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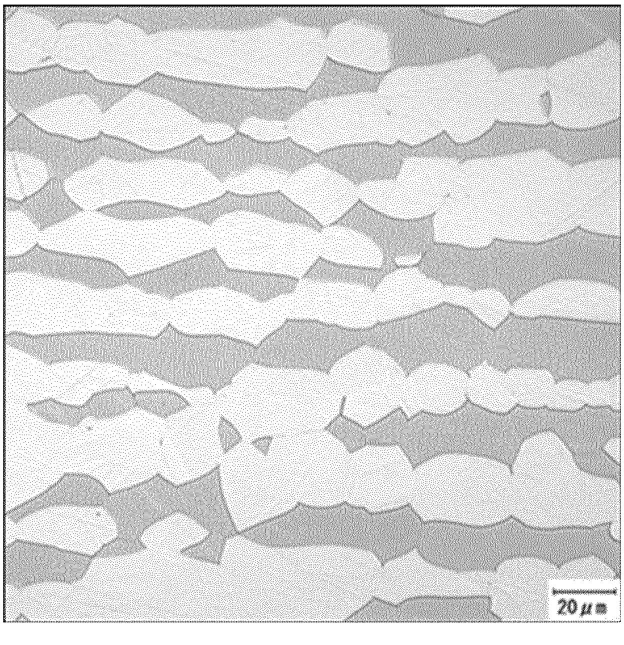
(54) STEEL MATERIAL AND AUTOMOBILE COMPONENT

(57) A steel material that has an average chemical composition containing Ni at 18.00 to 36.00% and Si at 5.50 to 12.00%, and has a metallurgical structure containing an austenite phase and ordered phases. In addition, an automobile component including the steel material.

FIG. 1



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Description

Technical Field

[0001] The present disclosure relates to a steel material and an automobile component.

Background Art

[0002] In recent years, there has been a demand for a steel material having higher mechanical characteristics and higher functionality than a common steel material. One example is as follows: for the sake of car-body weight decrease and safety performance, a steel material to be used for automobiles needs to have both higher strength and higher ductility so as to be moldable in conformity with the shape of a component, and also needs to have high corrosion resistance to achieve a longer life, depending on the position and environment of use of a member.

[0003] A steel material having excellent strength-ductility balance, called AHSS (Advanced High Strength Steel), has been developed in the past.

[0004] The first-generation AHSS typified by TRIP (Transformation-Induced Plasticity) steel has insufficient strength-ductility balance. Compared with this, the second-generation AHSS typified by a high-Mn steel has excellent strength-ductility balance, but contains a large amount of Mn, and this is one of the reasons why the AHSS is not utilized very much.

[0005] In light of the course of development of the first-generation AHSS and the second-generation AHSS, the third-generation AHSS typified by medium-Mn steel has been developed actively in recent years. One example of conventional development of the third-generation AHSS will now be described. Here, "%" means "% by mass".

[0006] For example, Patent Literature 1 discloses: "a steel sheet having a composition including Mn at 3 to 8%, Al at 2 to 4%, Si at 0.1 to 0.2%, C at 0.3 to 0.8%, and the balance including iron and impurities, wherein the steel sheet contains a ferrite phase, bainite phase, austenite phase, and martensite phase; and a process of providing the steel sheet".

[0007] Patent Literature 2 discloses: "a steel sheet having a composition including C at 0.1 to 0.4%, Mn at 1 to 3%, Si at 1 to 2%, Ti at 0.1 to 0.2%, and the balance including iron and impurities, wherein the steel sheet contains a ferrite phase, bainite phase, austenite phase, and martensite phase; and a process of providing the steel sheet".

[0008] Patent Literature 3 discloses "a hot-rolled steel strip or steel sheet including C at 0.12 to 0.24%, Mn at 0.8 to 2.1%, Si at 0.4 to 1.1%, Cr at 0.8 to 1.5%, Al at 0.05 to 0.3%, Mo at 0.05 to 0.25%, Nb at 0.018 to 0.035%, Ti at 0.01 to 0.1%, S at a maximum of 0.008%, P at a maximum of 0.025%, and N at a maximum of 0.005%".

Patent Literature 1: Japanese Patent Application Laid-Open (JP-A) No. 2016-141888
Patent Literature 2: JP-A No. 2016-223003
Patent Literature 3: JP-A No. 2020-514544

SUMMARY OF INVENTION

Technical Problem

[0009] According to Patent Literature 1 to 3, including Mn at 0.8 to 8% and forming the structure with the disordered phases (ferrite, austenite, martensite, bainite, and the like) made complicated results in affording strength, ductility, and strength-ductility balance.

[0010] Under the current situation, however, recent steel materials need to have high strength, high ductility, and high strength-ductility balance, and in addition, high corrosion resistance and high producibility, at a higher level than the current third-generation AHSS (Current 3rd GEN AHSS).

[0011] In view of this, an object of the disclosure is to provide a steel material having high strength, high ductility, and high strength-ductility balance, and in addition, high corrosion resistance and high producibility, at a higher level than the Current 3rd GEN AHSS.

Solution to Problem

[0012] To solve the above-described problems, the inventor has developed a steel material on the basis of a technical concept totally different from a conventional concept. As a result, the inventor has made the invention through the discovery that it is effective to contrive the following points (A) to (C).

(A) Ni, not Mn, is utilized as an austenite-stabilizing element.
(B) The steel material contains Si in a larger amount than conventionally.
(C) The metallurgical structure contains an austenite phase and ordered phases.

The inventor has made the invention through the additional discovery that, to solve the problems at a still higher level, it is effective to contrive about any one of the following points (D) to (I).

(D) The average chemical composition of the steel material satisfies the below-described Formula A.

(E) The ordered phases include a DO3 ordered phase, and the ratio of the DO3 ordered phase satisfies the below-described Formula B.

(F) The average chemical composition of the ordered phases satisfies the below-described Formula C.

(G) The average chemical composition of the austenite phase satisfies the below-described Formula D.

(H) The average crystal grain size of the ordered phases is 10.00 μm or less.

(I) The ordered phases include an antiphase boundary.

[0013] That is, means for solving the problems includes the following aspects.

<1>

A steel material including an average chemical composition including:

Ni at 18.00 to 36.00%,
Si at 5.50 to 12.00%,
Cu at 0 to 2.00%,
Al at 0 to 3.000%,
Mn at 0 to 2.00%,
C at 0 to 0.100%,
Cr at 0 to 0.40%
P at 0 to 0.200%,
S at 0 to 0.200%,
N at 0 to 0.200%,
B at 0 to 0.200%,
Sn at 0 to 0.20%,
Ge at 0 to 0.20%,
Ag at 0 to 0.20%,
Sb at 0 to 0.20%,
Te at 0 to 0.20%,
V at 0 to 0.200%,
Nb at 0 to 0.200%,
Ti at 0 to 0.200%,
Ca at 0 to 0.200%,
Mg at 0 to 0.200%,
Li at 0 to 0.20%,
Sr at 0 to 0.20%,
REM at 0 to 0.20%,
Zr at 0 to 0.20%,
Co at 0 to 0.20%,
Mo at 0 to 0.20%,
Ta at 0 to 0.20%,
W at 0 to 0.20%,
PGM at 0 to 0.20%,
Au at 0 to 0.20%,
Re at 0 to 0.20%
In at 0 to 0.20%,
Ga at 0 to 0.20%,
Cd at 0 to 0.20%,
Pb at 0 to 0.20%, and
with a balance being Fe and impurities,
by % by mass,
wherein the steel material has a metallurgical structure containing an austenite phase and ordered phases.

<2>

The steel material according to <1>, wherein the average chemical composition of the steel material satisfies the following Formula A:

$$\text{Formula A: } C + Mn/6 + Si/24 + Ni/40 + Cr/5 \leq 1.4$$

(wherein in Formula A, the symbol of each element symbol represents an amount (mass %) of the element).

<3>

The steel material according to <1> or <2>, wherein an average area ratio of the austenite phase is in a range of from 20 to 80%.

<4>

The steel material according to any one of <1> to <3>, wherein the ordered phases contain a DO3 ordered phase, and wherein a ratio of the DO3 ordered phase to all the ordered phases ([DO3 ordered phase]/[all the ordered phases]), as determined by X-ray diffractometry, satisfies the following Formula B:

$$\text{Formula B: [DO3 ordered phase]/[all the ordered phases]} \geq 0.20.$$

<5> The steel material according to any one of <1> to <4>, wherein the average chemical composition of the ordered phases satisfies the following Formula C:

$$\text{Formula C: } (Si_{ordered} + Al_{ordered})/(Ni_{ordered} + Cu_{ordered}) \geq 0.25$$

(wherein in Formula C, the symbol of each element symbol, followed by a subscript $_{ordered}$, represents the amount (mass %) of the element contained in the ordered phases).

<6> The steel material according to any one of <1> to <5>, wherein the average chemical composition of the austenite phase satisfies the following Formula D:

$$\text{Formula D: } Ni_{\gamma} + 0.65Cr_{\gamma} + 1.1Mn_{\gamma} + 0.4Si_{\gamma} + 13C_{\gamma} \geq 18.4$$

(wherein in Formula D, the symbol of each element symbol, followed by a subscript $_{\gamma}$, represents the amount (mass %) of the element contained in the austenite phase).

<7>

The steel material according to any one of <1> to <6>, wherein an average crystal grain size of the ordered phases is 10.00 μm or less.

<8>

The steel material according to any one of <1> to <7>, wherein the ordered phases include an antiphase boundary.

<9>

The steel material according to any one of <1> to <8>, having a tensile strength and a total elongation that give a product of 30000 MPa% or more.

<10>

The steel material according to any one of <1> to <9>, wherein the tensile strength is 1250 MPa or more.

<11>

An automobile component including the steel material according to any one of <1> to <10>.

Advantageous Effects of Invention

[0014] The disclosure can provide a steel material having high strength, high ductility, and high strength-ductility balance, and in addition, high corrosion resistance and high producibility, at a higher level than the Current 3rd GEN AHSS.

BRIEF DESCRIPTION OF DRAWINGS

[0015]

[FIG. 1] FIG. 1 is one example of an optical-microscopic photograph (at a magnification of 500 times; the white portion, the y phase; the gray portion, the ordered phases) of the metallurgical structure of a steel material, the test number 35, according to the disclosure, in which the steel material underwent hot-rolling and annealing but was yet to undergo finishing annealing.

[FIG. 2] FIG. 2 is one example of an optical-microscopic photograph (at a magnification of 500 times; the white portion, the y phase; the gray portion, the ordered phases) of the metallurgical structure of a steel material, the test number 36, according to the disclosure.

DESCRIPTION OF EMBODIMENTS

[0016] One example of the disclosure will be described below.

[0017] In the disclosure, the sign "%" as the amount of each element contained in a chemical composition means "mass %".

[0018] A numerical range expressed with "to" means a range the lower limit and upper limit of which are the numerical values before and after "to" respectively.

[0019] The term "step" encompasses not only an independent step but also a step an expected purpose of which is achieved even in a case in which the step cannot be clearly distinguished from another step.

