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(71) Applicant: **NIPPON STEEL CORPORATION**
Chiyoda-ku
Tokyo 100-8071 (JP)

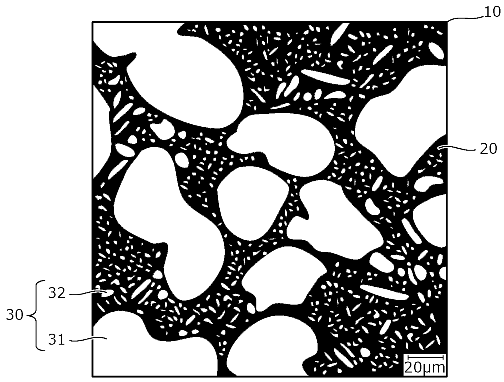
(72) Inventors:
- **OKADA, Seiya**
  Tokyo 100-8071 (JP)
- **ARAI, Yuji**
  Tokyo 100-8071 (JP)
- **NISHIBATA, Toshinobu**
  Tokyo 100-8071 (JP)

(74) Representative: **Zimmermann & Partner**
Patentanwälte mbB
Postfach 330 920
80069 München (DE)

(54) DUPLEX STAINLESS STEEL MATERIAL

(57) A duplex stainless steel material that has high strength and excellent low-temperature toughness is provided. A duplex stainless steel material according to the present disclosure consists of, by mass%, C: 0.030% or less, Si: 0.20 to 1.00%, Mn: 0.50 to 7.00%, P: 0.040% or less, S: 0.0200% or less, Al: 0.100% or less, Ni: 4.20 to 9.00%, Cr: 20.00 to 30.00%, Mo: 0.50 to 2.00%, Cu: 0.50 to 3.00%, N: 0.150 to 0.350%, and V: 0.01 to 1.50%, with the balance being Fe and impurities. The duplex stainless steel material has a yield strength of 552 MPa or more, and when an austenite grain with a minor axis of 20 μm or more is defined as primary austenite and the balance of austenite is defined as secondary austenite, the microstructure is composed of, in volume ratio, ferrite in an amount of 35 to 55%, primary austenite in an amount of 40 to 55%, and secondary austenite in an amount of 5 to 20%.

FIG. 1



Description

TECHNICAL FIELD

[0001] The present disclosure relates to a duplex stainless steel material.

BACKGROUND ART

[0002] Oil wells and gas wells (hereinafter, oil wells and gas wells are collectively referred to simply as "oil wells") may be in a corrosive environment containing a corrosive gas. Here, the term "corrosive gas" means carbon dioxide gas and/or hydrogen sulfide gas. That is, steel materials for use in oil wells are required to have excellent corrosion resistance in a corrosive environment.

[0003] To date, as a method for enhancing the corrosion resistance of a steel material, there has been a known method that increases the content of chromium (Cr) and forms a passive film mainly composed of Cr oxides on the surface of the steel material. Therefore, a duplex stainless steel material in which the content of Cr has been made high may in some cases be used in an environment where excellent corrosion resistance is required. It is known that, in particular, a duplex stainless steel material exhibits excellent corrosion resistance in seawater.

[0004] In recent years, deep wells below sea level are being actively developed. On the other hand, steel materials used for deep wells below sea level are required to not only have excellent corrosion resistance, but also to have high strength and excellent low-temperature toughness. Therefore, there is a need for duplex stainless steel materials that have high strength and excellent low-temperature toughness.

[0005] Japanese Patent Application Publication No. 10-60597 (Patent Literature 1), International Application Publication No. WO2012/111536 (Patent Literature 2), and Japanese Patent Application Publication No. 2016-3377 (Patent Literature 3) each propose a technique for increasing the strength and low-temperature toughness of a duplex stainless steel material.

[0006] Patent Literature 1 discloses a duplex stainless steel material which contains ferrite in an amount of 60 to 90% in area fraction, in which a Ni balance value (= Ni + 0.5Mn + 30(C + N) - 1.1(Cr + 1.5Si + Mo + 0.5Nb) + 8.2) is -15 to -10, and which satisfies the formula (content of Al $\times$ content of N $\leq$ 0.0023 $\times$ Ni balance value + 0.357). It is described in Patent Literature 1 that this duplex stainless steel material has high strength and excellent toughness.

[0007] Patent Literature 2 discloses a duplex stainless steel material that has a chemical composition consisting of, by mass%, C: 0.030% or less, Si: 0.20 to 1.00%, Mn: 8.00% or less, P: 0.040% or less, S: 0.0100% or less, Cu: more than 2.00 to 4.00% or less, Ni: 4.00 to 8.00%, Cr: 20.0 to 30.0%, Mo: 0.50 to less than 2.00%, N: 0.100 to 0.350%, and Al: 0.040% or less, with the balance being Fe and impurities, and that has a microstructure in which a ferrite ratio is 30 to 70%, and the hardness of ferrite is 300 Hv_{10gf} or more. It is described in Patent Literature 2 that this duplex stainless steel material has high strength and high toughness.

[0008] Patent Literature 3 discloses a duplex stainless steel material that is a duplex stainless steel tube which has a chemical composition consisting of, by mass%, C: 0.03% or less, Si: 0.2 to 1%, Mn: 0.5 to 2.0%, P: 0.040% or less, S: 0.010% or less, Al: 0.040% or less, Ni: 4 to less than 6%, Cr: 20 to less than 25%, Mo: 2.0 to 4.0%, N: 0.1 to 0.35%, O: 0.003% or less, V: 0.05 to 1.5%, Ca: 0.0005 to 0.02%, and B: 0.0005 to 0.02%, with the balance being Fe and impurities, and has a microstructure composed of a duplex microstructure of a ferrite phase and an austenite phase in which there is no precipitation of sigma phase, and in which a proportion occupied by the ferrite phase in the steel microstructure is 50% or less in area fraction, and the number of oxides having a particle size of 30 μm or more present in a visual field of 300 mm^2 is 15 or less. It is described in Patent Literature 3 that this duplex stainless steel material is excellent in strength, pitting resistance, and low-temperature toughness.

CITATION LIST

PATENT LITERATURE

[0009]

Patent Literature 1: Japanese Patent Application Publication No. 10-60597
Patent Literature 2: International Application Publication No. WO2012/111536
Patent Literature 3: Japanese Patent Application Publication No. 2016-3377

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0010] As described above, the aforementioned Patent Literatures 1 to 3 disclose duplex stainless steel materials that have high strength and excellent low-temperature toughness. However, a duplex stainless steel material that has high strength and excellent low-temperature toughness may also be obtained by a technique other than the techniques disclosed in the aforementioned Patent Literatures 1 to 3.

[0011] An objective of the present disclosure is to provide a duplex stainless steel material that has high strength and excellent low-temperature toughness.

SOLUTION TO PROBLEM

[0012] A duplex stainless steel material according to the present disclosure consists of, by mass%,

C: 0.030% or less,
Si: 0.20 to 1.00%,
Mn: 0.50 to 7.00%,
P: 0.040% or less,
S: 0.0200% or less,
Al: 0.100% or less,
Ni: 4.20 to 9.00%,
Cr: 20.00 to 30.00%,
Mo: 0.50 to 2.00%,
Cu: 0.50 to 3.00%,
N: 0.150 to 0.350%,
V: 0.01 to 1.50%,
Nb: 0 to 0.100%,
Ta: 0 to 0.100%,
Ti: 0 to 0.100%,
Zr: 0 to 0.100%,
Hf: 0 to 0.100%,
W: 0 to 0.200%,
Co: 0 to 0.500%,
Sn: 0 to 0.100%,
Sb: 0 to 0.100%,
Ca: 0 to 0.020%,
Mg: 0 to 0.020%,
B: 0 to 0.020%, and
rare earth metal: 0 to 0.200%,
with the balance being Fe and impurities,
wherein:

a yield strength is 552 MPa or more; and
when, in a microstructure, an austenite grain with a minor axis of 20 μm or more is defined as primary austenite, and the balance of austenite is defined as secondary austenite,
the microstructure is composed of, in volume ratio, ferrite in an amount of 35 to 55%, the primary austenite in an amount of 40 to 55%, and the secondary austenite in an amount of 5 to 20%.

ADVANTAGEOUS EFFECT OF INVENTION

[0013] The duplex stainless steel material according to the present disclosure has high strength and excellent low-temperature toughness.

BRIEF DESCRIPTION OF DRAWINGS

[0014]

[FIG. 1] FIG. 1 is a schematic diagram illustrating the appearance of microstructure during microstructure observation at a cross section at a central portion of the wall thickness of a duplex stainless seamless steel pipe that is one example of the duplex stainless steel material according to the present embodiment, the cross section being perpendicular to the pipe axis direction of the duplex stainless steel seamless pipe.

[FIG. 2] FIG. 2 is a view illustrating the relation between a volume ratio (%) of secondary austenite and a lowest temperature (°C) at which an absorbed energy is 30 J/cm^2 or more in duplex stainless steel materials which satisfy the chemical composition described above among the present examples.

DESCRIPTION OF EMBODIMENTS

[0015] First, the present inventors conducted studies regarding obtaining a duplex stainless steel material having a yield strength of 80 ksi (552 MPa) or more as a high strength. That is, the present inventors conducted investigations and studies regarding a method for obtaining a duplex stainless steel material that achieves both a yield strength of 80 ksi or more and excellent low-temperature toughness. As a result, the present inventors obtained the following findings.

[0016] First, the present inventors conducted studies from the viewpoint of the chemical composition with respect to a duplex stainless steel material that achieves both a yield strength of 80 ksi or more and excellent low-temperature toughness. As a result, the present inventors considered that if a duplex stainless steel material has a chemical composition consisting of, by mass%, C: 0.030% or less, Si: 0.20 to 1.00%, Mn: 0.50 to 7.00%, P: 0.040% or less, S: 0.0200% or less, Al: 0.100% or less, Ni: 4.20 to 9.00%, Cr: 20.00 to 30.00%, Mo: 0.50 to 2.00%, Cu: 0.50 to 3.00%, N: 0.150 to 0.350%, V: 0.01 to 1.50%, Nb: 0 to 0.100%, Ta: 0 to 0.100%, Ti: 0 to 0.100%, Zr: 0 to 0.100%, Hf: 0 to 0.100%, W: 0 to 0.200%, Co: 0 to 0.500%, Sn: 0 to 0.100%, Sb: 0 to 0.100%, Ca: 0 to 0.020%, Mg: 0 to 0.020%, B: 0 to 0.020%, and rare earth metal: 0 to 0.200%, with the balance being Fe and impurities, there is a possibility that a yield strength of 80 ksi or more and excellent low-temperature toughness can be obtained.

[0017] Here, the microstructure of a duplex stainless steel material having the chemical composition described above is composed of ferrite and austenite. Specifically, the microstructure of a duplex stainless steel material having the chemical composition described above is composed of, in volume ratio, ferrite in an amount of 35 to 55% with the balance being austenite. Note that, in the present description, the phrase "composed of ferrite and austenite" means that the amount of any phase other than ferrite and austenite is negligibly small.

