope of the present invention |

[Table 2]

| Steel Sheet No. | Steel No. | Annealing conditions | | | | Remarks |
|---|---|---|---|---|---|---|
| | | Heating | Cooling | | Residence time at a temperature range of 450°C to 600°C (s) | |
| | | Temperature (°C) | Average cooling rate (°C/s) | Cooling attained temperature at average cooling rate (°C) | | |
| 1 | A | 820 | 15 | 500 | 120 | Inventive example |
| 2 | A | 821 | 32 | 498 | 126 | Comparative example |
| 3 | A | 817 | 3 | 498 | 253 | Comparative example |
| 4 | B | 815 | 20 | 480 | 135 | Inventive example |
| 5 | C | 800 | 25 | 490 | 130 | Inventive example |
| 6 | D | 780 | 28 | 460 | 140 | Inventive example |
| 7 | E | 780 | 17 | 460 | 105 | Inventive example |
| 8 | F | 790 | 23 | 490 | 195 | Inventive example |
| 9 | G | 870 | 25 | 570 | 200 | Inventive example |
| 10 | G | 872 | 25 | 320 | 105 | Comparative example |
| 11 | G | 872 | 27 | 570 | 95 | Comparative example |
| 12 | H | 800 | 15 | 520 | 130 | Comparative example |
| 13 | I | 806 | 20 | 521 | 125 | Comparative example |
| 14 | J | 798 | 23 | 525 | 135 | Comparative example |
| 15 | K | 802 | 23 | 525 | 132 | Comparative example |
| 16 | L | 821 | 19 | 495 | 123 | Inventive example |
| 17 | M | 820 | 21 | 496 | 124 | Inventive example |
| 18 | N | 825 | 20 | 495 | 135 | Inventive example |

[Table 3]

| Steel sheet No. | Steel No. | Volume fraction of ferrite (%) | Volume fraction of pearlite (%) | Volume fraction of cementite at ferrite grain boundaries (%) | Another phase* and volume fraction (%) | Average grain size of ferrite (μm) | TS (MPa) | El (%) | λ (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 86.0 | 11.5 | 0.5 | M:2.0% | 3.0 | 631 | 27 | 85 | Inventive example |
| 2 | A | 81.6 | 12.2 | 3.2 | M:3.0% | 3.0 | 635 | 28 | 74 | Comparative example |
| 3 | A | 94.0 | 5.3 | 0.7 | - | 8.2 | 510 | 34 | 80 | Comparative example |
| 4 | B | 92.0 | 7.8 | 0.2 | - | 5.0 | 610 | 33 | 98 | Inventive example |
| 5 | C | 72.0 | 27.6 | 0.4 | - | 4.5 | 620 | 26 | 83 | Inventive example |
| 6 | D | 87.0 | 11.5 | 1.5 | - | 6.0 | 609 | 32 | 102 | Inventive example |
| 7 | E | 75.0 | 24.8 | 0.2 | - | 6.5 | 625 | 28 | 80 | Inventive example |
| 8 | F | 87.0 | 11.7 | 1.3 | - | 2.5 | 612 | 31 | 108 | Inventive example |
| 9 | G | 83.9 | 12.3 | 1.7 | M:2.1% | 3.5 | 625 | 27 | 87 | Inventive example |
| 10 | G | 80.0 | 12.5 | 1.5 | M:6.0% | 3.2 | 704 | 26 | 69 | Comparative example |
| 11 | G | 80.0 | 12.1 | 1.4 | M:6.5% | 3.7 | 695 | 26 | 70 | Comparative example |
| 12 | H | 64.6 | 32.0 | 0.4 | M:3.0% | 3.5 | 682 | 26 | 72 | Comparative example |
| 13 | I | 97.7 | 2.0 | 0.3 | - | 4.5 | 575 | 34 | 110 | Comparative example |
| 14 | J | 93.5 | 6.0 | 0.5 | - | 6.3 | 585 | 30 | 85 | Comparative example |

