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

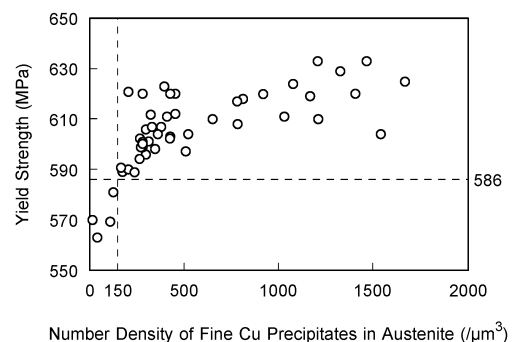
(72) Inventors:
• **OKADA, Seiya**
Tokyo 100-8071 (JP)
• **TOMIO, Yusaku**
Tokyo 100-8071 (JP)
• **ARAI, Yuji**
Tokyo 100-8071 (JP)

(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 a yield strength of 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance 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: 0.020% 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: 1.50 to 4.00%, N: 0.150 to 0.350%, and V: 0.01 to 1.50%, with the balance being Fe and impurities, and satisfies Formula (1) described in the description. A microstructure consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. The yield strength is 586 MPa or more. A number density of Cu precipitates having a major axis of 50 nm or less in the austenite is 150 to 1500 / μm^3 .

FIG. 1



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Description

TECHNICAL FIELD

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

BACKGROUND ART

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

[0003] A method in which the content of chromium (Cr) is increased to form a passive film mainly composed of Cr oxides on the surface of the steel material is already known as a method for improving the corrosion resistance of a steel material. Therefore, a duplex stainless steel material in which the content of Cr is made high may in some cases be used in an environment where excellent corrosion resistance is required. On the other hand, a duplex stainless steel material having a duplex microstructure consisting of a ferrite phase and an austenite phase is excellent in corrosion resistance with respect to pitting and/or crevice corrosion (hereinafter, referred to as "pitting resistance"), the corrosion being problematic in an aqueous solution containing chlorides.

[0004] In recent years, furthermore, deep wells below sea level are being actively developed. Therefore, there is a need to enhance the strength of duplex stainless steel materials. That is, there is a growing demand for a duplex stainless steel material with which both a high strength and excellent pitting resistance are obtained.

[0005] Japanese Patent Application Publication No. 5-132741 (Patent Literature 1), Japanese Patent Application Publication No. 9-195003 (Patent Literature 2), Japanese Patent Application Publication No. 2014-043616 (Patent Literature 3), and Japanese Patent Application Publication No. 2016-003377 (Patent Literature 4) each propose a duplex stainless steel that has a high strength and excellent corrosion resistance.

[0006] The duplex stainless steel disclosed in Patent Literature 1 has a chemical composition consisting of, in weight%, C: 0.03% or less, Si: 1.0% or less, Mn: 1.5% or less, P: 0.040% or less, S: 0.008% or less, sol. Al: 0.040% or less, Ni: 5.0 to 9.0%, Cr: 23.0 to 27.0%, Mo: 2.0 to 4.0%, W: more than 1.5 to 5.0%, and N: 0.24 to 0.32%, with the balance being Fe and unavoidable impurities, in which $PREW (= Cr + 3.3(Mo + 0.5W) + 16N)$ is 40 or more. Patent Literature 1 discloses that this duplex stainless steel exhibits excellent corrosion resistance and a high strength.

[0007] The duplex stainless steel disclosed in Patent Literature 2 consists of, in weight%, C: 0.12% or less, Si: 1% or less, Mn: 2% or less, Ni: 3 to 12%, Cr: 20 to 35%, Mo: 0.5 to 10%, W: more than 3 to 8%, Co: 0.01 to 2%, Cu: 0.1 to 5%, and N: 0.05 to 0.5%, with the balance being Fe and unavoidable impurities. Patent Literature 2 discloses that this duplex stainless steel has further excellent corrosion resistance, without lowering the strength.