[0018] Next, with respect to a duplex stainless steel material having the chemical composition described above in which the volume ratio of ferrite is 35 to 55%, the present inventors conducted detailed studies regarding a method for obtaining a yield strength of 80 ksi or more and excellent low-temperature toughness. Here, in a duplex stainless steel material having the chemical composition described above, ferrite is harder than austenite. Therefore, especially in a low-temperature environment, minute cracks generated in the duplex stainless steel material tend to easily propagate through the ferrite.

[0019] Therefore, with respect to a duplex stainless steel material having the chemical composition described above in which the volume ratio of ferrite is 35 to 55%, the present inventors conducted studies regarding causing fine austenite to disperse in the ferrite so as to increase the low-temperature toughness of the ferrite. If austenite is finely dispersed in ferrite, there is a possibility that the low-temperature toughness of the ferrite can be selectively increased. In such case, there is a possibility that the low-temperature toughness of a duplex stainless steel material having the chemical composition described above can be increased.

[0020] On the other hand, as the result of detailed studies conducted by the present inventors it was revealed that in a duplex stainless steel material having the chemical composition described above, there is a possibility that the yield strength will be reduced by causing fine austenite to disperse in ferrite. In other words, in a duplex stainless steel material having the chemical composition described above, there is a possibility that if the austenite is merely refined, even if the low-temperature toughness is increased, a yield strength of 80 ksi or more will not be obtained.

[0021] Therefore, the present inventors considered causing ferrite having a volume ratio of 35 to 55%, coarse austenite, and fine austenite to be intermixed in the microstructure of a duplex stainless steel material. In this case, there is a possibility that not only will the low-temperature toughness of the duplex stainless steel material be increased by the fine austenite dispersed in the ferrite, but also that the yield strength can be maintained by the coarse austenite.

[0022] Specifically the present inventors classified austenite in the microstructure of a duplex stainless steel material into coarse austenite grains with a minor axis of 20 μm or more, and fine austenite grains which is the remaining austenite other than the coarse austenite grains. More specifically, in the austenite of the microstructure of a duplex stainless steel material, the present inventors defined an austenite grain with a minor axis of 20 μm or more as "primary austenite", and defined the balance of the austenite as "secondary austenite". This point will be described more specifically using the drawings.

[0023] FIG. 1 is a schematic diagram illustrating the appearance of microstructure during microstructure observation at a cross section at a central portion of the wall thickness of a duplex stainless steel seamless pipe that is one example of the duplex stainless steel material according to the present embodiment, the cross section being perpendicular to the pipe axis direction of the duplex stainless steel seamless pipe. The vertical direction of an observation visual field region 10 in FIG. 1

corresponds to the pipe radial direction of the duplex stainless steel seamless pipe. The horizontal direction of the observation visual field region 10 in FIG. 1 corresponds to the pipe circumferential direction of the duplex stainless steel seamless pipe. That is, the observation visual field region 10 in FIG. 1 corresponds to a plane perpendicular to the pipe axis direction. Note that, the observation visual field region 10 in FIG. 1 has a length of 200 μm in the vertical direction and a length of 200 μm in the horizontal direction.

[0024] Referring to FIG. 1, regions shown in black represent ferrite 20, and regions shown in white represent austenite 30. Among the austenite 30, an austenite grain with a minor axis of 20 μm or more is defined as primary austenite 31, and an austenite grain with a minor axis of less than 20 μm is defined as secondary austenite 32. Note that, in the observation visual field region 10, the ferrite 20, the primary austenite 31, and the secondary austenite 32 can be identified by a method described later.

[0025] Next, the present inventors used method described later to evaluate the yield strength and the low-temperature toughness of duplex stainless steel materials which had the chemical composition described above and in which the volume ratio of ferrite was 35 to 55%. As a result, it was revealed that in a duplex stainless steel material which has the chemical composition described above and in which the volume ratio of ferrite is 35 to 55%, if the volume ratio of primary austenite is 40 to 55% and, in addition, the volume ratio of secondary austenite is 5 to 20%, both a yield strength of 80 ksi or more and excellent low-temperature toughness can be achieved. This point will now be described specifically using the drawings.

[0026] FIG. 2 is a view illustrating the relation between a volume ratio (%) of secondary austenite and a lowest temperature (°C) at which an absorbed energy is 30 J/cm^2 or more in duplex stainless steel materials which satisfy the chemical composition described above among examples that are described later. FIG. 2 was created using a volume ratio of secondary austenite (%) and a lowest temperature (°C), that is an index of low-temperature toughness, at which an absorbed energy was 30 J/cm^2 or more in, among examples described later, duplex stainless steel materials which satisfied the chemical composition described above and which had a microstructure including ferrite in an amount of 35 to 55% in volume ratio, and primary austenite in an amount of 40 to 55% in volume ratio.

[0027] Note that, the volume ratio of secondary austenite and the lowest temperature at which an absorbed energy is 30 J/cm^2 or more were determined using methods described later. Further, a white circle (O) in FIG. 2 means a steel material whose yield strength was 552 MPa or more. A black circle (●) in FIG. 2 means a steel material whose yield strength was less than 552 MPa.

[0028] Referring to FIG. 2, it can be confirmed that in a duplex stainless steel material having the chemical composition and microstructure described above, when the volume ratio of secondary austenite is 5% or more, the lowest temperature at which an absorbed energy is 30 J/cm^2 or more is -20°C or less, and thus excellent low-temperature toughness is exhibited. Referring further to FIG. 2, it can be confirmed that in a duplex stainless steel material having the chemical composition and microstructure described above, when the volume ratio of secondary austenite is more than 20%, although excellent low-temperature toughness is exhibited, a yield strength of 552 MPa or more is not obtained. That is, referring to FIG. 2, it can be confirmed that in a duplex stainless steel material having the chemical composition and microstructure described above, if the volume ratio of secondary austenite is 5 to 20%, both a yield strength of 552 MPa or more and excellent low-temperature toughness can be achieved.

[0029] Therefore, the duplex stainless steel material according to the present embodiment has the chemical composition described above, and is composed of, in volume ratio, ferrite in an amount of 35 to 55%, primary austenite in an amount of 40 to 55%, and secondary austenite in an amount of 5 to 20%. As a result, the duplex stainless steel material according to the present embodiment has a yield strength of 80 ksi (552 MPa) or more and has excellent low-temperature toughness.

[0030] The gist of the duplex stainless steel material according to the present embodiment, which has been completed based on the above findings, is as follows.

[0031]

[1]

A duplex stainless steel material consisting of, by mass%,
C: 0.030% or less,
Si: 0.20 to 1.00%,
Mn: 0.50 to 7.00%,
P: 0.040% or less,
S: 0.0200% or less,
Al: 0.100% or less,
Ni: 4.20 to 9.00%,
Cr: 20.00 to 30.00%,
Mo: 0.50 to 2.00%,
Cu: 0.50 to 3.00%,

N: 0.150 to 0.350%,
V: 0.01 to 1.50%,
Nb: 0 to 0.100%,
Ta: 0 to 0.100%,
Ti: 0 to 0.100%,
Zr: 0 to 0.100%,
Hf: 0 to 0.100%,
W: 0 to 0.200%,
Co: 0 to 0.500%,
Sn: 0 to 0.100%,
Sb: 0 to 0.100%,
Ca: 0 to 0.020%,
Mg: 0 to 0.020%,
B: 0 to 0.020%, and
rare earth metal: 0 to 0.200%,
with the balance being Fe and impurities,
wherein:

a yield strength is 552 MPa or more; and
when, in a microstructure, an austenite grain with a minor axis of 20 μm or more is defined as primary austenite, and the balance of austenite is defined as secondary austenite,
the microstructure is composed of, in volume ratio, ferrite in an amount of 35 to 55%, the primary austenite in an amount of 40 to 55%, and the secondary austenite in an amount of 5 to 20%.

[2] The duplex stainless steel material according to [1], containing one or more elements selected from a group consisting of:

Nb: 0.001 to 0.100%,
Ta: 0.001 to 0.100%,
Ti: 0.001 to 0.100%,
Zr: 0.001 to 0.100%,
Hf: 0.001 to 0.100%,
W: 0.001 to 0.200%,
Co: 0.001 to 0.500%,
Sn: 0.001 to 0.100%,
Sb: 0.001 to 0.100%,
Ca: 0.001 to 0.020%,
Mg: 0.001 to 0.020%,
B: 0.001 to 0.020%, and
rare earth metal: 0.001 to 0.200%.

[0032] Note that, the shape of the duplex stainless steel material according to the present embodiment is not particularly limited. The duplex stainless steel material according to the present embodiment may be a steel pipe, may be a round steel bar (a solid material), or may be a steel plate. Note that, the term "round steel bar" means a steel bar in which a cross section perpendicular to the axial direction is a circular shape. Further, the steel pipe may be a seamless steel pipe or may be a welded steel pipe.
[0033] Hereunder, the duplex stainless steel material according to the present embodiment is described in detail.

[Chemical composition]

[0034] The chemical composition of the duplex stainless steel material according to the present embodiment contains the following elements. The symbol "%" relating to an element means "mass%" unless otherwise noted.

C: 0.030% or less

[0035] Carbon (C) is unavoidably contained. That is, the lower limit of the content of C is more than 0%. C forms Cr carbides at grain boundaries and increases corrosion susceptibility at the grain boundaries. Therefore, if the content of C is too high, corrosion resistance of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of C is to be 0.030% or less. A preferable upper limit of the content of C is 0.028%, and more preferably is 0.025%. The content of C is preferably as low as possible. However, extremely reducing the content of C will significantly increase the production cost. Therefore, when industrial manufacturing is taken into consideration, a preferable lower limit of the content of C is 0.001%, more preferably is 0.003%, and further preferably is 0.005%.

Si: 0.20 to 1.00%

[0036] Silicon (Si) deoxidizes the steel. If the content of Si is too low, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, if the content of Si is too high, the low-temperature toughness of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of Si is to be 0.20 to 1.00%. A preferable lower limit of the content of Si is 0.25%, and more preferably is 0.30%. A preferable upper limit of the content of Si is 0.80%, more preferably is 0.70%, and further preferably is 0.60%.

Mn: 0.50 to 7.00%

[0037] Manganese (Mn) deoxidizes the steel, and desulfurizes the steel. Mn also increases hot workability of the steel material. If the content of Mn is too low, the aforementioned advantageous effects will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, Mn segregates to grain boundaries together with impurities such as P and S. Therefore, if the content of Mn is too high, corrosion resistance of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of Mn is to be 0.50 to 7.00%. A preferable lower limit of the content of Mn is 0.75%, and more preferably is 1.00%. A preferable upper limit of the content of Mn is 6.50%, and more preferably is 6.20%.

P: 0.040% or less

[0038] Phosphorus (P) is unavoidably contained. That is, the lower limit of the content of P is more than 0%. P segregates to grain boundaries. Therefore, if the content of P is too high, the low-temperature toughness and corrosion resistance of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of P is to be 0.040% or less. A preferable upper limit of the content of P is 0.035%, and more preferably is 0.030%. The content of P is preferably as low as possible. However, extremely reducing the content of P will significantly increase the production cost. Therefore, when industrial manufacturing is taken into consideration, a preferable lower limit of the content of P is 0.001%, and more preferably is 0.003%.