[0020] "Ferrite" is also referred to as "α", and "austenite" is also referred to as "y".

<<<Steel Material>>>

[0021] A steel material of the disclosure has a predetermined average chemical composition, and also has a metallurgical structure containing an austenite phase and ordered phases.

[0022] Owing to the structure, a steel material of the disclosure is a steel material having high strength, high ductility, and high strength-ductility balance, and in addition, high corrosion resistance and high producibility, at a higher level than the Current 3rd GEN AHSS.

[0023] A steel material of the disclosure has been discovered through the following findings.

[0024] The inventor has paid attention to, and made studies on, the chemical composition of a steel material in order to enhance the strength, ductility, and strength-ductility balance of the steel material, and in addition, the corrosion resistance and producibility of the steel material. As a result, the inventor has obtained the following findings.

[0025] A steel material results in having a metallurgical structure containing a y phase and ordered phases, by having a chemical composition mainly containing 18.00 to 36.00% Ni and 5.50 to 12.00% Si, and also containing an optional element other than Ni and Si in predetermined or smaller amounts (particularly Al and Mn in predetermined or smaller amounts) as described below. The metallurgical structure containing both the y phase, which is relatively soft and contributes to enhancing the ductility, and the ordered phases, which are hard and contribute to enhancing the strength, allows the steel material to possess enhanced strength, ductility, and strength-ductility balance. However, an excessive amount of the below-described optional element other than Ni and Si causes the strength or the ductility to deteriorate.

[0026] The steel material allowed to additionally contain Si in a large amount possesses enhanced corrosion resistance.

[0027] In general, containing 5.50 to 12.00% Si causes a steel material to embrittle, making hot working and cold working difficult. However, containing Ni sufficiently and having both the y phase and the ordered phases together inhibits the steel material from embrittling, and enables the steel material to undergo usually-employed hot working and cold working, bringing about high producibility. However, an excessively large amount of Si or an excessively small amount of Ni worsens the producibility.

[0028] The above-described findings have revealed that a steel material of the disclosure is a steel material having high strength, high ductility, and high strength-ductility balance, and in addition, high corrosion resistance and high producibility, at a higher level than the Current 3rd GEN AHSS.

[0029] The details of a steel material of the disclosure will be described below.

<<Average Chemical Composition of Steel Material>>

[0030] The average chemical composition of a steel material of the disclosure will be described below.

<Ni at 18.00 to 36.00%>

[0031] Ni contributes to the enhancement of ductility and strength-ductility balance. Containing Ni, which is a γ-stabilizing element, allows a steel material to have a stabilized γ phase. The y phase has relatively better ductility than the ordered phases. Containing the y phase allows a steel material to possess enhanced ductility and strength-ductility balance. Such an effect is achieved noticeably in a case in which the amount of Ni is 18.00% or more. An excessively small amount of Ni causes the stability of the y phase to be insufficient, thus causing cracks to be generated in a production step, with the result that the ductility of the steel material is insufficient, and that the strength-ductility balance is also insufficient.

[0032] An excessively large amount of Ni adversely affects the producibility, causes cracks to be generated in a production step, and in addition, brings about a result that ordered phases contributive to the enhancement of strength do not form sufficiently.

[0033] Accordingly, the amount of Ni is 18.00 to 36.00%.

[0034] The lower limit of the amount of Ni is preferably 20.00%, more preferably 22.00%.

[0035] The upper limit of the amount of Ni is preferably 32.00%, more preferably 30.00%.

<Si at 5.50 to 12.00%>

[0036] Si contributes to the enhancement of strength, strength-ductility balance, and corrosion resistance. Fe containing a large amount of Si has an ordered α phase. In a case in which a steel material has a metallurgical structure including only ordered phases in which the α phase is ordered, the steel material embrittles, and is difficult to utilize industrially. In a case in which a steel material includes both the y phase and the ordered phases, the steel material is inhibited from embrittling, and has sufficient ductility. The ordered phases are harder than the y phase, and contribute to the enhancement of strength. Furthermore, owing to containing Si, a protective layer containing Si oxide having excellent corrosion resistance is formed on the surface of the steel material. Accordingly, containing Si is effective to enhance the corrosion resistance. Such an effect is achieved in a case in which the amount of Si is 5.50% or more. An excessively small amount of Si causes the ordering of the α phase to be insufficient, thus causing the formation of the ordered phases to be insufficient, with the result that the strength of the steel material is insufficient, and that the strength-ductility balance is also insufficient. In addition, the formation of a Si oxide layer that functions as a protective layer on the surface of the steel material is insufficient, and thus, the enhancement of corrosion resistance is insufficient.

[0037] An excessively large amount of Si causes cracks to be generated in a production step, with the result that the ductility of the steel material is insufficient, and that the strength-ductility balance is also insufficient.

[0038] Accordingly, the amount of Si is 5.50 to 12.00%.

[0039] The lower limit of the amount of Si is preferably 6.50%, more preferably 8.00%.

[0040] The upper limit of the amount of Si is preferably 10.00%, more preferably 9.50%.

<Cu at 0 to 2.00%>

[0041] Cu is an optional element.

[0042] In the same manner as Ni, Cu has the effect of stabilizing the y phase and enhancing the ductility and the strength-ductility balance. Cu is smaller than Ni in the number of atoms solid-soluble in the y phase, and hence, containing excessive Cu causes Cu to precipitate, causing a decrease in ductility and producibility.

[0043] Accordingly, the amount of Cu is 0 to 2.00%.

[0044] The lower limit of the amount of Cu is preferably 0.20%.

[0045] The upper limit of the amount of Cu is preferably 1.50%.

<Al at 0 to 3.000%>

[0046] Al is an optional element.

[0047] In the same manner as Si, Al has the effect of ordering the α phase and enhancing the strength and the strength-ductility balance. In this regard, containing Al does not give the effect of enhancing the corrosion resistance. However, containing excessive Al decreases the solid-solubility limit of Si in the steel material. In addition, containing excessive Al inhibits the formation of ordered phases (specifically, a B2 ordered phase having FeSi as a basic chemical composition and a DO3 ordered phase having Fe_3Si as a basic chemical composition), and adversely affects the corrosion resistance.

[0048] Accordingly, the amount of Al is 0 to 3.000%.

[0049] The lower limit of the amount of Al is preferably 0.002%, 0.005%, 0.010%, or 0.100%.

[0050] The upper limit of the amount of Al is preferably 2.700%, 2.000%, 1.500%, or 1.000%.

<Mn at 0 to 2.00%>

[0051] Mn is an optional element.

[0052] In the same manner as Ni and Cu, Mn has the effect of stabilizing the y phase and enhancing the ductility and the strength-ductility balance. However, Mn has no special effect for corrosion resistance. Containing excessive Mn brings about the formation of MnS, which deteriorates the corrosion resistance.

[0053] Accordingly, the amount of Mn is 0 to 2.00%.

[0054] The lower limit of the amount of Mn is preferably 0.02%, 0.05%, or 0.10%.

[0055] The upper limit of the amount of Mn is preferably 1.60%, 1.40%, or 1.00%.

<C at 0 to 0.100%>

[0056] C is an optional element.

[0057] In the same manner as Ni, C has the effect of stabilizing the y phase and enhancing the ductility and the strength-ductility balance. However, containing excessive C promotes the formation of coarse Fe carbide, causing cracks to be generated in a production step.

[0058] Accordingly, the amount of C is 0 to 0.100%.

[0059] It is difficult to bring the amount of C to 0%, and thus, the lower limit of the amount of C is preferably 0.001%, 0.005%, or 0.010%.

[0060] The upper limit of the amount of C is preferably 0.085%, 0.075%, or 0.060%.

<Cr at 0 to 0.40%>

[0061] Cr is an optional element.

[0062] Cr has the effect of inhibiting the generation of corrosion that starts from an inclusion. However, containing excessive Cr causes embrittlement breakage.

[0063] Accordingly, the amount of Cr is 0 to 0.40%.

[0064] The lower limit of the amount of Cr is preferably 0.01%.

[0065] The upper limit of the amount of Cr is preferably 0.35%.

<P and S at 0 to 0.200%>

[0066] P and S are impurities, and decrease the toughness of a steel material.

[0067] Accordingly, the amount of each of P and S is 0 to 0.200%.

[0068] The smaller the amount of each of P and S, the more preferable. The amount may be 0.001% or more from the viewpoint of the cost of removal of P and S.

<N and B at 0 to 0.200%>

[0069] N and B are optional elements.

[0070] N and B are solid-solution-reinforcing elements, and have the effect of contributing to the enhancement of strength. In addition, N and B can be utilized to control pinning particles and inclusions. However, containing excessive N and B causes unnecessarily large nitride or boride to be formed, causing a decrease in ductility.

[0071] Accordingly, the amount of each of N and B is 0 to 0.200%.

[0072] The lower limit of the amount of each of N and B is preferably 0.001%.

[0073] The upper limit of the amount of each of N and B is preferably 0.150%.

<Sn, Ge, Ag, Sb, and Te at 0 to 0.20%>

[0074] Sn, Ge, Ag, Sb, and Te are optional elements.

[0075] Sn, Ge, Ag, Sb, and Te have the effect of contributing to the enhancement of corrosion resistance. However, containing excessive Sn, Ge, Ag, Sb, and Te embrittles the material, and causes a decrease in producibility.

[0076] Accordingly, the amount of each of Sn, Ge, Ag, Sb, and Te is 0 to 0.20%.

[0077] The lower limit of the amount of each of Sn, Ge, Ag, Sb, and Te is preferably 0.01%.

[0078] The upper limit of the amount of each of Sn, Ge, Ag, Sb, and Te is preferably 0.18%.

<V, Nb, and Ti at 0 to 0.200%>

[0079] V, Nb, and Ti are optional elements.

[0080] V, Nb, and Ti have the effect of forming carbonitride and the like to make the crystal grains finer. Ti also functions as a deoxidizing element. However, containing excessive V, Nb, and Ti causes these elements to undergo solidification segregation, and thus, causes producibility in terms of cracks to be decreased during casting and solidification.

[0081] Accordingly, the amount of each of V, Nb, and Ti is 0 to 0.200%.

[0082] The lower limit of the amount of each of V, Nb, and Ti is preferably 0.001%.

[0083] The upper limit of the amount of each of V, Nb, and Ti is preferably 0.080%.

<Ca and Mg at 0 to 0.200%>

[0084] Ca and Mg are optional elements.

[0085] Ca and Mg have the effect of enhancing producibility by forming an inclusion such as oxide or sulfide, modifying the metallurgical structure of an ingot, and inhibiting the generation of cracks during casting. However, containing excessive Ca and Mg increases the number, size, ratio of volume, and the like of inclusions, causing flaws and cracks during production.

[0086] Accordingly, the amount of each of Ca and Mg is 0 to 0.200%.

[0087] The lower limit of the amount of each of Ca and Mg is preferably 0.001%.

[0088] The upper limit of the amount of each of Ca and Mg is preferably 0.150%.