[0008] The duplex stainless steel disclosed in Patent Literature 3 has a chemical composition consisting of, by mass%, C: 0.03% or less, Si: 0.3% or less, Mn: 3.0% or less, P: 0.040% or less, S: 0.008% or less, Cu: 0.2 to 2.0%, Ni: 5.0 to 6.5%, Cr: 23.0 to 27.0%, Mo: 2.5 to 3.5%, W: 1.5 to 4.0%, N: 0.24 to 0.40%, and Al: 0.03% or less, with the balance being Fe and impurities, in which a σ phase susceptibility index $X (= 2.2Si + 0.5Cu + 2.0Ni + Cr + 4.2Mo + 0.2W)$ is 52.0 or less, a strength index $Y (= Cr + 1.5Mo + 10N + 3.5W)$ is 40.5 or more, and a pitting resistance equivalent $PREW (= Cr + 3.3(Mo + 0.5W) + 16N)$ is 40 or more. In a microstructure of the steel, in a cross section in a thickness direction which is parallel to a rolling direction, when a straight line is drawn to be parallel to the thickness direction from an outer layer to a depth of 1 mm, the number of boundaries between a ferrite phase and an austenite phase which intersect with the straight line is 160 or more. Patent Literature 3 discloses that the strength of this duplex stainless steel can be enhanced without loss of corrosion resistance, and that by combining the use of cold working with a high reduction rate, this duplex stainless steel exhibits excellent hydrogen embrittlement resistance characteristics.

[0009] The duplex stainless steel disclosed in Patent Literature 4 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, sol. 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 metal microstructure consisting of a duplex microstructure of a ferrite phase and an austenite phase in which there is no precipitation of a sigma phase, and in which a proportion occupied by the ferrite phase in the metal microstructure is 50% or less in area fraction, and the number of oxides having a particle size of 30 μm or more that exist in a visual field of 300 mm^2 is 15 or less. Patent Literature 4 discloses that this duplex stainless steel is excellent in a strength, pitting resistance, and low-temperature toughness.

CITATION LIST

PATENT LITERATURE

5 [0010]

Patent Literature 1: Japanese Patent Application Publication No. 5-132741
 Patent Literature 2: Japanese Patent Application Publication No. 9-195003
 Patent Literature 3: Japanese Patent Application Publication No. 2014-043616
 Patent Literature 4: Japanese Patent Application Publication No. 2016-003377

SUMMARY OF INVENTION

TECHNICAL PROBLEM

15 [0011] As mentioned above, deep wells below sea level are also being actively developed in recent years. In a deep well below sea level, the water temperature is low. That is, the duplex stainless steel material is also required to have excellent low-temperature toughness in addition to a high strength and excellent pitting resistance when it is to be used for a deep well below sea level. Therefore, a duplex stainless steel material having a yield strength of 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance may be obtained by a technique other than the techniques disclosed in the aforementioned Patent Literatures 1 to 4.

20 [0012] An objective of the present disclosure is to provide a duplex stainless steel material that has a yield strength of 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance.

SOLUTION TO PROBLEM

25 [0013] A duplex stainless steel material according to the present disclosure consists of, by mass%,

30 C: 0.030% or less,
 Si: 0.20 to 1.00%,
 Mn: 0.50 to 7.00%,
 P: 0.040% or less,
 S: 0.020% or less,
 Al: 0.100% or less,
 35 Ni: 4.20 to 9.00%,
 Cr: 20.00 to 30.00%,
 Mo: 0.50 to 2.00%,
 Cu: 1.50 to 4.00%,
 N: 0.150 to 0.350%,
 40 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%,
 45 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%,
 50 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,
 55 and satisfies Formula (1),
 wherein:

a microstructure consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite,

a yield strength is 586 MPa or more, and
in the austenite, a number density of Cu precipitates having a major axis of 50 nm or less is 150 to 1500 / μm^3 ;

$$\text{Cr} + 3.3(\text{Mo} + 0.5\text{W}) + 16\text{N} \geq 30.0 \quad (1)$$

where, a content in percent by mass of a corresponding element is substituted for each symbol of an element in Formula (1), and if a corresponding element is not contained, "0" is substituted for the symbol of the corresponding element.

ADVANTAGEOUS EFFECTS OF INVENTION

[0014] The duplex stainless steel material according to the present disclosure has a high yield strength of 586 MPa or more, and has excellent low-temperature toughness and excellent pitting resistance.