S: 0.0200% or less

[0039] Sulfur (S) is unavoidably contained. That is, the lower limit of the content of S is more than 0%. S segregates to grain boundaries. Therefore, if the content of S is too high, the low-temperature toughness and corrosion resistance of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of S is to be 0.0200% or less. A preferable upper limit of the content of S is 0.0180%, and more preferably is 0.0160%. The content of S is preferably as low as possible. However, extremely reducing the content of S will significantly increase the production cost. Therefore, when industrial manufacturing is taken into consideration, a preferable lower limit of the content of S is 0.0005%, and more preferably is 0.0010%.

Al: 0.100% or less

[0040] Aluminum (Al) is unavoidably contained. That is, the lower limit of the content of Al is more than 0%. Al deoxidizes the steel. On the other hand, if the content of Al is too high, coarse oxide-based inclusions will form and the low-temperature toughness of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of Al is to be 0.100% or less. A preferable lower limit of the content of Al is 0.001%, more preferably is 0.005%, and further preferably is 0.010%. A preferable upper limit of the content of Al is 0.090%, and more preferably is 0.085%. Note that, as used in the present description, the term "content of Al" means the content of "acidsoluble Al," that is, the content of sol. Al.

Ni: 4.20 to 9.00%

[0041] Nickel (Ni) stabilizes the austenitic microstructure of the steel material. That is, Ni is an element necessary for obtaining a stable duplex microstructure composed of ferrite and austenite. Ni also enhances corrosion resistance of the steel material. If the content of Ni is too low, the aforementioned advantageous effects will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, if the content of Ni is too high, even if the contents of other elements are within the range of the present embodiment, the volume ratio of austenite will be too high and the yield strength of the steel material will decrease. Therefore, the content of Ni is to be 4.20 to 9.00%. A preferable lower limit of the content of Ni is 4.25%, more preferably is 4.30%, further preferably is 4.35%, further preferably is 4.40%, and further preferably is 4.50%. A preferable upper limit of the content of Ni is 8.75%, more preferably is 8.50%, further preferably is 8.25%, further preferably is 8.00%, and further preferably is 7.75%.

Cr: 20.00 to 30.00%

[0042] Chromium (Cr) forms a passive film as an oxide on the surface of the steel material and thereby enhances corrosion resistance of the steel material. Cr also increases the volume ratio of the ferritic microstructure of the steel material. By obtaining a sufficient ferritic microstructure, corrosion resistance of the steel material is stabilized. If the content of Cr is too low, the aforementioned advantageous effects will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, if the content of Cr is too high, hot workability of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of Cr is to be 20.00 to 30.00%. A preferable lower limit of the content of Cr is 20.50%, more preferably is 21.00%, further preferably is 21.50%, and further preferably is 22.00%. A preferable upper limit of the content of Cr is 29.50%, more preferably is 29.00%, and further preferably is 28.00%.

Mo: 0.50 to 2.00%

[0043] Molybdenum (Mo) enhances corrosion resistance of the steel material. Mo also dissolves in the steel and increases the yield strength of the steel material. In addition, Mo forms fine carbides in the steel and increases the yield strength of the steel material. If the content of Mo is too low, the aforementioned advantageous effects will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, if the content of Mo is too high, hot workability of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of Mo is to be 0.50 to 2.00%. A preferable lower limit of the content of Mo is 0.55%, more preferably is 0.60%, and further preferably is 0.70%. A preferable upper limit of the content of Mo is less than 2.00%, more preferably is 1.85%, and further preferably is 1.50%.

Cu: 0.50 to 3.00%

[0044] Copper (Cu) increases the yield strength of the steel material. If the content of Cu is too low, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, if the content of Cu is too high, the hot workability of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of Cu is to be 0.50 to 3.00%. A preferable lower limit of the content of Cu is 0.60%, more preferably is 0.80%, further preferably is 0.90%, further preferably is 1.00%, and further preferably is 1.50%. A preferable upper limit of the content of Cu is 2.90%, more preferably is 2.75%, and further preferably is 2.50%.

N: 0.150 to 0.350%

[0045] Nitrogen (N) stabilizes the austenitic microstructure of the steel material. That is, N is an element necessary for obtaining a stable duplex microstructure composed of ferrite and austenite. N also enhances corrosion resistance of the steel material. If the content of N is too low, the aforementioned advantageous effects will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, if the content of N is too high, the low-temperature toughness and hot workability of the steel material will decrease even if the contents of other elements are within the range of the present embodiment. Therefore, the content of N is to be 0.150 to 0.350%. A preferable lower limit of the content of N is 0.170%, more preferably is 0.180%, and further preferably is 0.190%. A preferable upper limit of the content of N is 0.340%, and more preferably is 0.330%.

V: 0.01 to 1.50%

[0046] Vanadium (V) increases the yield strength of the steel material. If the content of V is too low, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment. On the other hand, if the content of V is too high, even if the contents of other elements are within the range of the present embodiment, strength of the steel material will be too high, and the low-temperature toughness and hot workability of the steel material will decrease. Therefore, the content of V is to be 0.01 to 1.50%. A preferable lower limit of the content of V is 0.02%, more preferably is 0.03%, further preferably is 0.05%, and further preferably is 0.10%. A preferable upper limit of the content of V is 1.20%, and more preferably is 1.00%.

[0047] The balance of the chemical composition of the duplex stainless steel material according to the present embodiment is Fe and impurities. Here, the term "impurities" in the chemical composition refers to substances which are mixed in from ore and scrap as the raw material or from the production environment or the like when industrially producing the duplex stainless steel material, and which are permitted within a range that does not adversely affect the duplex stainless steel material according to the present embodiment.

[Optional elements]

[0048] The chemical composition of the duplex stainless steel material according to the present embodiment may further contain one or more elements selected from the group consisting of Nb, Ta, Ti, Zr, Hf, and W in lieu of a part of Fe. Each of these elements is an optional element, and each of these elements increases strength of the steel material.

Nb: 0 to 0.100%

[0049] Niobium (Nb) is an optional element, and does not have to be contained. That is, the content of Nb may be 0%. When contained, Nb forms carbo-nitrides and increases strength of the steel material. If even a small amount of Nb is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Nb is too high, even if the contents of other elements are within the range of the present embodiment, strength of the steel material will be too high and the low-temperature toughness of the steel material will decrease. Therefore, the content of Nb is to be 0 to 0.100%. A preferable lower limit of the content of Nb is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of Nb is 0.080%, and more preferably is 0.070%.

Ta: 0 to 0.100%

[0050] Tantalum (Ta) is an optional element, and does not have to be contained. That is, the content of Ta may be 0%. When contained, Ta forms carbo-nitrides and increases strength of the steel material. If even a small amount of Ta is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Ta is too high, even if the contents of other elements are within the range of the present embodiment, strength of the steel material will be too high and the low-temperature toughness of the steel material will decrease. Therefore, the content of Ta is to be 0 to 0.100%. A preferable lower limit of the content of Ta is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of Ta is 0.080%, more preferably is 0.070%, and further preferably is 0.050%.

Ti: 0 to 0.100%

[0051] Titanium (Ti) is an optional element, and does not have to be contained. That is, the content of Ti may be 0%. When contained, Ti forms carbo-nitrides and increases strength of the steel material. If even a small amount of Ti is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Ti is too high, even if the contents of other elements are within the range of the present embodiment, strength of the steel material will be too high and the low-temperature toughness of the steel material will decrease. Therefore, the content of Ti is to be 0 to 0.100%. A preferable lower limit of the content of Ti is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of Ti is 0.080%, and more preferably is 0.070%.

Zr: 0 to 0.100%

[0052] Zirconium (Zr) is an optional element, and does not have to be contained. That is, the content of Zr may be 0%. When contained, Zr forms carbo-nitrides and increases strength of the steel material. If even a small amount of Zr is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Zr is too high, even if the contents of other elements are within the range of the present embodiment, strength of the steel material will be too high and the low-temperature toughness of the steel material will decrease. Therefore, the content of Zr is to be 0 to 0.100%. A preferable lower limit of the content of Zr is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of Zr is

0.080%, and more preferably is 0.070%.

Hf: 0 to 0.100%

[0053] Hafnium (Hf) is an optional element, and does not have to be contained. That is, the content of Hf may be 0%. When contained, Hf forms carbo-nitrides and increases strength of the steel material. If even a small amount of Hf is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Hf is too high, even if the contents of other elements are within the range of the present embodiment, strength of the steel material will be too high and the low-temperature toughness of the steel material will decrease. Therefore, the content of Hf is to be 0 to 0.100%. A preferable lower limit of the content of Hf is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of Hf is 0.080%, and more preferably is 0.070%.

W: 0 to 0.200%

[0054] Tungsten (W) is an optional element, and does not have to be contained. That is, the content of W may be 0%. When contained, W forms carbo-nitrides and increases strength of the steel material. If even a small amount of W is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of W is too high, even if the contents of other elements are within the range of the present embodiment, strength of the steel material will be too high and the low-temperature toughness of the steel material will decrease. Therefore, the content of W is to be 0 to 0.200%. A preferable lower limit of the content of W is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of W is 0.180%, and more preferably is 0.150%.

[0055] The chemical composition of the duplex stainless steel material according to the present embodiment may further contain one or more elements selected from the group consisting of Co, Sn, and Sb in lieu of a part of Fe. Each of these elements is an optional element, and each of these elements enhances corrosion resistance of the steel material.

Co: 0 to 0.500%

[0056] Cobalt (Co) is an optional element, and does not have to be contained. That is, the content of Co may be 0%. When contained, Co forms a coating on the surface of the steel material, and thereby enhances corrosion resistance of the steel material. Co also increases hardenability of the steel material and stabilizes strength of the steel material. If even a small amount of Co is contained, the aforementioned advantageous effects will be obtained to a certain extent. However, if the content of Co is too high, the production cost will increase extremely, even if the contents of other elements are within the range of the present embodiment. Therefore, the content of Co is to be 0 to 0.500%. A preferable lower limit of the content of Co is more than 0%, more preferably is 0.001%, further preferably is 0.010%, and further preferably is 0.020%. A preferable upper limit of the content of Co is 0.480%, more preferably is 0.460%, and further preferably is 0.450%.

Sn: 0 to 0.100%

[0057] Tin (Sn) is an optional element, and does not have to be contained. That is, the content of Sn may be 0%. When contained, Sn enhances corrosion resistance of the steel material. If even a small amount of Sn is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Sn is too high, even if the contents of other elements are within the range of the present embodiment, liquation cracking will occur at grain boundaries, which will cause hot workability of the steel material to decrease. Therefore, the content of Sn is to be 0 to 0.100%. A preferable lower limit of the content of Sn is more than 0%, more preferably is 0.001%, further preferably is 0.002%, and further preferably is 0.003%. A preferable upper limit of the content of Sn is 0.080%, and more preferably is 0.070%.