<Li, Sr, REM, and Zr at 0 to 0.20%>

[0089] Li, Sr, REM, and Zr are optional elements.

[0090] Li, Sr, REM, and Zr have the effect of contributing to the enhancement of oxidation resistance. However, containing excessive Li, Sr, REM, and Zr does not mean obtaining the effect of further enhancing the oxidation resistance, but only results in increasing the raw material cost.

[0091] Accordingly, the amount of each of Li, Sr, REM, and Zr is 0 to 0.20%.

[0092] The lower limit of the amount of each of Li, Sr, REM, and Zr is preferably 0.01%.

[0093] The upper limit of the amount of each of Li, Sr, REM, and Zr is preferably 0.18%.

[0094] Here, REM (rare earth element) is the generic term for 2 elements, Sc and Y, and 15 lanthanoid elements such as La, Ce, and Nd. REM represents one or more selected from these rare earth elements. The amount of REM is the total of the amounts of the rare earth elements.

<Co at 0 to 0.20%>

[0095] Co is an optional element.

[0096] Co has the effect of contributing to the enhancement of toughness. In addition, Co has the effect of stabilizing the y phase. However, containing excessive Co causes the corrosion resistance of the ordered phases to deteriorate, and causes the toughness of the steel material itself to deteriorate.

[0097] Accordingly, the amount of Co is 0 to 0.20%.

[0098] The lower limit of the amount of Co is preferably 0.01%.

[0099] The upper limit of the amount of Co is preferably 0.18%.

<Mo, Ta, W, PGM, Au, and Re at 0 to 0.20%>

[0100] Mo, Ta, W, PGM, Au, and Re are optional elements.

[0101] Mo, Ta, W, PGM, Au, and Re have the effect of contributing to the enhancement of corrosion resistance. However, containing excessive Mo, Ta, W, PGM, Au, and Re decreases the ductility of the ordered phases, thus causing the ductility of the steel material itself to decrease.

[0102] Accordingly, the amount of each of Mo, Ta, W, PGM, Au, and Re is 0 to 0.20%.

[0103] The lower limit of the amount of each of Mo, Ta, W, PGM, Au, and Re is preferably 0.01%.

[0104] The upper limit of the amount of each of Mo, Ta, W, PGM, Au, and Re is preferably 0.19%.

[0105] Here, PGM (platinum group element) is the generic term for six elements, Pt, Pd, Ru, Ir, Os, and Rh. PGM represents one or more selected from these platinum group elements. The amount of PGM is the total of the amounts of the platinum group elements.

<In, Ga, Cd, and Pb at 0 to 0.20%>

[0106] In, Ga, Cd, and Pb are optional elements.

[0107] In, Ga, Cd, and Pb have the effect of contributing to the enhancement of corrosion resistance. However, containing excessive In, Ga, Cd, and Pb decreases the toughness, causing a deterioration in producibility.

[0108] Accordingly, the amount of each of In, Ga, Cd, and Pb is 0 to 0.20%.

[0109] The lower limit of the amount of each of In, Ga, Cd, and Pb is preferably 0.01%.

[0110] The upper limit of the amount of each of In, Ga, Cd, and Pb is preferably 0.19%.

<Balance>

[0111] The balance of the average chemical composition of a steel material of the disclosure is Fe and impurities.

[0112] The impurities mean contaminative components due to raw materials, such as ore and scrap, and another cause in the industrial production of a steel material.

<Formula A>

[0113] To control flaws and cracks more stringently in hot working and cold working, it is preferable to further restrict a balance among the elements contained in the steel material. Specifically, it is preferable to restrict another element(s) contained in the steel material, besides Ni and Si as main constituent elements.

[0114] Accordingly, from the viewpoint of inhibiting flaws and cracks, the chemical composition of a steel material of the disclosure preferably satisfies the following Formula A:

$$\text{Formula A: } C + Mn/6 + Si/24 + Ni/40 + Cr/5 \leq 1.4$$

(wherein in Formula A, the symbol of each element symbol represents the amount (mass %) of the element).

[0115] The upper limit of the value of "C + Mn/6 + Si/24 + Ni/40 + Cr/5" (hereinafter also referred to as the "A value") in Formula A is more preferably 1.3, still more preferably 1.0.

[0116] The lower limit of the A value in Formula A is more preferably 0.6, still more preferably 0.8.

<<Metallurgical Structure>>

[0117] The metallurgical structure of a steel material of the disclosure contains a y phase and ordered phases.

[0118] To produce a steel material including a y phase and ordered phases, a steel material is allowed to contain Si and Ni in the above-described ranges, and in addition, allowed to contain an optional element(s) other than Ni and Si in predetermined or smaller amounts.

[0119] In a case in which Fe contains only Si out of Ni and Si, the steel material has excellent corrosion resistance, but embrittles in itself, is difficult to process, and thus, is difficult to utilize industrially.

[0120] However, in a case in which Fe is allowed to contain only Ni out of Ni and Si, the steel material exhibits sufficient ductility, but does not exhibit strength, strength-ductility balance, or corrosion resistance sufficiently.

[0121] Allowing a steel material to contain both Si and Ni in the above-described suitable ranges, together with allowing the steel material to contain an optional element(s) other than Ni and Si in predetermined or smaller amounts, produces a steel material containing a y phase and ordered phases.

<Average Area Ratio of y Phase, at 20 to 80%>

[0122] In a steel material of the disclosure, the average area ratio of the y phase is preferably 20 to 80%.

[0123] Containing the y phase and the ordered phases entails having high strength, high ductility, and high strength-ductility balance, and having high corrosion resistance. In addition, having the average area ratio of the y phase in the range of from 20 to 80% entails further enhancing the strength, ductility, and strength-ductility balance.

[0124] Instead of the ordered phases that are contained in the steel material, and are hard, the y phase contributes to strain due to plastic deformation, thus enhancing the ductility of the steel material, and consequently enhancing the strength-ductility balance.

[0125] The y phase having an average area ratio of 20% or more allows the y phase-a region that contributes to plastic deformation-to be present to a suitable degree, inhibits strain due to plastic deformation from being excessively introduced into the ordered phases, and thus, further enhances the ductility.

[0126] In addition, the y phase having an average area ratio of 80% or less enhances the ductility sufficiently, inhibits an excessive decrease in the introduction of strain due to plastic deformation into the ordered phases contributive to the enhancement of strength, and further enhances the strength and the strength-ductility balance.

[0127] Accordingly, to achieve the strength, ductility, and strength-ductility balance further suitably, the average area ratio of the y phase is preferably 20 to 80%.

[0128] The average area ratio of the y phase is more preferably 30 to 70%, still more preferably 40 to 60%.

[0129] Here, the average area ratio of the ordered phases is regarded as the average area ratio of the metallurgical structure excluding the y phase. That is, in the metallurgical structure, the balance other than the y phase is the ordered phases.

<Method of Measuring Average Area Ratio of y Phase>

[0130] In a case in which the steel material is a steel sheet, the average area ratio of the y phase is measured as follows.

[0131] The L cross section (a cross section obtained by cutting the steel sheet along the rolling direction and the thickness direction) and the T cross section (a cross section obtained by cutting the steel sheet along the direction perpendicular to the rolling direction and along the thickness direction) of the steel sheet are mirror-polished. The faces mirror-polished are etched using an aqueous solution containing oxalic acid at a concentration of 10%, so that the γ phase is colored white, and the ordered phases are colored gray. In this manner, a test piece having polished faces as observation faces is produced.

[0132] Then, in a case in which the average grain size of the ordered phases is 5.00 μm or more, the thicknesswise central portion of each cross section of the test piece is observed under an optical microscope at a magnification of 500 times. In a case in which the average grain size of the ordered phases is less than 5.00 μm, the thicknesswise central portion of each cross section of the test piece is observed under a scanning electron microscope at a magnification of 1000 times. The resulting images are analyzed to calculate the area ratio of the γ phase. Not less than 5 fields of view of the L cross section of the steel sheet and 5 fields of view of the T cross section of the steel sheet, totaling 10 fields of view, are used to calculate the area ratio of the γ phase in each field of view. The arithmetic average of the values calculated is regarded as the average area ratio of the γ phase.

[0133] In a case in which the steel material is a steel wire, a steel bar, or a steel pipe, the area ratio of the γ phase is measured, using a test piece produced to have a lengthwise cross section and a widthwise cross section as observation faces, instead of the L cross section and the T cross section. In a case in which the steel material is a steel wire and a steel bar, a portion to be observed under an optical microscope is a portion corresponding to the diametrically central portion of each of the steel wire and the steel bar in the cross section of the test piece. In a case in which the steel material is a steel pipe, a portion to be observed under an optical microscope is a portion corresponding to the thicknesswise central portion of the cross section of the test piece.

[0134] In a case in which the steel material is a steel strip, a shape steel, or a foil, the area ratio of the γ phase is measured in the same manner as in a case in which the steel material is a steel sheet.

<Ratio of DO3 Ordered Phase>

[0135] The ordered phases are classified into a B2 ordered phase having FeSi as a basic chemical composition and a DO3 ordered phase having Fe_3Si as a basic chemical composition. The DO3 ordered phase has higher strength and better enhanced strength-ductility balance than the B2 ordered phase.

[0136] Accordingly, the ratio of the DO3 ordered phase is preferably higher. Specifically, it is preferable that the ordered phases contain the DO3 ordered phase, and that the ratio of the DO3 ordered phase to all the ordered phases, as determined by X-ray diffractometry, satisfies the following Formula B. Allowing the ratio of the DO3 ordered phase to satisfy the following Formula B enhances the strength and the strength-ductility balance further.

$$\text{Formula B: [DO3 ordered phase]/[all the ordered phases]} \geq 0.20$$

[0137] In this regard, all the ordered phases are composed of the DO3 ordered phase and the B2 ordered phase.

[0138] The lower limit of the value of "[DO3 ordered phase]/[all the ordered phases]" (hereinafter referred to as the "B value") in Formula B is more preferably 0.25, still more preferably 0.30.

[0139] The upper limit of the B value in Formula B is preferably 1.00, more preferably 0.91.

[0140] In the same manner as various compounds exist in a range of compositional ratios, any case in which the ordered phases are B2 ordered phases may be a case in which the ratio of the Fe atom to the Si atom (Fe atom/Si atom) is not completely limited to 1/1 but encompasses the range of from 1/0.3 to 1/1.3, and any case in which the ordered phases are DO3 ordered phases may be a case in which the ratio of the Fe atom to the Si atom (Fe atom/Si atom) is not completely limited to 3/1 but encompasses the range of from 3/0.5 to 3/1.4.

[0141] In order that the ratio of the DO3 ordered phase satisfies Formula B, it is preferable that the finishing annealing temperature and the cooling rate after the finishing annealing are controlled.

[0142] Specifically, the finishing annealing temperature is preferably 600 to 1150°C, and the cooling rate after the finishing annealing is preferably 0.010 to 10.000°C/s.

[0143] Here, the annealing temperature is the surface temperature of the steel material.