BRIEF DESCRIPTION OF DRAWINGS

[0015]

[FIG. 1] FIG. 1 is a view illustrating a relation between a number density of fine Cu precipitates (/ μm^3) in austenite and a yield strength (MPa) of a steel material in the present Examples.

[FIG. 2] FIG. 2 is a view illustrating a relation between the number density of fine Cu precipitates (/ μm^3) in austenite and absorbed energy (J/cm²) which is an index of low-temperature toughness of the steel material in the present Examples.

DESCRIPTION OF EMBODIMENTS

[0016] First, the present inventors conducted studies with respect to a duplex stainless steel material having a yield strength of 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance, from the viewpoint of the chemical composition. 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: 0.020% 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: 1.50 to 4.00%, 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 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance will be obtained.

[0017] Here, the microstructure of a duplex stainless steel material having the chemical composition described above consists of ferrite and austenite. Specifically, the microstructure of the duplex stainless steel material having the chemical composition described above consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. Note that, in the present description, the phrase "consist of ferrite and austenite" means that an amount of any phase other than ferrite and austenite is negligibly small.

[0018] Next, the present inventors investigated various techniques for increasing the pitting resistance of the duplex stainless steel material that has the chemical composition described above and has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. As a result, the present inventors found that if the chemical composition of the duplex stainless steel material also satisfies the following Formula (1), the pitting resistance of the duplex stainless steel material will be increased:

$$\text{Cr} + 3.3(\text{Mo} + 0.5\text{W}) + 16\text{N} \geq 30.0 \quad (1)$$

where, a content in percent by mass of a corresponding element is substituted for each symbol of an element in Formula (1), and if a corresponding element is not contained, "0" is substituted for the symbol of the corresponding element.

[0019] Let Fn1 be defined as $\text{Fn1} = \text{Cr} + 3.3(\text{Mo} + 0.5\text{W}) + 16\text{N}$. Fn1 is an index relating to the pitting resistance of the steel material. If Fn1 is made high, the pitting resistance of the duplex stainless steel material can be increased. That is, if Fn1 is too low, the pitting resistance of the duplex stainless steel material will decrease. Accordingly, in the duplex stainless steel material according to the present embodiment, the chemical composition described above is satisfied, and Fn1 is made 30.0 or more.

[0020] Next, the present inventors investigated various techniques for increasing the low-temperature toughness and yield strength while maintaining the pitting resistance with respect to the duplex stainless steel material that satisfies the chemical composition described above, and in which Fn1 is made 30.0 or more, and which has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. As a result, the present inventors obtained the following findings.

[0021] First, the present inventors conducted studies regarding a technique for increasing the yield strength that focused on the microstructure of the duplex stainless steel material which satisfies the chemical composition described above and in which Fn1 is 30.0 or more. Specifically, in the microstructure of the duplex stainless steel material having the chemical composition described above, the strength of austenite is liable to be low in comparison to ferrite. Therefore, in the duplex stainless steel material that has the aforementioned chemical composition and microstructure and in which Fn1 is 30.0 or more, there is a possibility that the yield strength of the steel material overall will tend to decrease due to the characteristics of austenite. In other words, if the strength of austenite is selectively increased, there is a possibility that the yield strength of the duplex stainless steel material that has the aforementioned chemical composition and microstructure and in which Fn1 is 30.0 or more can be increased. Therefore, the present inventors investigated techniques for selectively increasing the strength of austenite while maintaining the pitting resistance and the low-temperature toughness.

[0022] In this connection, in a duplex stainless steel material, in some cases intermetallic compounds that are typified by the σ -phase precipitate. In the duplex stainless steel material in which the σ -phase precipitated, excellent pitting resistance cannot be obtained. Hence, when producing a duplex stainless steel material, as described in a preferred production method to be described later, a solution treatment is performed. Therefore, in the conventional duplex stainless steel materials, precipitates are significantly reduced in the steel materials.