Sb: 0 to 0.100%

[0058] Antimony (Sb) is an optional element, and does not have to be contained. That is, the content of Sb may be 0%. When contained, Sb enhances corrosion resistance of the steel material. If even a small amount of Sb is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Sb is too high, even if the contents of other elements are within the range of the present embodiment, high-temperature ductility of the steel material will decrease, and hot workability of the steel material will decrease. Therefore, the content of Sb is to be 0 to 0.100%. A preferable lower limit of the content of Sb is more than 0%, more preferably is 0.001%, further preferably is 0.002%, and further preferably is 0.003%. A preferable upper limit of the content of Sb is 0.080%, and more preferably is

0.070%.

[0059] The chemical composition of the duplex stainless steel material according to the present embodiment may further contain one or more elements selected from the group consisting of Ca, Mg, B, and rare earth metal in lieu of a part of Fe. Each of these elements is an optional element, and each of these elements increases hot workability of the steel material.

Ca: 0 to 0.020%

[0060] Calcium (Ca) is an optional element, and does not have to be contained. That is, the content of Ca may be 0%. When contained, Ca fixes S in the steel material as a sulfide to make it harmless, and thereby increases hot workability of the steel material. If even a small amount of Ca is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Ca is too high, even if the contents of other elements are within the range of the present embodiment, oxides in the steel material will coarsen and the low-temperature toughness of the steel material will decrease. Therefore, the content of Ca is to be 0 to 0.020%. A preferable lower limit of the content of Ca is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of Ca is 0.018%, and more preferably is 0.015%.

Mg: 0 to 0.020%

[0061] Magnesium (Mg) is an optional element, and does not have to be contained. That is, the content of Mg may be 0%. When contained, Mg fixes S in the steel material as a sulfide to make it harmless, and thereby increases hot workability of the steel material. If even a small amount of Mg is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of Mg is too high, even if the contents of other elements are within the range of the present embodiment, oxides in the steel material will coarsen and the low-temperature toughness of the steel material will decrease. Therefore, the content of Mg is to be 0 to 0.020%. A preferable lower limit of the content of Mg is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of Mg is 0.018%, and more preferably is 0.015%.

B: 0 to 0.020%

[0062] Boron (B) is an optional element, and does not have to be contained. That is, the content of B may be 0%. When contained, B suppresses segregation of S in the steel material to grain boundaries, and thereby increases hot workability of the steel material. If even a small amount of B is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of B is too high, even if the contents of other elements are within the range of the present embodiment, boron nitride (BN) will be formed and will cause the low-temperature toughness of the steel material to decrease. Therefore, the content of B is to be 0 to 0.020%. A preferable lower limit of the content of B is more than 0%, more preferably is 0.001%, further preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.005%. A preferable upper limit of the content of B is 0.018%, and more preferably is 0.015%.

Rare earth metal: 0 to 0.200%

[0063] Rare earth metal (REM) is an optional element, and does not have to be contained. That is, the content of REM may be 0%. When contained, REM fixes S in the steel material as a sulfide to make it harmless, and thereby increases hot workability of the steel material. If even a small amount of REM is contained, the aforementioned advantageous effect will be obtained to a certain extent. However, if the content of REM is too high, even if the contents of other elements are within the range of the present embodiment, oxides in the steel material will coarsen and the low-temperature toughness of the steel material will decrease. Therefore, the content of REM is to be 0 to 0.200%. A preferable lower limit of the content of REM is more than 0%, more preferably is 0.001%, further preferably is 0.005%, further preferably is 0.010%, and further preferably is 0.020%. A preferable upper limit of the content of REM is 0.180%, and more preferably is 0.160%.

[0064] Note that, in the present description the term "REM" means one or more elements selected from the group consisting of scandium (Sc) which is the element with atomic number 21, yttrium (Y) which is the element with atomic number 39, and the elements from lanthanum (La) with atomic number 57 to lutetium (Lu) with atomic number 71 that are lanthanoids. Further, in the present description the term "content of REM" refers to the total content of these elements.

[Yield strength]

[0065] The yield strength of the duplex stainless steel material according to the present embodiment is 552 MPa or more. The duplex stainless steel material according to the present embodiment has the chemical composition described above, and is composed of, in volume ratio, ferrite in an amount of 35 to 55%, primary austenite in an amount of 40 to 55%, and secondary austenite in an amount of 5 to 20%. As a result, the duplex stainless steel material according to the present embodiment has excellent low-temperature toughness even when the yield strength is 80 ksi (552 MPa) or more.

[0066] A preferable lower limit of the yield strength of the duplex stainless steel material according to the present embodiment is 560 MPa, more preferably is 570 MPa, and further preferably is 580 MPa. Although not particularly limited, the upper limit of the yield strength of the duplex stainless steel material according to the present embodiment is, for example, 724 MPa.

[0067] The yield strength of the duplex stainless steel material according to the present embodiment can be determined by the following method. Specifically, a tensile test is performed by a method in accordance with ASTM E8/E8M (2021). A test specimen is prepared from the steel material according to the present embodiment. If the steel material is a steel plate, a round bar test specimen is prepared from a center portion of the thickness. If the steel material is a steel pipe, an arc-shaped test specimen having a thickness which is the same as the wall thickness of the steel pipe and having a width of 25.4 mm and a gage length of 50.8 mm is prepared. If the steel material is a round steel bar, a round bar test specimen is prepared from an R/2 position in a cross section perpendicular to the axial direction of the round steel bar. Note that, as used in the present description, the term "R/2 position" means the center position of a radius R in a cross section perpendicular to the axial direction of the round steel bar. In the case of preparing a round bar test specimen, the size of the round bar test specimen is, for example, as follows: the parallel portion diameter is 6 mm and the gage length is 24 mm. Note that, the longitudinal direction of the round bar test specimen and the arc-shaped test specimen is to be parallel to the rolling direction of the steel material. A tensile test is carried out at normal temperature (25°C) in air using the test specimen, and the obtained 0.2% offset proof stress is defined as the yield strength (MPa).

[Microstructure]

[0068] The microstructure of the duplex stainless steel material according to the present embodiment is composed of ferrite and austenite. In the present description, the phrase "composed of ferrite and austenite" means that the amount of any phase other than ferrite and austenite is negligibly small. For example, in the microstructure of the duplex stainless steel material according to the present embodiment, the volume ratios of precipitates and inclusions are negligibly small as compared with the volume ratios of ferrite and austenite. That is, the microstructure of the duplex stainless steel material according to the present embodiment may contain minute amounts of precipitates, inclusions and the like, in addition to ferrite and austenite.

[0069] In the microstructure of the duplex stainless steel material according to the present embodiment, the volume ratio of ferrite is 35 to 55%. If the volume ratio of ferrite is too low, the yield strength will decrease. On the other hand, if the volume ratio of ferrite is too high, the low-temperature toughness of the steel material will decrease. However, in the microstructure of a duplex stainless steel material which has the chemical composition described above and which is produced by a preferable production method to be described later, the volume ratio of ferrite is 35 to 55%. Therefore, in the microstructure of the duplex stainless steel material according to the present embodiment, the volume ratio of ferrite is 35 to 55%.

[0070] In the microstructure of the duplex stainless steel material according to the present embodiment, the volume ratio of primary austenite is 40 to 55% and the volume ratio of secondary austenite is 5 to 20%. In the present description, in the austenite of the microstructure of the duplex stainless steel material, an austenite grain with a minor axis of 20 μm or more is defined as primary austenite, and the balance of the austenite is defined as secondary austenite.

[0071] As described above, the fine secondary austenite disperses in ferrite and increases the low-temperature toughness of the ferrite. As a result, the low-temperature toughness of the duplex stainless steel material increases. If the volume ratio of the secondary austenite is too low, the aforementioned advantageous effect will not be sufficiently obtained. On the other hand, if the volume ratio of the secondary austenite is too high, the yield strength of the duplex stainless steel material will decrease. As a result, a duplex stainless steel material having a yield strength of 80 ksi or more will not be obtained. Therefore, in the present embodiment, the volume ratio of secondary austenite is to be 5 to 20%. A preferable lower limit of the volume ratio of secondary austenite is 6%, more preferably is 7%, and further preferably is 10%. A preferable upper limit of the volume ratio of secondary austenite is 19%, more preferably is 18%, and further preferably is 15%.

[0072] In addition, as described above, because the coarse primary austenite is present, the yield strength of the duplex stainless steel material according to the present embodiment increases. If the volume ratio of the primary austenite is too low, the aforementioned advantageous effect will not be sufficiently obtained. On the other hand, if the volume ratio of the primary austenite is too high, the volume ratio of secondary austenite and/or ferrite will decrease, and in some cases the low-temperature toughness of the produced duplex stainless steel material will decrease. Therefore, in the present embodiment, the volume ratio of primary austenite is to be 40 to 55%. A preferable lower limit of the volume ratio of primary austenite is 41%, more preferably is 42%, and further preferably is 45%. A preferable upper limit of the volume ratio of primary austenite is 54%, more preferably is 53%, and further preferably is 50%.

[0073] As described above, the duplex stainless steel material according to the present embodiment has the chemical composition described above, and is composed of, in volume ratio, ferrite in an amount of 35 to 55%, primary austenite in an amount of 40 to 55%, and secondary austenite in an amount of 5 to 20%. As a result, the duplex stainless steel material according to the present embodiment has a yield strength of 80 ksi or more and has excellent low-temperature toughness. Note that, in the present embodiment, as described later, microstructure observation is performed at a cross section perpendicular to the rolling direction of the duplex stainless steel material. That is, in the duplex stainless steel material according to the present embodiment, at a cross section perpendicular to the rolling direction of the duplex stainless steel material, the microstructure is composed of, in volume ratio, ferrite in an amount of 35 to 55%, primary austenite in an amount of 40 to 55%, and secondary austenite in an amount of 5 to 20%.

[0074] The volume ratios of ferrite, primary austenite, and secondary austenite of the duplex stainless steel material according to the present embodiment can be determined by the following method. First, a test specimen for microstructure observation is prepared from the duplex stainless steel material according to the present embodiment. If the steel material is a steel plate, a test specimen having an observation surface with dimensions of 5 mm in the width direction and 5 mm in the thickness direction is prepared from a center portion of the thickness. If the steel material is a steel pipe, a test specimen having an observation surface with dimensions of 5 mm in the pipe radial direction and 5 mm in the pipe circumferential direction is prepared from a central portion of the wall thickness. If the steel material is a round steel bar, a test specimen having an observation surface (5 mm $\times$ 5 mm) perpendicular to the axial direction of the round steel bar is prepared from an R/2 position in a cross section perpendicular to the axial direction of the round steel bar. Note that, the size of the test specimen is not particularly limited as long as the aforementioned observation surface can be obtained.

[0075] The observation surface of the prepared test specimen is mirror-polished. The mirror-polished observation surface is electrolytically etched in a 7% potassium hydroxide etching solution to reveal the microstructure. The observation surface where the microstructure has been revealed is observed in 10 visual fields using an optical microscope. The area of each visual field is, for example, 40000 μm^2 (200 $\mu m \times 200\ \mu m$). In each visual field, ferrite and austenite are identified based on contrast. The area fraction of the identified ferrite is determined. The method for determining the area fraction of ferrite is not limited, and it suffices to use a well-known method. For example, the area fraction of ferrite can be determined using image analysis software.