[0144] In addition, the cooling rate after the finishing annealing is the average cooling rate obtained by dividing a temperature difference between the finishing annealing temperature and 400°C by the time taken to cool the finishing annealing temperature to 400°C.

<Method of Determining Types of Ordered Phases and Ratio of DO3 Ordered Phase>

[0145] In a case in which the steel material is a steel sheet, the types of the ordered phases and the ratio of the DO3 ordered phase (the B value in Formula B) are determined as follows.

[0146] The types of the ordered phases and the ratio of the DO3 ordered phase are determined by XRD (X-ray diffractometry).

[0147] The conditions for the X-ray diffractometry are as follows: CoKα rays are used as characteristic X rays; the voltage is 30 kV; and the current is 100 mA. The measurement range of the X-ray diffractometry is $10° \leq 2\theta \leq 110°$, the step is 0.04°, and the elapsed time is 2 s. The XRD measurement is made in accordance with the θ-2θ method.

[0148] The surface of a test piece (20 mm long and 20 mm wide) is polished until the thickness of the piece becomes half of the original thickness of the piece. Using the surface as an observation face, XRD is performed. By the position of an X-ray diffraction peak obtained, ordered phases-the B2 ordered phase and the DO3 ordered phase-are identified. In a case in which the diffraction peak intensity is equal to or lower than the background, the intensity is determined to be undetected, and the area ratio of the corresponding phase is regarded as 0%.

[0149] The ratio of the DO3 ordered phase, i.e., the B value ([DO3 ordered phase]/[all the ordered phases]) in Formula B is calculated from the data measured by XRD. Using CoKα rays, measurements are made in the range of 2θ from 10 to 110°. The information obtained is processed with the below-described method to calculate the B value in Formula B.

[0150] For the calculation of the B value in Formula B, a method is used in which the X-ray integrated intensity and the ratio of intensity both measured are converted into the diffraction intensities of a specific lattice plane, and from the average of the sum thereof, the phasic ratio is determined.

[0151] The calculating method will be described below. In this regard, the DO3 $Fe_3Si_{(220)}$ and the B2 $FeSi_{(210)}$ are selected as specific diffraction planes.

[0152] With the DO3 Fe_3Si, the integrated intensities of nine diffraction planes, (111), (200), (220), (311), (222), (400), (331), (420), and (422), are converted into the integrated intensities of the DO3 Fe_3Si (220).

[0153] With the B2 FeSi, the integrated intensities of nine diffraction planes, (110), (111), (200), (210), (211), (311), (023), (123), and (400), are converted into the integrated intensities of the B2 FeSi (210).

[0154] In this regard, the numerical values in ( ) are Miller indices (hkl) of the crystal. The integrated intensity in the range of 2θ and the ratio of intensity both measured are used to calculate the B value in Formula B in accordance with the following formula. The specifics are as follows.

[0155] First, the integrated intensity and ratio of intensity of the above-described diffraction planes are substituted in the following Formulas to calculate I_{B2} and I_{DO3}.

$$\text{Formula: } I_{B2} = \{\Sigma(I_{B2(hkl)}/R_{B2(hkl)})\}/n$$

$$n = 9$$

$I_{B2\ (hkl)}$ is an integrated intensity measured.
$R_{B2\ (hkl)}$ is a ratio of intensity, assuming that $R_{B2\ (210)}$ is 1.

$$\text{Formula: } I_{DO3} = \{\Sigma(I_{DO3(hkl)}/R_{DO3(hkl)})\}/n$$

$$n = 9$$

$I_{DO3(hkl)}$ is an integrated intensity measured.
$R_{DO3(hkl)}$ is a ratio of intensity, assuming that $R_{DO3(220)}$ is 1.

[0156] Next, I_{B2} and I_{DO3} both calculated are used to calculate the B value in Formula B in accordance with the following formula.

$$\text{B value in Formula B} = I_{DO3}/(I_{B2} + I_{DO3})$$

[0157] This procedure is performed on 10 positions in the central portion of the steel sheet in the direction perpendicular to the rolling direction, and the arithmetic average of the values is regarded as the B value in Formula B.

[0158] In a case in which the steel material is a steel wire and a steel bar, the types of the ordered phases and the ratio of the DO3 ordered phase are determined, using a test piece produced from the steel material in such a manner that a face of the test piece is polished until the thickness of the test piece becomes half of the diameter of each of the steel wire and the steel bar in the diametric direction of each of the steel wire and the steel bar, in which the face polished is an observation face.

[0159] In a case in which the steel material is a steel pipe, the types of the ordered phases and the ratio of the DO3 ordered phase are determined, using a test piece produced from the steel material in such a manner that a face of the test piece is polished until the thickness of the test piece becomes half of the plate thickness of the steel pipe in the diametric direction of the steel pipe, in which the face polished is an observation face.

[0160] In a case in which the steel material is a steel strip, a shape steel, or a foil, the types of the ordered phases and the ratio of the DO3 ordered phase are determined in the same manner as in a case in which the steel material is a steel sheet.

<Average Chemical Composition of Ordered Phases>

[0161] Whether the ordered phases are B2 ordered phases or DO3 ordered phases, the ordered phases are phases in which the α phase is ordered. Si, which is an α-phase-stabilizing element, is preferably distributed in a large amount in the ordered phases. In addition, Si is an element effective to enhance corrosion resistance. Si, which is effective to enhance corrosion resistance, is preferably distributed in a larger amount in the ordered phases that work as a more preferential anode than the y phase in a corrosion reaction.

[0162] Specifically, the average chemical composition of the ordered phases preferably satisfies the below-described Formula C.

[0163] In a corrosion reaction, the ordered phases work as a more preferential anode than the y phase. This behavior is more noticeable in a case in which Ni are Cu are less in the ordered phases, and more noticeable in a case in which Si and Al are more in the ordered phases. To enhance the corrosion resistance of the steel material, the ordered phases need to be a preferential anode. In the ordered phases, Ni and Cu are preferably less, and Si and Al are preferably more. In particular, Si in the ordered phases enhances the corrosion resistance of the ordered phases themselves, and hence, is preferably more.

[0164] Formula C represents this relationship.

[0165] Accordingly, the ordered phases having the average chemical composition that satisfy the following Formula C affords further enhanced corrosion resistance.

$$\text{Formula C: } (\mathrm{Si}_{\mathrm{ordered}} + \mathrm{Al}_{\mathrm{ordered}})/(\mathrm{Ni}_{\mathrm{ordered}} + \mathrm{Cu}_{\mathrm{ordered}}) \geq 0.25$$

(In Formula C, the symbol of each element symbol, followed by the subscript $_{\mathrm{ordered}}$, represents the amount (mass %) of the element contained in the ordered phases.)

[0166] In Formula C, the lower limit of the value of "$(\mathrm{Si}_{\mathrm{ordered}} + \mathrm{Al}_{\mathrm{ordered}})/(\mathrm{Ni}_{\mathrm{ordered}} + \mathrm{Cu}_{\mathrm{ordered}})$" (hereinafter also referred to as the "C value") is more preferably 0.29, still more preferably 0.39.

[0167] The upper limit of the C value in Formula C is more preferably 0.98, still more preferably 0.88.

[0168] In order that the average chemical composition of the ordered phases satisfies Formula C, it is preferable that the finishing annealing temperature and the holding time at the finishing annealing temperature are controlled.

[0169] Specifically, the finishing annealing temperature is preferably 600 to 1150°C, and the holding time at the finishing annealing temperature is preferably satisfies the following Formula 1. Satisfying the following Formula 1 allows the diffusive movement of atoms to be sufficient between the ordered phases and the y phase, and thus, the average chemical composition of the ordered phases satisfies Formula C.

$$\text{Formula 1: } 100 \times t^{0.5}/T \geq 0.87$$

(In Formula 1, t represents a holding time (sec), and T represents a finishing annealing temperature (°C).)

[0170] Here, the holding time is the time until the start of cooling after the finishing annealing temperature of interest is reached.

<Average Chemical Composition of y Phase>

[0171] The average chemical composition of the y phase influences the ductility and the strength-ductility balance. The y phase preferably has an average chemical composition that does not impair the ductility or the strength-ductility balance.

[0172] Specifically, the average chemical composition of the γ phase preferably satisfies the following Formula D. The y phase having an average chemical composition that satisfies the following Formula D achieves further enhanced ductility and strength-ductility balance, enabling the ductility and strength-ductility balance of the steel material itself to be enhanced.

$$\text{Formula D: } \mathrm{Ni}_{\gamma} + 0.65\ \mathrm{Cr}_{\gamma} + 1.1\ \mathrm{Mn}_{\gamma} + 0.4\ \mathrm{Si}_{\gamma} + 13\ \mathrm{C}_{\gamma} \geq 18.4$$

(In Formula D, the symbol of each element symbol, followed by the subscript $_{\gamma}$, represents the amount (mass %) of the element contained in the y phase.)

[0173] The lower limit of the value of "$\mathrm{Ni}_{\gamma} + 0.65\ \mathrm{Cr}_{\gamma} + 1.1\ \mathrm{Mn}_{\gamma} + 0.4\ \mathrm{Si}_{\gamma} + 13\ \mathrm{C}_{\gamma}$" (hereinafter referred to as the "D value") in Formula D is more preferably 18.7, still more preferably 22.2.

[0174] The upper limit of the D value in Formula D is preferably 39.5, more preferably 37.0.

[0175] In order that the average chemical composition of the y phase satisfies Formula D, it is preferable that the finishing annealing temperature and the holding time at the finishing annealing temperature are controlled.

[0176] Specifically, the finishing annealing temperature is preferably 600 to 1150°C, and the holding time at the finishing annealing temperature is preferably satisfies the following Formula 2. Satisfying the following Formula 2 allows the diffusive movement of atoms to be sufficient between the ordered phases and the y phase, and thus, the average chemical composition of the y phase satisfies Formula D.

$$\text{Formula 2: } 500 \times t^{0.5}/T \geq 1.77$$

(In Formula 2, t represents a holding time (sec), and T represents a finishing annealing temperature (°C).)

<Average Chemical Composition of Each of y Phase and Ordered Phases>

[0177] In a case in which the steel material is a steel sheet, the average chemical composition of each of the y phase and the ordered phases is determined as follows.

[0178] The L cross section and T cross section of a steel sheet are mirror-polished to obtain a test piece. The thicknesswise central portion of the cross section of the steel sheet in the test piece is observed under a scanning electron microscope at a magnification of 1000 times in a case in which the average grain size of the ordered phases is 5.00 μm or more and at a magnification of 2000 times in a case in which the average grain size of the ordered phases is less than 5.00 μm. An elemental analysis is performed with an EPMA (Electron Probe Micro Analyzer), an accessory to the scanning electron microscope, to determine the average chemical composition of each of the y phase and the ordered phases.