[0023] On the other hand, precipitates in a steel material increase the yield strength of the steel material. That is, there is a possibility that by purposely increasing precipitates which conventionally have been reduced, the strength of austenite will be increased and the yield strength of the duplex stainless steel material will be increased. However, as mentioned above, depending on the type of precipitates, in some cases the low-temperature toughness and the pitting resistance of the steel material will be reduced. Therefore, the present inventors considered that if precipitates which do not tend to decrease the low-temperature toughness and pitting resistance can be selectively precipitated in austenite, it may be possible to increase the yield strength and low-temperature toughness while maintaining the pitting resistance of the duplex stainless steel material.

[0024] Specifically, among precipitates, the present inventors focused on copper (Cu). Cu precipitates as a Cu precipitate in a steel material, and increases the yield strength of the steel material. In particular, in austenite, if a large number of fine Cu precipitates having a major axis of 50 nm or less (hereunder, also referred to simply as "fine Cu precipitates") precipitate, there is a possibility that the yield strength will be increased to 586 MPa or more while maintaining the pitting resistance and low-temperature toughness of the steel material.

[0025] Therefore, first, the present inventors conducted detailed investigations and studies regarding a relation between fine Cu precipitates in austenite and the yield strength in the duplex stainless steel material which satisfies the chemical composition described above, in which Fn1 is made 30.0 or more, and which has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. Hereunder, this is described specifically using the drawings.

[0026] FIG. 1 is a view illustrating the relation between the number density of fine Cu precipitates ($/\mu\text{m}^3$) in austenite and the yield strength (MPa) of the steel material in the present Examples. FIG. 1 was created using the number densities of fine Cu precipitates ($/\mu\text{m}^3$) in austenite and the yield strengths (MPa) with respect to, among Examples to be described later, duplex stainless steel materials satisfying the chemical composition described above and in which Fn1 was made 30.0 or more and which had the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. Note that, the number density of fine Cu precipitates and the yield strength were determined by methods that are described later. Further, each of the Examples illustrated in FIG. 1 exhibited excellent pitting resistance.

[0027] Referring to FIG. 1, it was revealed that in the duplex stainless steel material satisfying the chemical composition described above and in which Fn1 is made 30.0 or more and which has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite, if the number density of fine Cu precipitates in austenite is $150 /\mu\text{m}^3$ or more, the yield strength will be 586 MPa or more. On the other hand, in the aforementioned duplex stainless steel material, if the number density of fine Cu precipitates in austenite is less than $150 /\mu\text{m}^3$, the yield strength will be less than 586 MPa. That is, it was revealed that in the aforementioned steel material, when the number density of fine Cu precipitates in austenite is $150 /\mu\text{m}^3$ or more, a yield strength of 586 MPa or more is obtained while maintaining excellent pitting resistance.

[0028] Next, the present inventors conducted detailed investigations and studies regarding the relation between fine Cu precipitates in austenite and the low-temperature toughness in the duplex stainless steel material satisfying the chemical composition described above in which Fn1 is made 30.0 or more and which has the microstructure consisting

of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. This is described specifically hereunder using the drawings.

[0029] FIG. 2 is a view illustrating a relation between the number density of fine Cu precipitates ($/\mu\text{m}^3$) in austenite and absorbed energy (J/cm^2) which is an index of the low-temperature toughness of the steel material in the present Examples. FIG. 2 was created using the number densities of fine Cu precipitates ($/\mu\text{m}^3$) in austenite and the absorbed energy (J/cm^2) with respect to, among Examples to be described later, duplex stainless steel materials that satisfied the chemical composition described above, and in which Fn1 was made 30.0 or more and which had the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. Note that, the number density of fine Cu precipitates and the absorbed energy were determined by methods that are described later.

[0030] Referring to FIG. 2, it was revealed that in the duplex stainless steel material satisfying the chemical composition described above and in which Fn1 is made 30.0 or more and which has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite, when the number density of fine Cu precipitates in austenite is $1500 /\mu\text{m}^3$ or less, the absorbed energy is $60.0 \text{ J}/\text{cm}^2$ or more and excellent low-temperature toughness is exhibited. On the other hand, it can be confirmed that in the aforementioned duplex stainless steel material, when the number density of fine Cu precipitates in austenite is more than $1500 /\mu\text{m}^3$, the absorbed energy is less than $60.0 \text{ J}/\text{cm}^2$ and excellent low-temperature toughness is not exhibited.