(continued)

| Steel sheet No. | Steel No. | Volume fraction of ferrite (%) | Volume fraction of pearlite (%) | Volume fraction of cementite at ferrite grain boundaries (%) | Another phase* and volume fraction (%) | Average grain size of ferrite ($\mu$m) | TS (MPa) | El (%) | $\lambda$ (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 15 | K | 93.0 | 6.0 | 1.0 | - | 5.1 | 582 | 31 | 95 | Comparative example |
| 16 | L | 85.5 | 14.0 | 0.5 | - | 2.3 | 623 | 32 | 95 | Inventive example |
| 17 | M | 86.3 | 13.0 | 0.7 | - | 2.5 | 625 | 31 | 94 | Inventive example |
| 18 | N | 84.5 | 15.0 | 0.5 | - | 2.5 | 625 | 32 | 96 | Inventive example |

* M: martensite

## Claims

1. A high-strength steel sheet having a composition containing 0.10% to 0.18% C, more than 0.5% to 1.5% Si, 0.5% to 1.5% Mn, 0.05% or less P, 0.005% or less S, and 0.05% or less Al on a mass basis, the remainder being Fe and inevitable impurities, the high-strength steel sheet having a microstructure containing ferrite and pearlite, wherein the volume fraction of the ferrite is 70% to 97%, the volume fraction of the pearlite is 3% or more, the volume fraction of cementite present at grain boundaries of the ferrite is 2% or less, the sum of the volume fractions of phases other than the ferrite, the pearlite, and the cementite is less than 3%, and the average grain size of the ferrite is 7 $\mu$m or less.

2. The high-strength steel sheet according to Claim 1, further containing at least one selected from the group consisting of 0.01% to 1.0% Cr, 0.01% to 0.1% Ti, and 0.01% to 0.1% V on a mass basis.

3. The high-strength steel sheet according to Claim 1, further having a tensile strength TS of 600 MPa to 700 MPa.

4. The high-strength steel sheet according to Claim 1, further having a hole expansion ratio $\lambda$ of 80% or more.

5. The high-strength steel sheet according to Claim 1, wherein the volume fraction of the ferrite is 80% to 95%.

6. The high-strength steel sheet according to Claim 1, wherein the volume fraction of the pearlite is 3% to 30%.

7. The high-strength steel sheet according to Claim 1, wherein the volume fraction of the pearlite is 5% to 28%.

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

   a step of preparing a steel slab having a chemical composition containing 0.10% to 0.18% C, more than 0.5% to 1.5% Si, 0.5% to 1.5% Mn, 0.05% or less P, 0.005% or less S, and 0.05% or less Al on a mass basis, the remainder being Fe and inevitable impurities;
   a step of hot-rolling the steel slab into a hot-rolled sheet; and
   a step of annealing the hot-rolled sheet in such a way that the hot-rolled sheet is heated to a two-phase temperature range between the $Ac_1$ transformation temperature and the $Ac_3$ transformation temperature, is cooled to a temperature range of 450°C to 600°C at an average cooling rate of 5 °C/s to 30 °C/s, and is then held at this temperature range for 100 s or more.

9. The method for producing the high-strength steel sheet according to Claim 8, wherein the steel slab further contains at least one selected from the group consisting of 0.01% to 1.0% Cr, 0.01% to 0.1% Ti, and 0.01% to 0.1% V on a mass basis.

10. The method for producing the high-strength steel sheet according to Claim 8, wherein the annealing step includes heating to the two-phase temperature range between the $Ac_1$ transformation temperature and the $Ac_3$ transformation temperature, cooling to a temperature range of 450°C to 600°C at an average cooling rate of 10 °C/s to 20 °C/s, and then holding at this temperature range for 100 s to 300 s.

**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/JP2012/007663

A. CLASSIFICATION OF SUBJECT MATTER
*C22C38/00*(2006.01)i, *C21D9/46*(2006.01)i, *C22C38/06*(2006.01)i, *C22C38/28*(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C22C1/00-49/14, C21D9/46

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

| | | | |
|---|---|---|---|
| Jitsuyo Shinan Koho | 1922-1996 | Jitsuyo Shinan Toroku Koho | 1996-2013 |
| Kokai Jitsuyo Shinan Koho | 1971-2013 | Toroku Jitsuyo Shinan Koho | 1994-2013 |

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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☒ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

* Special categories of cited documents:
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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 21 February, 2013 (21.02.13) | 05 March, 2013 (05.03.13) |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| Japanese Patent Office | |
| Facsimile No. | Telephone No. |

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INTERNATIONAL SEARCH REPORT

International application No. PCT/JP2012/007663

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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