[0076] The austenite grain with a minor axis of 20 μm or more is identified among the austenite of each visual field identified based on contrast. Note that, in the present description, the minor axis of austenite is defined as follows. First, any austenite is identified in each visual field. Note that, in the present description, the phrase "any austenite is identified" means one austenite grain whose outer circumference is surrounded by ferrite is identified. A line segment with the longest length among line segments linking an arbitrary two points of the outer circumference of the relevant austenite is defined as the major axis of the relevant austenite. A rectangle that circumscribes the relevant austenite is then drawn in a manner so that the major axis of the relevant austenite is the long side. At this time, the short side of the drawn rectangle is defined as the minor axis of the relevant austenite.

[0077] In each visual field, the area fraction of the identified austenite with a minor axis of 20 μm or more (the primary austenite) is determined. The method for determining the area fraction of the primary austenite is not limited, and it suffices to use a well-known method. For example, the area fraction can be determined using image analysis software. Further, the area fraction (%) of secondary austenite can be determined using the area fraction (%) of ferrite and the area fraction (%) of primary austenite as determined by the above methods, and the following Formula (A).

(Area fraction (%) of secondary austenite) = 100 - {(area fraction (%) of ferrite) + (area fraction (%) of primary austenite)} (A)

[0078] In the present embodiment, the arithmetic average value of the area fractions (%) of ferrite obtained in the 10 visual fields by the above method is defined as the volume ratio (%) of ferrite. In addition, in the present embodiment, the arithmetic average value of the area fractions (%) of primary austenite obtained in the 10 visual fields by the above method is defined as the volume ratio (%) of primary austenite. Further, in the present embodiment, the arithmetic average value of the area fractions (%) of secondary austenite obtained in the 10 visual fields by the above method is defined as the volume ratio (%) of secondary austenite.

[0079] Note that, as mentioned above, in the duplex stainless steel material according to the present embodiment, in some cases the microstructure includes precipitates or inclusions or the like in addition to ferrite, primary austenite, and secondary austenite. However, as described above, the volume ratios of precipitates or inclusions or the like are negligibly small as compared with the volume ratios of ferrite, primary austenite, and secondary austenite. Therefore, in the present description, when calculating the volume ratios of ferrite, primary austenite, and secondary austenite by the above method, the volume ratios of precipitates, inclusions and the like are ignored.

[Low-temperature toughness]

[0080] The duplex stainless steel material according to the present embodiment has the chemical composition described above, and is composed of, in volume ratio, ferrite in an amount of 35 to 55%, primary austenite in an amount of 40 to 55%, and secondary austenite in an amount of 5 to 20%. As a result, the duplex stainless steel material according to the present embodiment has excellent low-temperature toughness even when the yield strength thereof is 80 ksi (552 MPa) or more. In the present embodiment, excellent low-temperature toughness is defined as follows.

[0081] The low-temperature toughness of the duplex stainless steel material according to the present embodiment is evaluated by a Charpy impact test in accordance with ASTM E23 (2018). A V-notch test specimen in accordance with ASTM E23 (2018) is prepared from the steel material according to the present embodiment. Specifically, if the steel material is a steel plate, a V-notch test specimen having a notched surface parallel to the thickness direction and the rolling direction is to be prepared from a center portion of the thickness. If the steel material is a steel pipe, a V-notch test specimen having a notched surface parallel to the wall thickness direction and the pipe axis direction is to be prepared from a central portion of the wall thickness. If the steel material is a round steel bar, a V-notch test specimen having a notched surface parallel to the radial direction of the cross section and to the rolling direction is to be prepared from an R/2 position in a cross section perpendicular to the axial direction. Note that, the longitudinal direction of the V-notch test specimen is to be parallel to the rolling direction of the steel material.

[0082] The prepared V-notch test specimen is subjected to a Charpy impact test in accordance with ASTM E23 (2018). The Charpy impact test is performed under eight conditions set in increments of 10°C in the range of 0 to -70°C, and the absorbed energy (J) at each temperature is determined. The determined absorbed energy (J) is divided by the cross-sectional area (cm^2) of the V-notch test specimen to determine the absorbed energy (J/cm^2) per unit area at each temperature. Note that, the term "cross-sectional area of the V-notch test specimen" means the area of a cross section perpendicular to the longitudinal direction of the V-notch test specimen at a position at the bottom of the V-notch. Specifically, when using a full-size 2-mm V-notch test specimen, the absorbed energy (J/cm^2) per unit area can be determined by dividing the determined absorbed energy (J) by the cross-sectional area 0.8 cm^2 (width of 0.8 cm $\times$ thickness of 1.0 cm) of the V-notch test specimen.

[0083] From among the absorbed energies per unit area at each temperature that are determined, the lowest temperature (°C) at which an absorbed energy is 30 J/cm^2 or more is determined. Specifically, for example, in a case where the absorbed energy per unit area at 0°C, -10°C, -20°C, and -30°C is 30 J/cm^2 or more, and the absorbed energy per unit area at -40°C, -50°C, -60°C, and -70°C is less than 30 J/cm^2, the lowest temperature is -30°C. In the present embodiment, if the lowest temperature at which an absorbed energy per unit area is 30 J/cm^2 or more is -20°C or less, it is determined that the duplex stainless steel material has excellent low-temperature toughness. Note that, in the present description the absorbed energy per unit area is also referred to simply as "absorbed energy".

[Shape of duplex stainless steel material]

[0084] As described above, the shape of the duplex stainless steel material according to the present embodiment is not particularly limited. The duplex stainless steel material according to the present embodiment, for example, may be a steel pipe, may be a steel plate, may be a round steel bar, or may be a wire rod. Preferably, the duplex stainless steel material according to the present embodiment is a seamless steel pipe. In a case where the duplex stainless steel material according to the present embodiment is a seamless steel pipe, even if the wall thickness is 5 mm or more, the duplex stainless steel material has a yield strength of 552 MPa or more and excellent low-temperature toughness.

[Production method]

[0085] One example of a method for producing the duplex stainless steel material according to the present embodiment composed as described above will now be described. Note that, a method for producing the duplex stainless steel material according to the present embodiment is not limited to the production method described hereunder. One example of a method for producing the duplex stainless steel material of the present embodiment includes a starting material preparation process, a hot working process, a secondary austenite precipitation treatment process, and a solution treatment process. Hereunder, each production process is described in detail.

[Starting material preparation process]

[0086] In the starting material preparation process according to the present embodiment, a starting material having the chemical composition described above is prepared. The starting material may be prepared by producing the starting material, or may be prepared by purchasing the starting material from a third party. That is, the method for preparing the starting material is not particularly limited.

[0087] In the case of producing the starting material, for example, the starting material is produced by the following method. A molten steel having the chemical composition described above is produced. A cast piece (a slab, a bloom, or a billet) is produced by a continuous casting process using the molten steel. An ingot may also be produced by an ingot-making process using the molten steel. As required, a slab, a bloom, or an ingot may be subjected to blooming to produce a billet. The starting material is produced by the above process.

[Hot working process]

[0088] In the hot working process according to the present embodiment, the starting material prepared in the aforementioned preparation process is subjected to hot working to produce an intermediate steel material. In the present description, the term "intermediate steel material" refers to a plate-shaped steel material in a case where the end product is a steel plate, refers to a hollow shell in a case where the end product is a steel pipe, refers to a steel material having a circular cross-sectional shape in a case where the end product is a round steel bar, and refers to a wireshaped steel material in a case where the end product is a wire rod. The hot working may be hot forging, may be hot extrusion, or may be hot rolling. The hot working method is not particularly limited, and it suffices to use a well-known method.

[0089] If the intermediate steel material is a hollow shell (seamless steel pipe), in the hot working process, for example, the Ugine-Sejoumet process or the Ehrhardt push bench process (that is, hot extrusion) may be performed, or the intermediate steel material may be subjected to piercing-rolling (that is, hot rolling) according to the Mannesmann process. Note that, hot working may be performed only one time or may be performed multiple times. For example, after performing the aforementioned piercing-rolling on the starting material, the aforementioned hot extrusion may be performed. For example, in addition, after performing the aforementioned piercing-rolling on the starting material, tube drawing may be performed. That is, in the hot working process, hot working is performed by a well-known method to produce an intermediate steel material having the desired shape.

[0090] Note that, if the steel material is a round steel bar or a steel plate, the intermediate steel material may be produced as follows. If the steel material is a round steel bar, first, the starting material is heated in a heating furnace. Although not particularly limited, the heating temperature is, for example, 1100 to 1300°C. After being extracted from the heating furnace, the starting material is subjected to hot working to produce an intermediate steel material in which a cross section perpendicular to the axial direction is a circular shape. The hot working is, for example, blooming performed using a blooming mill or hot rolling performed using a continuous mill. In a continuous mill, a horizontal stand having a pair of grooved rolls arranged one on the other in the vertical direction, and a vertical stand having a pair of grooved rolls arranged side by side in the horizontal direction are alternately arranged.

[0091] If the steel material is a steel plate, first, the starting material is heated in a heating furnace. Although not particularly limited, the heating temperature is, for example, 1100 to 1300°C. After being extracted from the heating furnace, the starting material is subjected to hot rolling using a blooming mill and a continuous mill to produce an intermediate steel material in the shape of a steel plate.

[Secondary austenite precipitation treatment process]

[0092] In the secondary austenite precipitation treatment process according to the present embodiment, the intermediate steel material produced by the aforementioned hot working process is subjected to a heat treatment to cause secondary austenite to precipitate in the intermediate steel material. Specifically, in the present embodiment, in the secondary austenite precipitation treatment process, preferably the intermediate steel material is heated, and is held for three minutes or more within the range of 900 to 960°C.

[0093] Preferably, the heating rate from 400 to 800°C when heating the intermediate steel material is set to 0.35°C/sec or more. In the case of an intermediate steel material having the chemical composition described above, if the heating rate from 400 to 800°C is too slow, in some cases flaws or cracks may occur in the intermediate steel material due to precipitates temporarily formed when the temperature is increasing. Therefore, in the present embodiment, preferably the heating rate from 400 to 800°C when heating the intermediate steel material is set to 0.35°C/sec or more. Although not particularly limited, the upper limit of the heating rate from 400 to 800°C when heating the intermediate steel material is, for example, 0.60°C/sec. Note that, a method for heating the intermediate steel material is not particularly limited, and a well-known method can be used. For example, the intermediate steel material may be heated using a holding furnace or a high-frequency heating furnace.

[0094] In the present embodiment, preferably the intermediate steel material heated at the aforementioned heating rate is held for three minutes or more at a temperature within the range of 900 to 960°C. In the secondary austenite precipitation treatment process, if the temperature at which the intermediate steel material is held (holding temperature) is too high, secondary austenite will not precipitate sufficiently. In such case, a sufficient volume ratio of secondary austenite will not be obtained in the produced duplex stainless steel material. As a result, sufficient low-temperature toughness will not be obtained in the produced duplex stainless steel material. On the other hand, if the holding temperature is too low, too large an amount of secondary austenite will precipitate. In such case, the volume ratio of primary austenite in the produced duplex stainless steel material will decrease. As a result, in some cases the yield strength of the steel material will be less than 552 MPa.