[0179] The average chemical composition of the ordered phases is analyzed as follows. Using an enlarged image obtained by enlarging the observation face by 3000 times, a 30 μm × 30 μm region of the face is analyzed to identify ordered phases. In this case, objects to be identified are ordered phases having an average crystal grain size of 0.5 μm or more. From the ordered phases identified, 10 ordered phases the largest in grain size are selected. The chemical component in the central portion of the crystal grains of each of these 10 ordered phases (the central portion of the crystal grains in the largest-diameter direction) is analyzed using an EPMA method. As elements to be measured using a method EPMA, the elements shown in the average chemical composition of a steel material of the disclosure is used.

[0180] Then, from one field of view to be measured, the amount of each element to be measured in the ordered phases is measured in mass %. The elements to be measured in mass % in the 10 ordered phases are substituted for the C value in Formula C ($(Si_{ordered} + Al_{ordered})/(Ni_{ordered} + Cu_{ordered})$). The C values in Formula C are arithmetically averaged to calculate the representative value of the C value in Formula C for each field of view.

[0181] This procedure is performed on 5 fields of view of the L cross section and 5 fields of view of the T cross section, totaling 10 fields of view. The representative values of the C value in Formula C, as obtained from the fields of view, are arithmetically averaged further with the number of fields of view. The resulting whole arithmetic average value is regarded as the representative value of the C value in Formula C for the steel sheet.

[0182] The average chemical composition of the y phase is analyzed using the same method as the average chemical composition of the ordered phases, except that the phase for analysis is the y phase instead of the ordered phases. Thus, each element to be measured in mass % in the y phase is determined to obtain the representative value of the D value in Formula D.

[0183] Here, in the EPMA method, a measurement is made at an accelerating voltage of 15 KeV. Making a measurement using the EPMA method under such conditions makes it possible to make a point analysis on an area approximately 0.2 to 0.5 μm at one point.

[0184] In a case in which the steel material is a steel wire, a steel bar, or a steel pipe, the average chemical composition of each of the y phase and the ordered phases is determined, using a test piece produced to have a lengthwise cross section and a widthwise cross section as observation faces, instead of the L cross section and the T cross section. In a case in which the steel material is a steel wire and a steel bar, a portion to be observed under a scanning electron microscope is a portion corresponding to the diametrically central portion of each of the steel wire and the steel bar in the cross section of the test piece. In a case in which the steel material is a steel pipe, a portion to be observed under a scanning electron microscope is a portion corresponding to the thicknesswise central portion of the cross section of the test piece.

[0185] In a case in which the steel material is a steel strip, a shape steel, or a foil, the average chemical composition of each of the y phase and the ordered phases is determined in the same manner as in a case in which the steel material is a steel sheet.

<Average Crystal Grain Size of Ordered Phases>

[0186] The ordered phases are harder than the γ phase, and the characteristics of the ordered phases influence the strength of the steel material. Decreasing the average grain size of the ordered phases enables the strength of the steel material to be further enhanced. In particular, the ordered phases having an average crystal grain size of 10.00 μm or less enhance the strength of the steel material noticeably.

[0187] Accordingly, the average crystal grain size of the ordered phases is preferably 10.00 μm or less, more preferably 8.00 μm or less, still more preferably 5.00 μm or less.

[0188] However, the lower limit of the average crystal grain size of the ordered phases is, for example, 0.50 μm from the viewpoint of the possibility of achieving production conditions.

[0189] To bring the average crystal grain size of the ordered phases to 10.00 μm or less, one of the following conditions (1) and (2) should be satisfied.

- Condition (1) -

[0190] In a case in which a cold working process is performed two or more times, it is preferable to control the following: the intermediate annealing temperature between the cold working processes to be performed two or more times; the finishing annealing temperature; the holding time at the finishing annealing temperature; and the degree of cold working.

[0191] Specifically, the degree of cold working is preferably 10% or more. The intermediate annealing temperature and the finishing annealing temperature are preferably 600°C to 1000°C. The holding time at the finishing annealing temperature preferably satisfies the following Formula 3-1. Satisfying the following Formula 3-1 enables the crystal grain growth to be inhibited in a suitable range, and thus, the average crystal grain size of the ordered phases becomes 10 μm or less.

$$\text{Formula 3-1: } (t \times T)^{0.5} \geq 106$$

(In Formula 3-1, t represents the holding time (sec) of a finishing annealing temperature, and T represents the finishing annealing temperature (°C).)

- Condition (2) -

[0192] It is preferable to control the finishing annealing temperature and the degree of cold working. Specifically, the degree of cold working and the finishing annealing temperature preferably satisfy the following Formula 3-2. Satisfying the following Formula 3-2 enables the crystal grain growth to be inhibited in a suitable range, and thus, the average crystal grain size of the ordered phases becomes 10 μm or less.

$$\text{Formula 3-2: } (R/T) \geq 0.06$$

(In Formula 3-2, R represents a degree of cold working (%), and T represents a finishing annealing temperature (°C).)

[0193] Here, the degree of cold working (%) is defined by the formula: ((the cross-sectional area of a material before processing) - (the cross-sectional area of a material after processing))/(the cross-sectional area of a material before processing) × 100.

[0194] In this regard, for example, the degree of cold working means the ratio of cold rolling in a case in which the steel material is a steel sheet, and means the ratio of cold wiredrawing in a case in which the steel material is a steel wire.

<Average Crystal Grain Size of Ordered Phases>

[0195] In a case in which the steel material is a steel sheet, the average crystal grain size of the ordered phases is measured as follows.

[0196] The L cross section and T cross section of a steel sheet are mirror-polished. Then, the cross-sectional faces are etched using an aqueous solution containing oxalic acid at a concentration of 10%, so that the y phase is colored white, and the ordered phases are colored gray. Thus, a test piece having polished faces as observation faces is produced. Not less than 5 fields of view of the L cross section of the steel sheet and 5 fields of view of the T cross section of the steel sheet, totaling 10 fields of view, are observed. Then, the fields of view are observed under an optical microscope at a magnification of 500 times and under a scanning electron microscope at a magnification of 1000 times. In a case in which the average grain size of the ordered phases is 5.00 μm or more, an image observed under an optical microscope at magnification of 500 times is adopted. In a case in which the average grain size of the ordered phases is less than 5.00 μm, an image observed under a scanning electron microscope at a magnification of 1000 times is adopted.
Using the image adopted, the crystal grain size of the ordered phases of each field of view is calculated in accordance with the intercept method that is described in JIS G 0551: 2020, and employs straight test lines.

[0197] Then, with the 10 fields of view, the arithmetic average of the crystal grain sizes of the ordered phases calculated is calculated, and used as the average crystal grain size of the steel material.

[0198] In a case in which the steel material is a steel wire, a steel bar, or a steel pipe, a test piece is produced, and a lengthwise cross section and a widthwise cross section of the test piece, instead of the L cross section and the T cross section, are used as observation faces. The average crystal grain size of the ordered phases is thus measured. In a case in which the steel material is a steel wire and a steel bar, a portion to be observed under an optical microscope or a scanning electron microscope is a portion corresponding to the diametrically central portion of each of the steel wire and the steel bar in the cross section of the test piece. In a case in which the steel material is a steel pipe, a portion to be observed under an optical microscope or a scanning electron microscope is a portion corresponding to the thicknesswise central portion of the cross section of the test piece.

[0199] In a case in which the steel material is a steel strip, a shape steel, or a foil, the average crystal grain size of the ordered phases is measured in the same manner as in a case in which the steel material is a steel sheet.

<Antiphase Boundary in Ordered Phases>

[0200] Whether the ordered phases are B2 ordered phases or DO3 ordered phases, an antiphase boundary can be formed in the ordered phases. In a case in which an antiphase boundary is formed in the ordered phases, particularly the vicinity of the antiphase boundary, among other ordered phases that are preferential anodes, becomes a selective anode. In the antiphase boundary vicinity that has become a selective anode, a metal atom such as Fe and a Si atom, which form ordered phases, have a strong bonding force therebetween, and thus, the metal atom such as Fe is less likely to be ionized, thus contributing to better corrosion resistance. The antiphase boundary that works as a selective anode has excellent corrosion resistance, hence allows the corrosion resistance of the steel material itself to be further enhanced, and facilitates the formation of a passivated film containing a Si oxide having excellent corrosion resistance.

[0201] Because of this, the ordered phases preferably contain an antiphase boundary. More specifically, one ordered phase preferably contains one or more antiphase boundaries.

[0202] In this regard, an antiphase boundary means a boundary between the phases that pertain to the configuration of atoms in the ordered phases, and are oriented differently from each other by 180 degrees (half a period).

[0203] To form an antiphase boundary in the ordered phases, it is preferable to control the finishing annealing temperature, the holding time at the finishing annealing temperature, and the average crystal grain size of the ordered phases after the finishing annealing.

[0204] Specifically, the finishing annealing temperature is preferably 600 to 990°C. The relationship among the finishing annealing temperature, the holding time at the finishing annealing temperature, and the average crystal grain size of the ordered phases after the finishing annealing preferably satisfies the following Formula 4. With the following Formula 4 satisfied, a lattice defect such as dislocation that originates the formation of ordered phases is introduced sufficiently in the ordered phases, and thus, an antiphase boundary is formed in the ordered phases.

$$\text{Formula 4: } 8 \times 10^{-3} \times (T \times t)^{0.5} \geq d$$

(In Formula 4, t represents the holding time (sec), T represents the finishing annealing temperature (°C), and d represents the average crystal grain size of the ordered phases after the finishing annealing.)

<Presence or Absence of Antiphase Boundary in Ordered Phases>

[0205] In a case in which the steel material is a steel sheet, whether there is any antiphase boundary in the ordered phases is verified as follows.

[0206] Whether there is any antiphase boundary in the ordered phases is verified using a transmission electron microscope. A test piece (having a diameter of 3 mm) having a face is produced, in which an observation position of the face is made 500 nanometers or less thick by a thin-film method, and in which the face is used as an observation face. In the observation under a transmission electron microscope, the DO3 Fe_3Si is observed in the orientation to the {002} plane.

[0207] The observation is performed at an observational magnification of 40000 times, 80000 times, and 400000 times in each of 10 fields of view in total. Ordered phases having an average crystal grain size of 0.5 μm or more are identified as objects to be measured. From the ordered phases identified, 10 ordered phases the largest in grain size are selected. In a case in which at a magnification of any of 40000 times, 80000 times, and 400000 times, one or more antiphase boundaries are observed in one or more of the 10 ordered phases, the presence of "an antiphase boundary in the ordered phases" is determined; and in a case in which at the magnification, no antiphase boundary is observed in the 10 ordered phases, the absence of "an antiphase boundary in the ordered phases" is determined.

[0208] In a case in which the steel material is a wire, a bar, or a steel pipe, the presence or absence of an antiphase boundary in the ordered phases is verified, using a test piece (having a diameter of 3 mm) produced as follows: a widthwise cross-sectional face of a material is polished until the thickness of the material becomes 100 micrometers or less; then, the face is electropolished in such a manner that the thickness at the observation position is made 500 nanometers or less; and the face polished is used as an observation face.

[0209] In a case in which the steel material is a steel strip, a shape steel, or a foil, the area ratio of the γ phase is measured in the same manner as in a case in which the steel material is a steel sheet.