[0031] That is, referring to FIG. 1 and FIG. 2, it was revealed that in the duplex stainless steel material that satisfies the chemical composition described above and in which Fn1 is made 30.0 or more and which has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite, if the number density of fine Cu precipitates in austenite is 150 to $1500 /\mu\text{m}^3$, the duplex stainless steel material has a high yield strength of 586 MPa or more and exhibits excellent low-temperature toughness while also maintaining excellent pitting resistance. Accordingly, in the present embodiment, the number density of fine Cu precipitates in austenite is made 150 to $1500 /\mu\text{m}^3$. As a result, the duplex stainless steel material according to the present embodiment has a high yield strength of 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance.

[0032] 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.

[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: 0.020% 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: 1.50 to 4.00%,
 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,
 and satisfying Formula (1),
 wherein:

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a microstructure consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite,
a yield strength is 586 MPa or more, and
in the austenite, a number density of Cu precipitates having a major axis of 50 nm or less is 150 to 1500 / μm^3 ;

$$\text{Cr} + 3.3(\text{Mo} + 0.5\text{W}) + 16\text{N} \geq 30.0 \quad (1)$$

where, a content in percent by mass of a corresponding element is substituted for each symbol of an element in Formula (1), and if a corresponding element is not contained, "0" is substituted for the symbol of the corresponding element.

[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%.

[3] The duplex stainless steel material according to [1] or [2], 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%, and
W: 0.001 to 0.200%.

[4] The duplex stainless steel material according to any one of [1] to [3], containing one or more elements selected from a group consisting of:

Co: 0.001 to 0.500%,
Sn: 0.001 to 0.100%, and
Sb: 0.001 to 0.100%.

[5] The duplex stainless steel material according to any one of [1] to [4], containing one or more elements selected from a group consisting of:

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%.

[0033] A 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 (solid material), or may be a steel plate. Note that, the term "round steel bar" refers to a steel bar in which a cross section in a direction perpendicular to an axial direction is a circular shape. Further, the steel pipe may be a seamless steel pipe

or may be a welded steel pipe.

[0034] Hereunder, the duplex stainless steel material according to the present embodiment is described in detail. Note that, in the following description, the duplex stainless steel material is also referred to simply as a "steel material".

5 [Chemical composition]

[0035] 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 percent" unless otherwise noted.

10 C: 0.030% or less

[0036] Carbon (C) is unavoidably contained. That is, a lower limit of the content of C is more than 0%. C forms Cr carbides at grain boundaries and increases the corrosion susceptibility at the grain boundaries. Therefore, if the content of C is too high, the pitting 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%, and more preferably is 0.005%.

20 Si: 0.20 to 1.00%

[0037] 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 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 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%, and more preferably is 0.60%.

30 Mn: 0.50 to 7.00%

[0038] Manganese (Mn) deoxidizes the steel and desulfurizes the steel. Furthermore, Mn improves the 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, even if the contents of other elements are within the range of the present embodiment, the pitting resistance of the steel material in a high-temperature environment will decrease. Thus, 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%.

40 P: 0.040% or less

[0039] 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 pitting 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%.

50 S: 0.020% or less

[0040] 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 pitting 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 0.020% or less. A preferable upper limit of the content of S is 0.018%, and more preferably is 0.016%. 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 0.0001%, more preferably is 0.0003%, further preferably is 0.001%, and

further preferably is 0.002%.

Al: 0.100% or less

- 5 **[0041]** 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 "acid-soluble Al," that is, the content of sol. Al.

Ni: 4.20 to 9.00%

- 15 **[0042]** Nickel (Ni) stabilizes the austenitic microstructure of the steel material. That is, Ni is an element necessary for obtaining a stable duplex microstructure consisting of ferrite and austenite. Ni also increases the pitting 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%.