[0095] Therefore, in the secondary austenite precipitation treatment process according to the present embodiment, preferably the holding temperature is set within the range of 900 to 960°C. A more preferable lower limit of the holding temperature is 905°C, and further preferably is 910°C. A more preferable upper limit of the holding temperature is 955°C, and further preferably is 950°C.

[0096] In the secondary austenite precipitation treatment process, if the time (holding time) for which the intermediate steel material is held within the range of 900 to 960°C is too short, secondary austenite will not precipitate sufficiently. In such case, a sufficient volume ratio of secondary austenite will not be obtained in the produced duplex stainless steel material. As a result, sufficient low-temperature toughness will not be obtained in the produced duplex stainless steel material. Therefore, in the secondary austenite precipitation treatment process according to the present embodiment, preferably the holding time is set to three minutes or more. A more preferable lower limit of the holding time is four minutes, and further preferably is five minutes.

[0097] Note that, the upper limit of the holding time is not particularly limited. However, even if the holding time is very long, the effect thereof will be saturated. Therefore, in the secondary austenite precipitation treatment process according to the present embodiment, the upper limit of the holding time is preferably set to 20 minutes. A more preferable upper limit of the holding time is 19 minutes, and further preferably is 18 minutes.

[Solution treatment process]

[0098] In the solution treatment process, a solution treatment is performed on the intermediate steel material subjected to the aforementioned secondary austenite precipitation treatment process. A method for performing the solution treatment is not particularly limited, and it suffices to perform a well-known method. For example, the intermediate steel material is loaded into a heat treatment furnace, and after being held at a desired temperature, is rapidly cooled. Note that, in the case of performing a solution treatment by loading a hollow shell into a heat treatment furnace, holding the hollow shell at a desired temperature, and thereafter performing rapidly cooling, the term "solution treatment temperature" means the temperature (°C) of the heat treatment furnace for performing the solution treatment. In this case, in addition, the term "solution treatment time" means the time for which the intermediate steel material is held at the solution treatment temperature.

[0099] Preferably, the solution treatment temperature in the solution treatment process of the present embodiment is set within the range of 980 to 1110°C. If the solution treatment temperature is too low, precipitates (for example, σ phase that is an intermetallic compound or the like) may remain in the intermediate steel material after the solution treatment. In such case, the corrosion resistance of the produced duplex stainless steel material will decrease. Furthermore, if the solution treatment temperature is too low, too much secondary austenite will precipitate. In such case, in the produced duplex stainless steel material, in some cases the yield strength of the steel material may be less than 552 MPa. On the other hand, if the solution treatment temperature is too high, in some cases the precipitated secondary austenite will dissolve and the volume ratio of secondary austenite in the produced duplex stainless steel material will decrease. In such case, the low-temperature toughness of the steel material will decrease.

[0100] When performing a solution treatment by loading an intermediate steel material into a heat treatment furnace, holding the intermediate steel material at a desired temperature, and thereafter performing rapid cooling, the solution treatment time is not particularly limited, and it suffices that the solution treatment time is in accordance with a well-known condition. The solution treatment time is, for example, 5 to 180 minutes. The rapid cooling method is, for example, water cooling.

[Other processes]

[0101] Note that, as necessary, the duplex stainless steel material on which the solution treatment was performed may be subjected to a pickling treatment. In this case, the pickling treatment is not particularly limited and it suffices that the pickling treatment is performed by a well-known method. Further, the duplex stainless steel material on which the solution treatment was performed may be subjected to cold rolling. Even in a case where cold rolling is performed, as long as the aforementioned requirement regarding the volume ratio of ferrite, the volume ratio of primary austenite, and the volume ratio of secondary austenite is satisfied, a yield strength of 80 ksi (552 MPa) or more and excellent low-temperature toughness can both be achieved.

[0102] The duplex stainless steel material according to the present embodiment can be produced by performing the processes described above. Note that the method for producing the duplex stainless steel material described above is one example, and the duplex stainless steel material may also be produced by the other methods. Hereunder, the present invention is described in more detail by way of examples.

EXAMPLES

[0103] Molten steels having the chemical compositions shown in Table 1A and Table 1B were melted using a 50 kg vacuum furnace, and ingots were produced by an ingot-making process. Note that, the symbol "-" in Table 1B means that the content of the corresponding element was at an impurity level. For example, it means that the content of Nb, the content of Ta, the content of Ti, the content of Zr, the content of Hf, the content of W, the content of Co, the content of Sn, the content of Sb, the content of Ca, the content of Mg, the content of B, and the content of REM of Test No. 1 were each 0% when rounded off to third decimal places.

[Table 1A]

[0104]

TABLE 1A

Steel Type	Chemical Composition (unit is mass%; balance is Fe and impurities)											
	C	Si	Mn	P	S	Al	Ni	Cr	Mo	Cu	N	V
A	0.006	0.46	5.70	0.003	0.0033	0.058	4.80	23.40	1.40	2.20	0.190	0.96
B	0.022	0.50	1.70	0.018	0.0122	0.052	6.80	24.80	1.00	2.00	0.220	0.96
C	0.015	0.40	2.10	0.027	0.0001	0.046	5.10	24.60	1.30	2.50	0.190	0.78
D	0.021	0.35	5.70	0.030	0.0002	0.041	6.00	22.10	0.70	1.30	0.240	0.13
E	0.023	0.58	5.80	0.004	0.0116	0.064	7.10	26.20	1.10	2.00	0.180	0.83
F	0.006	0.45	4.90	0.010	0.0155	0.016	7.50	29.00	1.20	1.40	0.300	0.19
G	0.024	0.40	5.90	0.005	0.0133	0.090	6.20	25.30	1.00	2.10	0.170	0.14
H	0.010	0.52	3.00	0.028	0.0078	0.062	6.40	26.10	1.00	1.10	0.290	0.56
I	0.024	0.38	3.80	0.004	0.0005	0.051	4.30	27.70	1.30	1.10	0.200	0.46
J	0.023	0.42	5.80	0.025	0.0048	0.038	6.90	22.30	0.70	1.80	0.210	0.92
K	0.021	0.38	5.00	0.011	0.0033	0.074	7.50	26.40	1.00	1.50	0.240	0.85
L	0.017	0.34	6.00	0.029	0.0030	0.031	7.30	27.50	1.00	2.20	0.250	0.62
M	0.013	0.32	2.50	0.005	0.0088	0.021	5.50	26.20	1.20	1.90	0.240	0.32
N	0.019	0.37	3.80	0.017	0.0090	0.080	6.70	28.00	1.40	1.90	0.220	0.70
O	0.008	0.45	4.30	0.016	0.0059	0.068	6.50	26.70	1.10	1.80	0.230	0.29
P	0.012	0.38	2.30	0.013	0.0061	0.025	7.20	26.40	0.70	2.10	0.220	0.24
Q	0.025	0.41	2.50	0.018	0.0137	0.067	4.70	26.40	0.90	2.10	0.220	0.79
R	0.020	0.44	4.60	0.020	0.0117	0.030	6.90	27.30	0.80	1.50	0.250	0.62
S	0.022	0.52	1.30	0.018	0.0019	0.040	5.90	26.00	1.00	2.60	0.340	0.50
T	0.020	0.59	3.00	0.008	0.0122	0.029	4.90	26.60	0.70	2.20	0.320	0.79
U	0.005	0.51	0.70	0.008	0.0148	0.018	5.50	27.70	0.90	1.60	0.160	0.94
V	0.018	0.88	6.60	0.024	0.0055	0.074	8.80	29.50	1.90	0.60	0.155	1.35
W	0.015	0.55	0.75	0.025	0.0012	0.033	6.00	21.30	1.80	2.80	0.220	0.05
X	0.023	0.37	4.80	0.024	0.0010	0.013	4.50	27.70	1.50	2.60	0.380	0.47
Y	0.021	0.41	1.90	0.029	0.0144	0.073	4.60	25.30	1.20	2.60	0.120	0.80
Z	0.008	0.31	1.40	0.019	0.0152	0.060	2.30	25.50	1.40	1.50	0.290	0.91

[Table 1B]

[0105]

TABLE 1B

Steel Type	Chemical Composition (unit is mass%; balance is Fe and impurities)												
	Nb	Ta	Ti	Zr	Hf	W	Co	Sn	Sb	Ca	Mg	B	REM
A	-	-	-	-	-	-	-	-	-	-	-	-	-
B	0.015	-	-	-	-	-	-	-	-	-	-	-	-
C	-	0.034	-	-	-	-	-	-	-	-	-	-	-
D	-	-	0.053	-	-	-	-	-	-	-	-	-	-
E	-	-	-	0.067	-	-	-	-	-	-	-	-	-
F	-	-	-	-	0.060	-	-	-	-	-	-	-	-
G	-	-	-	-	-	0.050	-	-	-	-	-	-	-
H	-	-	-	-	-	-	0.078	-	-	-	-	-	-
I	-	-	-	-	-	-	-	0.042	-	-	-	-	-
J	-	-	-	-	-	-	-	-	0.050	-	-	-	-
K	-	-	-	-	-	-	-	-	-	0.010	-	-	-
L	-	-	-	-	-	-	-	-	-	-	0.010		
M	-	-	-	-	-	-	-	-	-	-	-	0.014	
N	-	-	-	-	-	-	-	-	-	-	-	-	0.028
O	0.035	0.014	-	-	-	-	0.193	-	-	-	-	-	-
P	-	-	0.013	-	-	-	-	-	-	0.007	-	-	-
Q	-	-	-	-	-	-	-	0.022	-	-	0.009	-	-
R	-	-	-	0.029	-	-	-	-	0.057	-	-	0.008	0.094
S	-	-	-	-	-	-	-	-	-	-	-	-	-
T	-	-	-	-	-	-	-	-	-	-	-	-	-
U	-	-	-	-	-	-	-	-	-	-	-	-	-
V	0.071	-	-	-	-	0.180	0.450	-	-	-	-	-	-
W	-	-	0.070	-	-	-	-	-	-	-	-	-	0.150
X	-	-	-	-	-	-	-	-	-	-	-	-	-
Y	-	-	-	-	-	-	-	-	-	-	-	-	-
Z	-	-	-	-	-	-	-	-	-	-	-	-	-

[0106] The ingot of each steel type was heated to the heating temperature (°C) for hot working described in Table 2, and thereafter subjected to hot rolling to produce a hollow shell (seamless steel pipe) having an outer diameter of 177.8 mm and a wall thickness of 12.65 mm. The hollow shell of each test number on which the hot working had been performed was subjected to a secondary austenite precipitation treatment in which the hollow shell was heated at a heating rate (°C/sec) from 400 to 800°C described in Table 2, and held for only a holding time (mins) at a holding temperature (°C) which are described in Table 2. In addition, a solution treatment was performed at a solution treatment temperature (°C) for a solution treatment time (mins) which are described in Table 2.