<Characteristics of Steel Material>

[0210] The product of the tensile strength and total elongation of a steel material of the disclosure is preferably 30000 MPa% or more, more preferably 50000 MPa% or more.

[0211] The tensile strength of a steel material of the disclosure is preferably 1250 MPa or more, more preferably 1500 MPa or more.

[0212] The total elongation of a steel material of the disclosure is preferably 24% or more, more preferably 33% or more.

<Method of Measuring Tensile Strength and Total Elongation>

[0213] In a case in which the steel material is a steel sheet, a test piece cut out so as to have the L direction (rolling direction) parallel with the axis of stress is used to measure the tensile strength (TS/MPa) and the total elongation (EL/%) in a test performed in accordance with the Metallic materials-Tensile testing-Method described in JIS Z 2241: 2011.

[0214] The total elongation is total elongation at break in JIS Z 2241: 2011. The measurement is performed under conditions that give 0.002 s^{-1} as a rate of cross-head displacement.

[0215] In a case in which the steel material is a steel wire, a steel bar, and a steel pipe, a test piece cut out so as to have the longitudinal direction parallel with the axis of stress is produced and used to measure the tensile strength and the total elongation.

[0216] In a case in which the steel material is a steel strip, a shape steel, or a foil, the tensile strength and the total elongation are measured in the same manner as in a case in which the steel material is a steel sheet.

<<Method of Producing Steel Material of the Disclosure>>

[0217] Examples of a method of producing a steel material of the disclosure include a producing method including: a step of hot-working (for example, hot-rolling or hot-wiredrawing) a steel billet of a steel material having the above-described average chemical composition of a steel material of the disclosure to obtain a processing material; a step of annealing the processing material; a step of cold-working (for example, cold-rolling or cold-wiredrawing) the processing material annealed; and a step of performing finishing annealing on the processing material cold-worked. However, the material may be left in the form of a hot-rolled sheet without undergoing cold working and finishing annealing.

[0218] The hot working is performed, for example, at a heating temperature of 900 to 1150°C.

[0219] In a case in which the hot-worked material is annealed, the annealing may be performed, for example, at a holding temperature of 600 to 1150°C in the atmospheric air for a holding time of 1 to 1200 s.

[0220] In the cold working, cold rolling is performed, for example, at room temperature in the atmospheric air. The cold working may be performed a plurality of times, and intermediate annealing may be performed between a plurality of times of cold working.

[0221] The finishing annealing may be performed, for example, at a holding temperature of 600 to 1250°C in the atmospheric air for a holding time of 1 to 50000 s.

[0222] If necessary, descaling, temper rolling, and shape leveling with a tension leveler may be performed after the finishing annealing.

[0223] In a method of producing a steel material of the disclosure, a steel billet having the above-described average chemical composition of a steel material of the disclosure is processed as described above to obtain a steel material having a metallurgical structure containing a γ phase and ordered phases.

[0224] Here, in a case in which the steel material is a steel sheet, a steel strip, a shape steel, or a foil, a method of producing a steel material of the disclosure includes performing hot rolling as hot working and cold rolling as cold working to produce a steel sheet, a steel strip, or a foil.

[0225] In a case in which the steel material is a steel wire or a steel bar, a method of producing a steel material of the disclosure includes performing hot wiredrawing as hot working and cold wiredrawing as cold working to produce a steel wire or a steel bar.

[0226] In a case in which the steel material is a welded steel pipe, a method of producing a steel material of the disclosure includes performing hot rolling as hot working and cold rolling as cold working to obtain a steel sheet or a steel strip, and then molding the steel sheet or the steel strip in pipe form to produce a steel pipe. In a case in which the steel material is a seamless steel pipe, a method of producing a steel material of the disclosure includes performing hot rolling as hot working and cold drawing as cold working to produce a seamless steel pipe.

[0227] To provide the above-described suitable aspects in a method of producing a steel material of the disclosure, a steel material is preferably produced under the above-described respective production conditions.

<Examples of Steel Material>

[0228] Examples of a steel material of the disclosure include steel sheets, steel strips, steel wires, steel bars, shape steels, steel pipes, and foils.

[0229] A steel material of the disclosure can be used suitably for an automobile component that requires high strength, high ductility, and high strength-ductility balance, and in addition, high corrosion resistance and high producibility, at a higher level than the Current 3rd GEN AHSS.

Examples

[0230] The disclosure will be described more specifically below with reference to Examples. The disclosure is not limited to the following Examples, and can be carried out, if appropriate, with modifications made within the scope conformable to the spirit of the disclosure. Such modifications are encompassed in the technical scope of the disclosure.

[0231] A slab having the average chemical composition shown in Table 1 was cast, and the slab cast was hot-rolled at a heating temperature of 900 to 1150°C to obtain a hot-rolled sheet having a thickness of 4.0 mm. The hot-rolled sheet was annealed and descaled. Then, under the conditions shown in Table 2, the sheet was cold-rolled, and the cold-rolled sheet underwent finishing annealing. Thus, a steel sheet was obtained as a steel material.

[0232] In this regard, the hot-rolled sheet was annealed at a heating rate of 5°C/sec and a cooling rate of 1°C/sec. In addition, the finishing annealing of the cold-rolled sheet was performed at a heating rate of 10°C/sec.

[0233] In this regard, the finishing annealing of the cold-rolled sheet was performed in an Ar atmosphere, but is not limited to the atmosphere.

[0234] Additionally, in Example 35, the hot-rolled sheet was not cold-rolled, and did not undergo the finishing annealing of a cold-rolled sheet.

[Table 1]

	Type of Steel	Average Chemical Composition (mass %) The Balance includes Fe and Impurities									Formula A
		Ni	Si	Al	Mn	C	Cr	P	S	Another Optional Element(s)	
Example	A	18.00	5.55	0.002	0.03	0.001	<0.01	0.009	0.003		0.7
Example	B	35.96	11.58	0.004	0.01	0.003	0.02	<0.001	0.009		1.4
Example	C	24.04	8.11	0.021	0.53	0.015	0.01	0.055	0.014		1.0
Example	D	20.17	7.53	0.941	0.21	0.009	0.03	0.097	0.026	Cu at 1.95	0.9
Example	E	22.51	7.73	<0.001	<0.001	<0.001	<0.001	0.048	<0.001		0.9
Example	F	20.97	6.99	<0.001	1.59	0.084	0.15	0.001	0.002		1.2
Example	G	20.75	7.02	1.115	1.98	<0.001	0.40	<0.001	<0.001	N at 0.002, B at 0.003	1.2
Example	H	20.19	5.99	1.989	<0.01	0.099	0.39	0.018	0.146	Sn at 0.08, Ge at 0.03, Ag at 0.01, Sb at 0.02, Te at 0.01	0.9
Example	I	32.45	9.44	0.121	1.49	0.049	0.08	0.033	0.020	Ca at 0.01, Mg at 0.01	1.2
Example	J	19.52	7.46	1.280	1.55	0.051	0.33	0.134	0.088	Li at 0.01, Sr at 0.02, REM at 0.01, Zr at 0.01	1.2
Example	K	27.93	9.94	0.490	0.39	0.071	0.05	0.145	0.045	Co at 0.02, Mo at 0.02, Ta at 0.01, W at 0.01	1.3
Example	L	29.99	7.98	0.002	0.09	0.001	0.21	0.200	0.018	PGM at 0.01, Au at 0.01, Re at 0.02	1.1
Example	M	30.52	8.52	0.479	1.82	0.041	0.18	0.147	0.097	In at 0.01, Ga at 0.01, Cd at 0.01, Pb at 0.01	1.5
Example	N	23.52	7.78	2.763	0.95	0.001	0.09	0.077	0.169	V at 0.001, Nb at 0.003, Ti at 0.002	1.1
Comparative Example	O	30.94	10.97	3.014	0.37	0.009	0.29	0.188	0.035		1.4
Comparative Example	P	24.96	9.99	0.049	2.11	0.048	0.05	0.005	0.107		1.4
Comparative Example	Q	23.87	8.86	0.008	0.85	0.105	0.11	0.066	0.112		1.2
Comparative Example	R	22.88	9.47	1.496	0.09	0.029	0.34	0.030	0.187	Cu at 2.05	1.1

(continued)

	Type of Steel	Average Chemical Composition (mass %) The Balance includes Fe and Impurities									Formula A
		Ni	Si	Al	Mn	C	Cr	P	S	Another Optional Element(s)	
Comparative Example	S	15.95	4.01	0.012	0.01	0.004	0.01	0.163	0.035		0.6
Comparative Example	T	37.21	11.02	0.009	0.04	0.043	0.08	0.190	0.018		1.5
Comparative Example	U	33.82	12.38	0.005	0.49	0.001	0.11	0.035	0.158		1.5
Comparative Example	W	24.88	3.86	0.011	0.02	0.007	0.05	0.066	0.077		0.8
Comparative Example	X	18.00	5.46	0.002	0.03	0.001	<0.01	0.009	0.003		0.7

[Table 2]

	Test No.	Type of Steel	Annealing Temperature after Hot Rolling	Degree of Cold Working	Finishing Annealing			Formula 1	Formula 2	Formula 3-1	Formula 4	Formula 3-2
					Temperature T	Holding Time t	Cooling Rate					
			°C	%	°C	sec	°C/s					
Example	1	A	1200	50	800	1000	0.010	3.95	19.76	894	7.16	0.06
Example	2	B	980	60	600	30000	10.000	28.87	144.34	4243	33.94	0.10
Example	3	C	1150	25	700	2000	4.940	6.39	31.94	1183	9.47	0.04
Example	4	D	1080	10	1100	10	7.950	0.29	1.44	105	0.84	0.01
Example	5	E	880	95	900	300	0.980	1.92	9.62	520	4.16	0.11
Example	6	F	1050	55	680	4000	0.120	9.30	46.50	1649	13.19	0.08
Example	7	G	1100	80	780	2800	1.040	6.78	33.92	1478	11.82	0.10
Example	8	H	900	60	850	320	1.000	2.10	10.52	522	4.17	0.07
Example	9	I	700	15	1150	8	8.000	0.25	1.23	96	0.77	0.01
Example	10	J	800	24	1080	11	0.100	0.31	1.54	109	0.87	0.02
Example	11	K	750	45	980	250	0.090	1.61	8.07	495	3.96	0.05
Example	12	L	780	33	1000	200	5.000	1.41	7.07	447	3.58	0.03
Example	13	M	950	65	940	260	4.950	1.72	8.58	494	3.95	0.07
Example	14	N	900	48	900	1000	0.050	3.51	17.57	949	7.59	0.05
Comparative Example	15	O	1000	30	950	11	5.050	0.35	*1.75*	102	0.82	0.03
Comparative Example	16	P	1000	35	1150	300	1.940	*1.51*	7.53	587	4.70	0.03
Comparative Example	17	Q	1000	25	1130	300	8.440	1.53	7.66	582	4.66	0.02
Comparative Example	18	R	1000	90	1050	300	9.950	1.65	8.25	561	4.49	0.09
Comparative Example	19	S	1000	60	1100	300	0.012	1.57	7.87	574	4.60	0.05