25 Cr: 20.00 to 30.00%

- [0043]** Chromium (Cr) increases the pitting resistance of the steel material. Specifically, Cr forms a passive film as oxides on the surface of the steel material. As a result, the pitting resistance of the steel material increases. Cr also increases the volume ratio of the ferritic microstructure of the steel material. By obtaining a sufficient ferritic microstructure, the pitting 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, 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 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%, and further preferably is 21.50%. 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%

- 40 **[0044]** Molybdenum (Mo) increases the pitting 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, 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 Mo is to be 0.50 to 2.00%. A preferable lower limit of the content of Mo is 0.60%, more preferably is 0.70%, and further preferably is 0.80%. 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: 1.50 to 4.00%

- 50 **[0045]** Copper (Cu) precipitates as fine Cu precipitates in austenite of the steel material, and thereby 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 1.50 to 4.00%. A preferable lower limit of the content of Cu is 1.60%, more preferably is 1.80%, further preferably is 1.90%, further preferably is 2.00%, and further preferably is 2.50%. A preferable upper limit of the content of Cu is 3.90%, more preferably is 3.75%, and further preferably is 3.50%.

N: 0.150 to 0.350%

[0046] Nitrogen (N) stabilizes the austenitic microstructure of the steel material. That is, N is an element necessary for obtaining a stable duplex microstructure consisting of ferrite and austenite. N also increases the pitting 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, even if the contents of other elements are within the range of the present embodiment, the low-temperature toughness and hot workability of the steel material will decrease. 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%

[0047] 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, the 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%, and further preferably is 0.05%. A preferable upper limit of the content of V is 1.20%, and more preferably is 1.00%.

[0048] 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 those elements and the like 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]

[0049] The chemical composition of the duplex stainless steel material described above may further contain one or more elements selected from a 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 increases the strength of the steel material.

Nb: 0 to 0.100%

[0050] 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 the 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, the 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%

[0051] 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 the 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, the 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%, and more preferably is 0.070%.

Ti: 0 to 0.100%

[0052] 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 the 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, the 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%

[0053] 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 the 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, the 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%

[0054] 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 the 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, the 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%

[0055] 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 the 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, the 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%.

[0056] The chemical composition of the duplex stainless steel material described above may further contain one or more elements selected from a group consisting of Co, Sn, and Sb in lieu of a part of Fe. Each of these elements is an optional element, and enhances the corrosion resistance of the steel material.

Co: 0 to 0.500%

[0057] 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 the corrosion resistance of the steel material. Co also increases the hardenability of the steel material and stabilizes the 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%

[0058] 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 the 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 and consequently the hot workability of the steel material will 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%

[0059] 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 the 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, the high-temperature ductility of the steel material will decrease, and the 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%.

[0060] The chemical composition of the duplex stainless steel material described above may further contain one or more elements selected from a 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 increases the hot workability of the steel material.

Ca: 0 to 0.020%

[0061] 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 the 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%

[0062] 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 the 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%

[0063] 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 the 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%

[0064] 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 the 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%.

[0065] Note that, in the present description the term "REM" means one or more elements selected from a group consisting of scandium (Sc) with atomic number 21, yttrium (Y) 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.

[Regarding Formula (1)]

[0066] The chemical composition of the duplex stainless steel material according to the present embodiment also satisfies the following Formula (1):

$$\text{Cr} + 3.3(\text{Mo} + 0.5\text{W}) + 16\text{N} \geq 30.0 \quad (1)$$

where, a content in percent by mass of a corresponding element is substituted for each symbol of an element in Formula (1), and if a corresponding element is not contained, "0" is substituted for the symbol of the corresponding element.

[0067] Fn1 (= Cr + 3.3(Mo + 0.5W) + 16N) is an index relating to the pitting resistance of the steel material. If Fn1 is made high, the pitting resistance of the duplex stainless steel material can be increased. That is, if Fn1 is too low, the pitting resistance of the duplex stainless steel material will decrease. Accordingly, in the duplex stainless steel material according to the present embodiment, the chemical composition described above is satisfied, and Fn1 is made 30.0 or more.

[0068] A preferable lower limit of Fn1 is 30.5, more preferably is 31.0, and further preferably is 31.5. It is preferable for the value of Fn1 to be high. However, in the duplex stainless steel material according to the present embodiment which has the chemical composition described above, the upper limit of Fn1 is substantially 42.5. Note that, in the present embodiment, a value obtained by rounding off to the first decimal place of the obtained numerical value is adopted as Fn1.

[Microstructure]

[0069] The microstructure of the duplex stainless steel material according to the present embodiment consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite. In the present description, the phrase "consist 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, volume ratios of precipitates and inclusions are negligibly low as compared with the volume ratio 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.