[Table 2]

[0107]

TABLE 2

Test Number	Steel Type	Hot Working	Secondary Austenite Precipitation Treatment			Solution Treatment	
		Heating Temperature (°C)	Heating Rate from 400 to 800°C (°C/sec)	Holding Temperature (°C)	Holding Time (mins)	Solution Treatment Temperature (°C)	Solution Treatment Time (mins)
1	A	1270	0.43	930	17	985	23
2	B	1250	0.52	940	10	1020	28
3	C	1270	0.42	960	5	1075	36
4	D	1290	0.43	950	4	1085	71
5	E	1300	0.49	940	6	1080	51
6	F	1290	0.35	950	3	1025	89
7	G	1270	0.55	950	15	1065	29
8	H	1300	0.54	960	5	1095	21
9	I	1260	0.47	920	9	1020	57
10	J	1280	0.53	900	3	1015	51
11	K	1260	0.46	940	17	985	63
12	L	1270	0.47	930	13	1070	49
13	M	1290	0.48	940	20	1105	67
14	N	1300	0.54	930	6	1035	54
15	O	1290	0.54	905	8	1040	45
16	P	1290	0.50	900	10	1015	61
17	Q	1300	0.39	915	12	1035	76
18	R	1300	0.49	910	3	1030	88
19	S	1260	0.43	960	3	1030	35
20	T	1260	0.49	960	5	1040	40
21	U	1260	0.40	900	20	1055	33
22	V	1270	0.41	950	5	1070	20
23	W	1270	0.42	950	5	1070	20
24	A	1250	0.48	955	1	1075	47
25	O	1290	0.53	905	1	1040	40
26	A	1290	0.36	850	3	1000	66
27	O	1290	0.37	850	5	1030	35
28	R	1290	0.52	1000	8	1070	33
29	S	1270	0.38	1000	5	1030	35
30	F	1250	0.46	-	-	1000	30
31	S	1270	0.55	-	-	1030	35
32	G	1270	0.44	920	3	940	22
33	S	1270	0.35	920	10	930	20
34	Q	1270	0.15	915	12	1035	35
35	T	1260	0.13	960	5	1040	30

(continued)

Test Number	Steel Type	Hot Working	Secondary Austenite Precipitation Treatment			Solution Treatment	
		Heating Temperature (°C)	Heating Rate from 400 to 800°C (°C/sec)	Holding Temperature (°C)	Holding Time (mins)	Solution Treatment Temperature (°C)	Solution Treatment Time (mins)
36	X	1270	0.40	960	5	1075	40
37	Y	1250	0.48	910	15	1020	25
38	Z	1270	0.36	930	15	1080	27

[0108] A seamless steel pipe of each test number was obtained by the above process. The obtained seamless steel pipe of each test number was subjected to a tensile test, a microstructure observation test, and a Charpy impact test. Note that, cracking was confirmed in the obtained seamless steel pipes of Test Nos. 34 and 35. Therefore, these seamless steel pipes were not subjected to evaluation tests.

[Tensile test]

[0109] The seamless steel pipe of each test number excluding Test Nos. 34 and 35 was subjected to a tensile test in accordance with ASTM E8/E8M (2021). Specifically, an arc-shaped test specimen for a tensile test was prepared from a central portion of the wall thickness of the seamless steel pipe of each test number. The thickness of the arc-shaped test specimen was made the same as the wall thickness of the steel pipe, the width was made 25.4 mm, and the gage length was made 50.8 mm. The arc-shaped test specimen of each test number was used to carry out a tensile test at normal temperature (25°C) in air, and the 0.2% offset proof stress (MPa) was determined. The determined 0.2% offset proof stress was defined as the yield strength (MPa). The obtained yield strength of each test number is shown in the column "YS (MPa)" in Table 3.

[Table 3]

[0110]

TABLE 3

Test Number	YS (MPa)	Microstructure			Low-temperature Toughness
		Ferrite Volume Ratio (%)	Primary Austenite Volume Ratio (%)	Secondary Austenite Volume Ratio (%)	Lowest Temperature (°C)
1	655	39	42	19	-30
2	572	45	46	9	-50
3	614	51	41	8	-30
4	627	36	48	16	-70
5	669	38	52	10	-50
6	703	40	50	10	-20
7	614	43	50	7	-20
8	683	46	46	8	-40
9	634	47	46	7	-20
10	717	36	50	14	-40
11	600	40	52	8	-40
12	696	42	52	6	-30
13	676	46	44	10	-40

(continued)

Test Number	YS (MPa)	Microstructure			Low-temperature Toughness
		Ferrite Volume Ratio (%)	Primary Austenite Volume Ratio (%)	Secondary Austenite Volume Ratio (%)	Lowest Temperature (°C)
14	621	39	48	13	-70
15	558	37	46	17	-40
16	676	36	48	16	-60
17	565	44	44	12	-60
18	600	36	50	14	-40
19	689	53	42	5	-20
20	676	43	51	6	-20
21	552	37	43	20	-50
22	593	50	43	7	-40
23	599	48	44	8	-40
24	607	47	50	3	-10
25	567	47	51	2	-10
26	517	36	42	22	-50
27	523	36	41	23	-50
28	641	54	45	1	0
29	566	56	42	2	-10
30	710	44	55	1	0
31	572	55	44	1	0
32	503	38	23	39	-20
33	520	40	22	38	-30
34	-	-	-	-	-
35	-	-	-	-	-
36	621	46	50	4	-10
37	510	45	27	28	-50
38	707	69	28	3	10

[Microstructure observation test]

[0111] The seamless steel pipe of each test number excluding Test Nos. 34 and 35 was subjected to microstructure observation, and the volume ratios of ferrite, primary austenite, and secondary austenite were determined. Specifically, a test specimen for microstructure observation having an observation surface with dimensions of 5 mm in the pipe radial direction × 5 mm in the pipe circumferential direction was prepared from a central portion of the wall thickness of the seamless steel pipe of each test number. The observation surface of the test specimen of each test number was polished to obtain a mirror surface, and then electrolytically etched in a 7% potassium hydroxide etching solution. The observation surface on which the microstructure had been revealed by the electrolytic etching was observed in 10 visual fields using an optical microscope. The area of each visual field was 40000 μm^2 (200 μm × 200 μm).

[0112] In each visual field of each test number, phases other than ferrite and austenite in the microstructure were negligibly small. That is, the seamless steel pipe of each test number had a microstructure composed of ferrite, primary austenite, and secondary austenite. In each visual field of each test number, ferrite and austenite were each identified based on contrast. In addition, austenite with a minor axis of 20 μm or more (primary austenite) was identified by the method described above. The area fractions (%) of the identified ferrite and primary austenite were determined by image analysis. In addition, based on the area fractions (%) of ferrite and primary austenite, the area fraction (%) of secondary austenite was determined by Formula (A) which is described above. The arithmetic average value of the area fractions of ferrite in the 10 visual fields was defined as the ferrite volume ratio (%). The arithmetic average value of the area fractions of primary austenite in the 10 visual fields was defined as the primary austenite volume ratio (%). The arithmetic average value of the area fractions of secondary austenite in the 10 visual fields was defined as the secondary austenite volume ratio (%). The determined ferrite volume ratio (%), primary austenite volume ratio (%), and secondary austenite volume ratio (%) of each test number are shown in Table 3.

[Charpy impact test]

[0113] The seamless steel pipe of each test number excluding Test Nos. 34 and 35 was subjected to a Charpy impact test in accordance with ASTM E23 (2018), and the low-temperature toughness was evaluated. First, a V-notch test specimen for the Charpy impact test was prepared from the seamless steel pipe of each test number in accordance with ASTM E23 (2018). Specifically, a V-notch test specimen having a notched surface parallel to the wall thickness direction and the pipe axis direction was prepared from a central portion of the wall thickness of the seamless steel pipe of each test number. Note that, the longitudinal direction of the V-notch test specimen was parallel to the rolling direction of the steel material. Further, the V-notch test specimen was a full-size V-notch test specimen (having a width of 10 mm, a thickness of 10 mm, and a length of 55 mm), and the V-notch depth was made 2 mm. Here, the term "width" of the V-notch test specimen means the distance between the surface in which the V-notch was formed and the surface on the opposite side thereto in the V-notch test specimen.

[0114] For each test number, three of the prepared V-notch test specimens were cooled under each of the eight conditions, i.e. a temperature of 0°C, -10°C, -20°C, - 30°C, -40°C, -50°C, -60°C, and -70°C, respectively. Each of the cooled test specimens was subjected to the Charpy impact test in accordance with ASTM E23 (2018), and the absorbed energy (J) was determined. Note that, the arithmetic average value for the three test specimens at each temperature was defined as the absorbed energy (J). The determined absorbed energy (J) was divided by the cross-sectional area (cm^2) of the V-notch test specimen to determine the absorbed energy per unit area (J/cm^2) at each temperature. Note that, the cross-sectional area of the V-notch test specimen (cm^2) was taken as 0.8 cm^2 (width of 0.8 cm $\times$ thickness of 1.0 cm) as defined by the aforementioned method.

[0115] Among the determined absorbed energies per unit area at the respective temperatures, the lowest temperature (°C) at which the absorbed energy per unit area is 30 J/cm^2 or more was determined. The determined lowest temperature of each test number is shown in Table 3.

[Evaluation results]

[0116] Referring to Table 1A to Table 3, in the seamless steel pipes of Test Nos. 1 to 23, the chemical composition was appropriate. In addition, the production method was also the preferable production method described in the present description. As a result, the yield strength was 552 MPa or more. Further, the volume ratio of ferrite was 35 to 55%, the volume ratio of primary austenite was 40 to 55%, and the volume ratio of secondary austenite was 5 to 20%. As a result, the lowest temperature at which the absorbed energy per unit area was 30 J/cm^2 or more was - 20°C or less. That is, the seamless steel pipes of Test Nos. 1 to 23 had a yield strength of 80 ksi or more and excellent low-temperature toughness.

[0117] On the other hand, for the seamless steel pipes of Test Nos. 24 and 25, the holding time in the secondary austenite precipitation treatment process was too short. As a result, the volume ratio of secondary austenite was less than 5%. Consequently, the lowest temperature at which the absorbed energy per unit area was 30 J/cm^2 or more was more than -20°C. That is, these seamless steel pipes did not have excellent low-temperature toughness.

[0118] For the seamless steel pipes of Test Nos. 26 and 27, the holding temperature in the secondary austenite precipitation treatment process was too low. As a result, the volume ratio of secondary austenite was more than 20%. Consequently, the yield strength was less than 552 MPa. That is, these seamless steel pipes did not have a yield strength of 80 ksi or more.

[0119] For the seamless steel pipes of Test Nos. 28 and 29, the holding temperature in the secondary austenite precipitation treatment process was too high. As a result, the volume ratio of secondary austenite was less than 5%. Consequently, the lowest temperature at which the absorbed energy per unit area was 30 J/cm^2 or more was more than -20°C. That is, these seamless steel pipes did not have excellent low-temperature toughness.

[0120] The seamless steel pipes of Test Nos. 30 and 31 were not subjected to the secondary austenite precipitation treatment process. As a result, the volume ratio of secondary austenite was less than 5%. Consequently, the lowest temperature at which the absorbed energy per unit area was 30 J/cm^2 or more was more than -20°C. That is, these seamless steel pipes did not have excellent low-temperature toughness.

[0121] For the seamless steel pipes of Test No. 32 and 33, the solution treatment temperature in the solution treatment process was too low. As a result, the volume ratio of primary austenite was less than 40%, and in addition, the volume ratio of secondary austenite was more than 20%. Consequently, the yield strength was less than 552 MPa. That is, these seamless steel pipes did not have a yield strength of 80 ksi or more.