(continued)

	Test No.	Type of Steel	Annealing Temperature after Hot Rolling	Degree of Cold Working	Finishing Annealing			Formula 1	Formula 2	Formula 3-1	Formula 4	Formula 3-2
					Temperature T	Holding Time t	Cooling Rate					
			°C	%	°C	sec	°C/s					
Comparative Example	20	T	1000	70	1080	300	0.150	1.60	8.02	569	4.55	0.06
Comparative Example	21	U	1000	55	600	300	0.090	2.89	14.43	424	3.39	0.09
Comparative Example	22	W	1000	45	700	300	0.020	2.47	12.37	458	3.67	0.06
Example	23	A	900	5	800	3000	0.010	6.85	34.23	1549	12.39	0.01
Example	24	A	850	10	820	50	0.010	0.86	4.31	202	1.62	0.01
Example	25	A	900	10	800	1000	0.009	3.95	19.76	894	7.16	0.01
Example	26	A	1050	10	800	1000	10.100	3.95	19.76	894	7.16	0.01
Example	27	A	900	95	900	15	0.011	0.43	2.15	116	0.93	0.11
Example	28	A	900	85	1200	200	0.012	1.18	5.89	490	3.92	0.07
Example	29	A	900	85	580	100	0.012	1.72	8.62	241	1.93	0.15
Example	30	A	900	85	600	20	0.019	0.75	3.73	110	0.88	0.14
Example	31	A	untested	95	990	10	0.992	0.32	1.60	99	0.80	0.10
Example	32	B	1000	60	1040	30	1.451	0.53	2.63	177	1.41	0.06
Example	33	B	1050	75	1000	10	1.984	0.32	1.58	100	0.80	0.08
Example	34	B	980	45	700	10	2.229	0.45	2.26	84	0.67	0.06
Example	35	E	1050	0	Not Conducted	Not Conducted	Not Conducted	Not Conducted	Not Conducted	Not Conducted	Not Conducted	-
Example	36	E	1050	80	900	180	1.011	1.49	7.45	402	3.22	0.09
Comparative Example	37	X	1200	50	800	1000	0.010	3.95	19.76	894	7.16	0.06
Example	38	B	1000	60	600	40	0.010	1.05	5.27	155	1.24	0.10
Example	39	B	1000	80	800	100	0.010	1.25	6.25	283	2.26	0.10

(continued)

	Test No.	Type of Steel	Annealing Temperature after Hot Rolling	Degree of Cold Working	Finishing Annealing			Formula 1	Formula 2	Formula 3-1	Formula 4	Formula 3-2
					Temperature T	Holding Time t	Cooling Rate					
			°C	%	°C	sec	°C/s					
Example	40	B	1000	80	700	20	0.010	0.64	3.19	118	0.95	0.11

[0235] The producibility of the steel material itself produced was examined. In addition, a test piece produced from the steel material was used to examine the metallurgical structure, to examine the strength, ductility, and strength-ductility balance, and to examine the corrosion resistance.

(Examination of metallurgical Structure)

[0236] The following characteristics of the metallurgical structure were determined in accordance with the above-described methods.

- Area ratio of y phase
- Average chemical composition of each of y phase and ordered phases
- Type and ratio of ordered phases
- Average crystal grain size of ordered phases
- Presence or absence of antiphase boundary in ordered phases
- Tensile strength (TS/MPa) and total elongation (EL/%)

[0237] In the determination of the presence or absence of an antiphase boundary in the ordered phases, the evaluation was YES in a case in which one or more antiphase boundaries were observed in one or more of 10 ordered phases, and the evaluation was NO in a case in which no antiphase boundary was observed in 10 ordered phases.

[0238] In addition, tensile strength was used as an index of strength, total elongation was used as an index of ductility, and the product of tensile strength and total elongation was used as an index of strength-ductility balance.

[0239] Then, the mechanical characteristics were determined to be favorable in a case in which the tensile strength (TS) was 900 MPa or more, in which the total elongation (EL) was 22.0% or more, and in which the strength-ductility balance (TS × EL) was 19800 MPa·% or more.

(Examination of Corrosion Resistance)

[0240] In the examination of corrosion resistance, two methods of evaluation were used.

[0241] In the first corrosion resistance evaluation method, an SST (salt spray test) described in JIS Z 2371: 2015 was performed. After the test, a corroded product was removed using a method described in JIS Z 2371: 2015. Then, the external appearance was observed, the corrosion mass loss was calculated, and the dimensions of the steel material were measured. The external appearance was observed to verify the presence or absence of a corrosion pit, and the rate of corrosion was calculated from the corrosion mass loss, the density of the steel material, and the dimensions of the steel material. The test pieces were rated as follows: "A (excellent)" in a case in which no corrosion pit having a diameter of 20 μm or more was observed, and the rate of corrosion was 0.1 mm/year or less; "B (favorable)" in a case in which a corrosion pit having a diameter of 20 μm or more was observed, and the rate of corrosion was 0.1 mm/year or less; "C (acceptable)" in a case in which no corrosion pit having a diameter of 20 μm or more was observed, but the rate of corrosion was 0.1 mm/year or more and 0.5 mm/year or less; and "D (unacceptable)" in a case in which a corrosion pit having a diameter of 20 μm or more was observed, and the rate of corrosion was 0.1 mm/year or more. The SST was performed with 5% neutral salt water.

[0242] The second corrosion resistance evaluation method was the Methods of Pitting Potential Measurement described in JIS G 0577: 2014. The test solution was an aqueous solution of 3.5 mass% sodium chloride, and the other measurement conditions were as described in JIS G 0577: 2014. The pitting potential $V'c,_{100}$ was measured in units of mV vs. SSE, and the corrosion resistance was evaluated according to how large the measurement was.

[0243] In a case in which no corrosion pit was generated even by polarization to a potential equal to or higher than the oxygen-generating potential, the rating was "no corrosion pit".

[0244] Additionally, in a case in which a corrosion pit was generated, but the pitting potential was 400 mV or more, the material was regarded as having corrosion resistance.

(Examination of Producibility)

[0245] In the examination of producibility, the external appearance of the steel material produced was observed with naked eyes, and examined for cracks, flaws, and size. The range of examination is a range that is the surface area of the steel material, including the end of the surface, and is equal to or larger than 1 m × 1 m.

[0246] Then, a material not found having a crack or flaw 3 mm or more in length was rated "A (excellent)". In addition, the test pieces were rated as follows: "B (favorable)" in a case in which the largest length of any crack or flaw found in a test piece was 3 mm or more and 5 mm or less; "C (acceptable)" in a case in which the largest length was 5 mm or more and 8 mm or less; and "D (unacceptable)" the largest length was more than 8 mm.

[0247] Table 3 shows the results of each examination test.

[0248] In Table 3, the denotation "NO" in the column of the y phase means "no y phase", and the denotation "NO" in the column of the ordered phases means "no ordered phase".

[Table 3]

	Test No.	γ Phase		Ordered Phases				Characteristics of Steel Material					Producibility
		Area Ratio	Formula D	Formula B	Formula C	Average Crystal Grain Size d	Antiphase Boundary	TS	EL	TS × EL	Corrosion Resistance		
		%				μm	Present?	Mpa	%		SST	Pitting Potential	
Example	1	35	18.7	0.28	0.26	5.50	YES	1021	36.8	37573	A	no corrosion pit	A
Example	2	20	36.9	0.20	0.84	10.00	YES	1446	29.5	42657	A	no corrosion pit	A
Example	3	30	25.7	0.56	0.49	8.18	YES	1259	60.3	75918	A	no corrosion pit	A
Example	4	78	22.8	0.24	0.44	22.30	NO	998	44.4	44311	A	689	A
Example	5	45	23.9	0.89	0.45	4.01	YES	2319	25.1	58207	A	no corrosion pit	A
Example	6	24	24.3	0.23	0.39	9.96	YES	1511	22.2	33544	A	no corrosion pit	A
Example	7	33	24.1	0.63	0.52	9.50	YES	2014	39.9	80359	A	no corrosion pit	A
Example	8	38	22.2	0.77	0.42	3.97	YES	1507	34.6	52142	A	no corrosion pit	B
Example	9	80	37.3	0.20	0.73	28.90	NO	1003	41.1	41223	A	949	A
Example	10	75	23.8	0.33	0.56	9.97	NO	1144	38.1	43586	A	728	B
Example	11	51	30.9	0.35	0.88	3.60	YES	1202	48.7	58537	A	no corrosion pit	B
Example	12	55	32.0	0.49	0.65	9.81	NO	1337	58.4	78081	A	845	B
Example	13	49	23.3	0.91	0.29	3.80	YES	1738	40.5	70389	A	no corrosion pit	C
Example	14	29	19.9	0.22	0.29	2.60	YES	1271	30.6	38893	A	no corrosion pit	B

(continued)

	Test No.	γ Phase		Ordered Phases				Characteristics of Steel Material					Producibility
		Area Ratio	Formula D	Formula B	Formula C	Average Crystal Grain Size d	Antiphase Boundary	TS	EL	TS × EL	Corrosion Resistance		
		%				μm	Present?	Mpa	%		SST	Pitting Potential	
Comparative Example	15	0	NO	0.00	0.24	10.12	YES	721	1.3	937	D	10	D
Comparative Example	16	100	31.3	NO	NO	NO	NO	795	44.6	35457	D	54	A
Comparative Example	17	95	28.3	0.23	0.77	4.42	NO	895	41.2	36874	B	279	D
Comparative Example	18	90	26.6	0.18	0.74	4.30	NO	948	19.4	18391	B	318	D
Comparative Example	19	94	18.3	0.75	0.33	9.85	NO	992	26.8	26586	C	191	B
Comparative Example	20	89	40.5	0.82	0.66	4.33	NO	1083	15.2	16462	C	185	C
Comparative Example	21	12	31.3	0.15	0.28	2.10	YES	841	13.1	11017	B	337	D
Comparative Example	22	100	26.0	NO	NO	NO	NO	848	59.7	50626	D	48	A
Example	23	33	18.6	0.23	0.27	9.45	YES	1275	57.7	73568	A	no corrosion pit	A
Example	24	35	18.7	0.22	0.24	1.73	NO	1834	50.4	92434	B	671	A
Example	25	38	18.7	0.18	0.25	6.90	YES	1202	44.5	53489	A	no corrosion pit	A
Example	26	38	18.7	0.02	0.29	6.61	YES	1119	38.2	42746	A	no corrosion pit	A
Example	27	47	18.9	0.53	0.13	0.95	NO	2859	39.6	113216	B	569	A
Example	28	83	19.5	0.19	0.35	3.88	NO	1247	42.4	52873	B	655	A

(continued)

	Test No.	γ Phase		Ordered Phases				Characteristics of Steel Material					Producibility
		Area Ratio	Formula D	Formula B	Formula C	Average Crystal Grain Size d	Antiphase Boundary	TS	EL	TS × EL	Corrosion Resistance		
		%				μm	Present?	Mpa	%		SST	Pitting Potential	
Example	29	18	18.5	0.17	0.31	4.22	NO	1087	22.7	24675	B	603	A
Example	30	25	18.4	0.20	0.19	0.95	NO	2487	36.2	90029	B	521	A
Example	31	52	12.7	0.47	0.12	0.50	YES	2271	50.1	113777	A	no corrosion pit	A
Example	32	69	39.2	0.39	0.22	1.53	NO	2477	26.2	64897	B	486	A
Example	33	78	11.2	0.31	0.11	0.70	NO	2983	23.5	70101	B	477	A
Example	34	41	37.9	0.25	0.17	0.50	YES	2591	24.9	64516	A	no corrosion pit	A
Example	35	60	24.4	1.00	0.49	39.44	YES	896	64.9	58150	A	no corrosion pit	A
Example	36	52	24.1	1.00	0.55	0.50	YES	1251	51.2	64051	A	no corrosion pit	A
Comparative Example	37	38	18.5	0.22	0.19	7.75	NO	889	25.7	22847	D	25	A
Example	38	10	21.3	0.20	0.26	1.05	YES	1055	23.2	24476	A	no corrosion pit	A
Example	39	35	24.2	0.28	0.25	3.15	NO	1318	42.4	55883	A	604	A
Example	40	25	23.5	0.25	0.21	0.92	YES	2208	39.3	86774	A	no corrosion pit	A

[0249] The above-described results have revealed that, compared with a steel material in Comparative Examples, the steel materials in Examples in the disclosure have high strength, high ductility, and high strength-ductility balance, and in addition, high corrosion resistance, at a higher level than the Current 3rd GEN AHSS.