[0122] For the seamless steel pipes of Test Nos. 34 and 35, in the secondary austenite precipitation treatment process, the heating rate from 400 to 800°C was too slow. As a result, cracking was confirmed in these seamless steel pipes. Therefore, the yield strength and the low-temperature toughness of these seamless steel pipes were not evaluated.

[0123] In the seamless steel pipe of Test No. 36, the content of N was too high. As a result, the volume ratio of secondary austenite was less than 5%. Consequently, the lowest temperature at which the absorbed energy per unit area was 30 J/cm^2 or more was more than -20°C. That is, this seamless steel pipe did not have excellent low-temperature toughness.

[0124] In the seamless steel pipe of Test No. 37, the content of N was too low. As a result, the volume ratio of primary austenite was less than 40%, and in addition, the volume ratio of secondary austenite was more than 20%. Consequently, the yield strength was less than 552 MPa. That is, this seamless steel pipe did not have a yield strength of 80 ksi or more.

[0125] In the seamless steel pipe of Test No. 38, the content of Ni was too low. As a result, the volume ratio of ferrite was more than 55%, the volume ratio of primary austenite was less than 40%, and furthermore, the volume ratio of secondary austenite was less than 5%. Consequently, the lowest temperature at which the absorbed energy per unit area was 30 J/cm^2 or more was more than -20°C. That is, this seamless steel pipe did not have excellent low-temperature toughness.

[0126] An embodiment of the present disclosure has been described above. However, the embodiment described above is merely an example for carrying out the present disclosure. Therefore, the present disclosure is not limited to the above-described embodiment, and can be implemented by appropriately modifying the above-described embodiment within a range that does not depart from the gist of the present disclosure.

REFERENCE SIGNS LIST

[0127]

10 Observation Visual Field Region
20 Ferrite
30 Austenite
31 Primary Austenite
32 Secondary Austenite

Claims

1. A duplex stainless steel material consisting of, by mass%,

C: 0.030% or less,
Si: 0.20 to 1.00%,
Mn: 0.50 to 7.00%,
P: 0.040% or less,
S: 0.0200% or less,
Al: 0.100% or less,
Ni: 4.20 to 9.00%,
Cr: 20.00 to 30.00%,
Mo: 0.50 to 2.00%,
Cu: 0.50 to 3.00%,
N: 0.150 to 0.350%,
V: 0.01 to 1.50%,
Nb: 0 to 0.100%,
Ta: 0 to 0.100%,
Ti: 0 to 0.100%,
Zr: 0 to 0.100%,
Hf: 0 to 0.100%,
W: 0 to 0.200%,
Co: 0 to 0.500%,
Sn: 0 to 0.100%,
Sb: 0 to 0.100%,
Ca: 0 to 0.020%,
Mg: 0 to 0.020%,
B: 0 to 0.020%, and

rare earth metal: 0 to 0.200%,
with the balance being Fe and impurities,
wherein:

a yield strength is 552 MPa or more; and
when, in a microstructure, an austenite grain with a minor axis of 20 μm or more is defined as primary austenite, and the balance of austenite is defined as secondary austenite,
the microstructure is composed of, in volume ratio, ferrite in an amount of 35 to 55%, the primary austenite in an amount of 40 to 55%, and the secondary austenite in an amount of 5 to 20%.

2. The duplex stainless steel material according to claim 1, containing one or more elements selected from a group consisting of:

Nb: 0.001 to 0.100%,
Ta: 0.001 to 0.100%,
Ti: 0.001 to 0.100%,
Zr: 0.001 to 0.100%,
Hf: 0.001 to 0.100%,
W: 0.001 to 0.200%,
Co: 0.001 to 0.500%,
Sn: 0.001 to 0.100%,
Sb: 0.001 to 0.100%,
Ca: 0.001 to 0.020%,
Mg: 0.001 to 0.020%,
B: 0.001 to 0.020%, and
rare earth metal: 0.001 to 0.200%.

FIG. 1

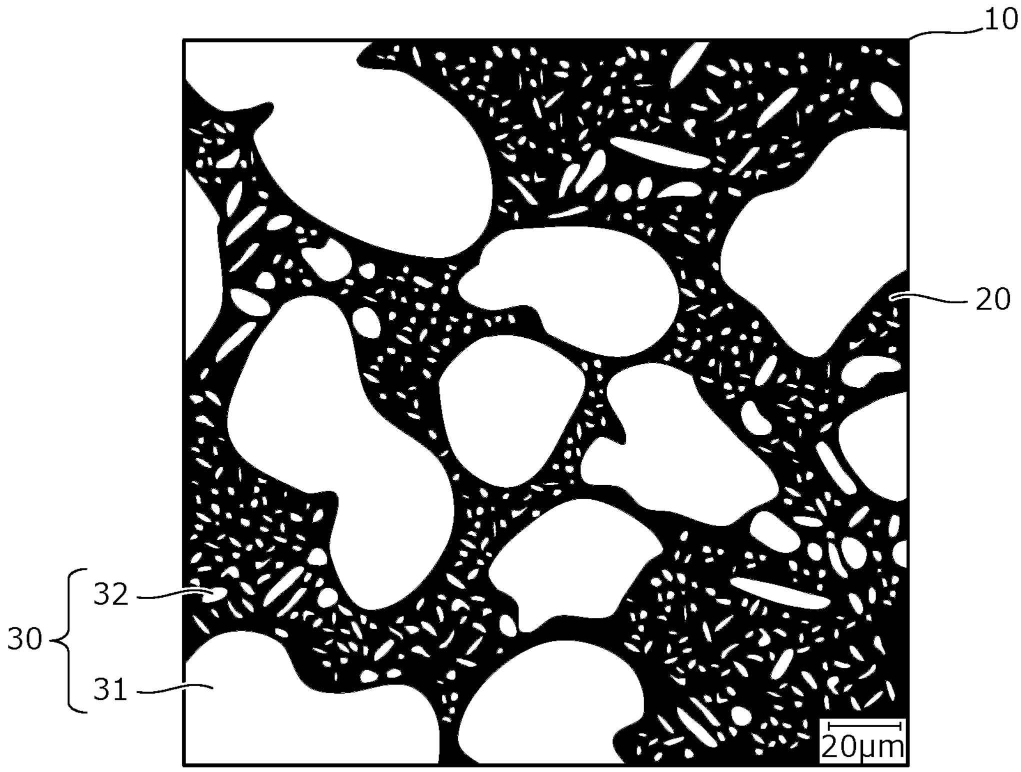
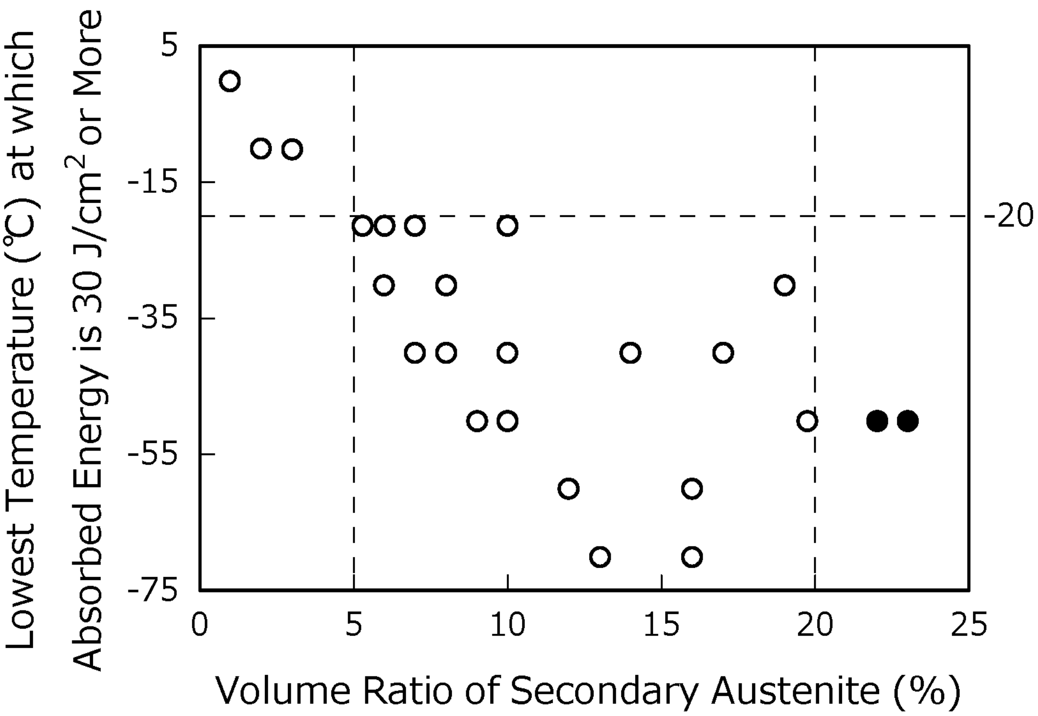

10
20
32
30
31
20μm

FIG. 2


Lowest Temperature (℃) at which Absorbed Energy is 30 J/cm2 or More
5
-15
-35
-55
-75
-20
0
5
10
15
20
25
Volume Ratio of Secondary Austenite (%)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2023/005219

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; ***C22C 38/60***(2006.01)i; *C21D 6/00*(2006.01)n; *C21D 8/10*(2006.01)n
FI: C22C38/00 302H; C22C38/60; C21D6/00 102L; C21D8/10 D

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; C21D6/00; C21D8/10; C21D9/08

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 1971-2023
Registered utility model specifications of Japan 1996-2023
Published registered utility model applications of Japan 1994-2023

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	WO 2021/033672 A1 (NIPPON STEEL CORP.) 25 February 2021 (2021-02-25) claims, paragraphs [0087]-[0092], tables 1, 2	1-2
A	JP 2021-167445 A (NIPPON STEEL CORP.) 21 October 2021 (2021-10-21) claims, paragraphs [0100]-[0106], tables 1-3	1-2
A	WO 2018/043214 A1 (JFE STEEL CORP.) 08 March 2018 (2018-03-08) claims, paragraphs [0051]-[0060], tables 1, 2	1-2
A	CN 102463270 A (SUZHOU BEST METAL PRODUCTS CO., LTD.) 23 May 2012 (2012-05-23) claims	1-2

☐ 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
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"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	Date of mailing of the international search report
20 April 2023	**09 May 2023**

Name and mailing address of the ISA/JP	Authorized officer
Japan Patent Office (ISA/JP) **3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915** **Japan**	Telephone No.

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

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/005219

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
WO 2021/033672 A1	25 February 2021	EP 4019651 A1 claims, paragraphs [0088]-[0093], tables 1, 2 US 2022/0145438 A1	
JP 2021-167445 A	21 October 2021	(Family: none)	
WO 2018/043214 A1	08 March 2018	EP 3508596 A1 claims, paragraphs [0051]-[0060], tables 1, 2 US 2019/0211416 A1 CN 109642282 A	
CN 102463270 A	23 May 2012	(Family: none)	

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

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 10060597 A **[0005] [0009]**
- WO 2012111536 A **[0005] [0009]**
- JP 2016003377 A **[0005] [0009]**