[0250] The results have also revealed that the steel materials in Examples in the disclosure have fewer cracks or flaws, and have excellent producibility.

[0251] Here, FIG. 1 illustrates an optical-microscopic photograph (at a magnification of 500 times; the white portion, the γ phase; the gray portion, the ordered phases) of the metallurgical structure of a steel material, the test number 35, in Examples in the disclosure, in which the steel material underwent hot-rolling and annealing but was yet to undergo finishing annealing. In addition, FIG. 2 illustrates an example of an optical-microscopic photograph (at a magnification of 500 times; the white portion, the γ phase; the gray portion, the ordered phases) of the metallurgical structure of a steel material, the test number 36, in Examples in the disclosure.

[0252] As shown in FIG. 1 and FIG. 2, it is understood that a steel material in Examples in the disclosure is totally different from the metallurgical structure according to a conventional technology. In addition, it is also understood that the metallurgical structure has been made fine through cold working and finishing annealing.

[0253] Suitable embodiments of the disclosure have been described in detail above, but the disclosure is not limited to such examples. It is obvious that any person having usual knowledge in the technical fields to which the disclosure belongs can conceive various examples of changes and examples of modifications in the category of the technical concept recited in CLAIMS. It is also understood that the examples obviously belong to the technical scope of the disclosure.

Claims

1. steel material comprising an average chemical composition including, by mass%:

Ni at 18.00 to 36.00%,
Si at 5.50 to 12.00%,
Cu at 0 to 2.00%,
Al at 0 to 3.000%,
Mn at 0 to 2.00%,
C at 0 to 0.100%,
Cr at 0 to 0.40%
P at 0 to 0.200%,
S at 0 to 0.200%,
N at 0 to 0.200%,
B at 0 to 0.200%,
Sn at 0 to 0.20%,
Ge at 0 to 0.20%,
Ag at 0 to 0.20%,
Sb at 0 to 0.20%,
Te at 0 to 0.20%,
V at 0 to 0.200%,
Nb at 0 to 0.200%,
Ti at 0 to 0.200%,
Ca at 0 to 0.200%,
Mg at 0 to 0.200%,
Li at 0 to 0.20%,
Sr at 0 to 0.20%,
REM at 0 to 0.20%,
Zr at 0 to 0.20%,
Co at 0 to 0.20%,
Mo at 0 to 0.20%,
Ta at 0 to 0.20%,
W at 0 to 0.20%,
PGM at 0 to 0.20%,
Au at 0 to 0.20%,
Re at 0 to 0.20%,
In at 0 to 0.20%,
Ga at 0 to 0.20%,

Cd at 0 to 0.20%,
Pb at 0 to 0.20%,
with a balance being Fe and impurities,
wherein the steel material has a metallurgical structure containing an austenite phase and ordered phases.

2. The steel material according to claim 1, wherein the average chemical composition of the steel material satisfies the following Formula A:

$$\text{Formula A: } C + Mn/6 + Si/24 + Ni/40 + Cr/5 \leq 1.4,$$

wherein, in Formula A, each element symbol represents an amount (mass%) of the element.

3. The steel material according to claim 1 or 2, wherein an average area ratio of the austenite phase is in a range of from 20 to 80%.

4. The steel material according to any one of claims 1 to 3, wherein the ordered phases contain a DO3 ordered phase, and wherein a ratio of the DO3 ordered phase to all the ordered phases ([DO3 ordered phase]/[all the ordered phases]), as determined by X-ray diffractometry, satisfies the following Formula B:

$$\text{Formula B: [DO3 ordered phase]/[all the ordered phases]} \geq 0.20.$$

5. The steel material according to any one of claims 1 to 4, wherein the average chemical composition of the ordered phases satisfies the following Formula C:

$$\text{Formula C: } (Si_{ordered} + Al_{ordered})/(Ni_{ordered} + Cu_{ordered}) \geq 0.25,$$

wherein, in Formula C, each element symbol, followed by a subscript $_{ordered}$, represents an amount (mass%) of the element contained in the ordered phases.

6. The steel material according to any one of claims 1 to 5, wherein the average chemical composition of the austenite phase satisfies the following Formula D:

$$\text{Formula D: } Ni_{\gamma} + 0.65Cr_{\gamma} + 1.1Mn_{\gamma} + 0.4Si_{\gamma} + 13C_{\gamma} \geq 18.4,$$

wherein, in Formula D, each element symbol, followed by a subscript $_{\gamma}$, represents an amount (mass%) of the element contained in the austenite phase.

7. The steel material according to any one of claims 1 to 6, wherein an average crystal grain size of the ordered phases is 10.00 μm or less.

8. The steel material according to any one of claims 1 to 7, wherein the ordered phases include an antiphase boundary.

9. The steel material according to any one of claim 1 to 8, having a tensile strength and a total elongation that give a product of 30000 MPa% or more.

10. The steel material according to any one of claims 1 to 9, wherein the tensile strength is 1250 MPa or more.

11. An automobile component comprising the steel material according to any one of claims 1 to 10.

FIG. 1

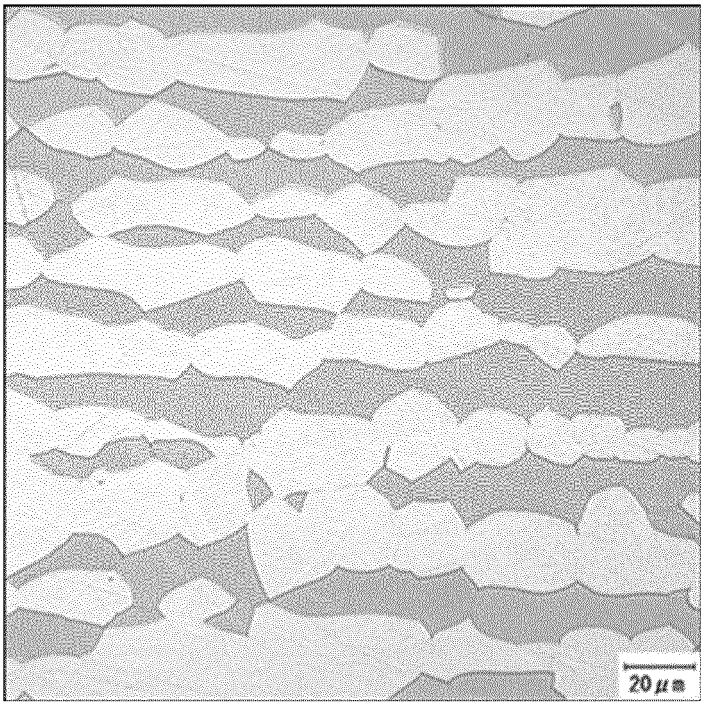
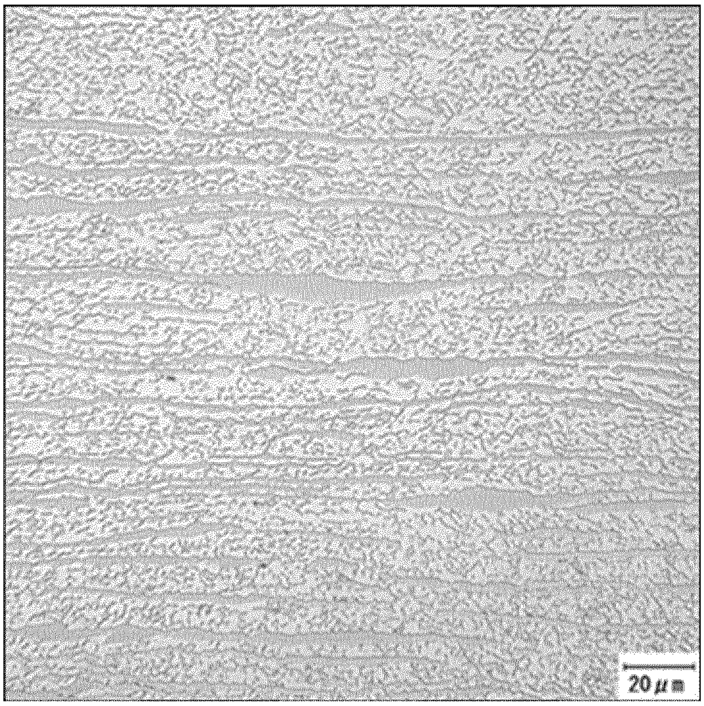


FIG. 2



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2022/033178

A. CLASSIFICATION OF SUBJECT MATTER

C21D 6/00(2006.01)n; *C21D 9/46*(2006.01)n; ***C22C 38/00***(2006.01)i; ***C22C 38/60***(2006.01)i
FI: C22C38/00 302Z; C22C38/60; C21D9/46 P; C21D6/00 101Z

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)

C22C38/00-38/60

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 1971-2022
Registered utility model specifications of Japan 1996-2022
Published registered utility model applications of Japan 1994-2022

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2000-17395 A (ISHIDA, Kiyohito) 18 January 2000 (2000-01-18) entire text, in particular, table 1, sample no. 1-3, 9	1-11

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"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
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search **28 October 2022**	Date of mailing of the international search report **08 November 2022**
Name and mailing address of the ISA/JP **Japan Patent Office (ISA/JP)** **3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915** **Japan**	Authorized officer Telephone No.

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

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2022/033178

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
JP 2000-17395 A	18 January 2000	(Family: none)	

Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

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- JP 2016141888 A **[0008]**
- JP 2016223003 A **[0008]**
- JP 2020514544 A **[0008]**