[0070] In the microstructure of the duplex stainless steel material according to the present embodiment, the volume ratio of ferrite is 30.0 to 70.0%. If the volume ratio of ferrite is too low, in some cases the yield strength and/or the pitting resistance of the steel material may decrease. On the other hand, if the volume ratio of ferrite is too high, in some cases the low-temperature toughness and/or hot workability of the steel material may decrease. Therefore, in the microstructure of the duplex stainless steel material according to the present embodiment, the volume ratio of ferrite is 30.0 to 70.0%. A preferable lower limit of the volume ratio of ferrite is 31.0%, and more preferably is 32.0%. A preferable upper limit of the volume ratio of ferrite is 68.0%, and more preferably is 65.0%.

[0071] In the present embodiment, the volume ratio of ferrite in the duplex stainless steel material can be determined by a method in accordance with ASTM E562 (2019). 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 a rolling direction and 5 mm in a thickness direction is prepared from a center portion of a thickness. If the steel material is a steel pipe, a test specimen having an observation surface with dimensions of 5 mm in a pipe axis direction and 5 mm in a pipe diameter direction is prepared from a center portion of a wall thickness. If the steel material is a round steel bar, a test specimen having an observation surface with dimensions of 5 mm in an axial direction and 5 mm in a radial direction is prepared from an R/2 position. In the present description, the R/2 position of a round steel bar means a center position of a radius R in a cross section perpendicular

to the axial direction of the round steel bar. Note that, a size of the test specimen is not particularly limited as long as the aforementioned observation surface can be obtained.

[0072] 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 on which the microstructure has been revealed is observed in 10 visual fields using an optical microscope. An area of each visual field is not particularly limited, and for example is 1.00 mm² (magnification of 100×). In each visual field, ferrite is identified based on contrast. An area fraction of the identified ferrite is measured by a point counting method in accordance with ASTM E562 (2019). In the present embodiment, an arithmetic average value of the area fractions of ferrite obtained in the 10 visual fields is defined as the volume ratio (%) of ferrite. In the present embodiment, a value obtained by rounding off to first decimal place of the obtained value is adopted as the volume ratio (%) of ferrite.

[Number density of fine Cu precipitates]

[0073] In the duplex stainless steel material according to the present embodiment, the number density of Cu precipitates having a major axis of 50 nm or less in austenite is 150 to 1500 /μm³. As mentioned above, in the present description, Cu precipitates having a major axis of 50 nm or less are also referred to as "fine Cu precipitates". Note that, in the present description, the term "Cu precipitates" means precipitates composed of Cu and impurities. Specifically, in the present embodiment, in elementary analysis performed by Energy Dispersive X-ray Spectrometry (hereunder, also referred to as an "EDS") to be described later, among the element concentrations for Fe, Cr, Ni, Cu, Mn, Mo, and Si, those precipitates in which a concentration of 15.0% by mass or more of Cu is detected are defined as "Cu precipitates".

[0074] As mentioned above, in duplex stainless steel materials, conventionally precipitates in the steel materials have been reduced for the purpose of increasing the pitting resistance of the steel materials. On the other hand, fine Cu precipitates in austenite increase the yield strength of a steel material. In addition, the influence of fine Cu precipitates on the low-temperature toughness and the pitting resistance of a steel material is small. Therefore, in the duplex stainless steel material according to the present embodiment, fine Cu precipitates that have little influence on low-temperature toughness and pitting resistance are purposely caused to precipitate in austenite. As a result, in the duplex stainless steel material according to the present embodiment, the yield strength of the steel material can be increased while maintaining the pitting resistance.

[0075] On the other hand, if too large a number of fine Cu precipitates precipitate in austenite, although the pitting resistance of the steel material will be maintained, the low-temperature toughness of the steel material will decrease. Therefore, in the present embodiment, the number density of fine Cu precipitates in austenite is made to fall within the range of 150 to 1500 /μm³. In a duplex stainless steel material which has the chemical composition and the microstructure described above and which satisfies Formula (1), if the number density of fine Cu precipitates in austenite is made 150 to 1500 /μm³, a high yield strength of 586 MPa or more can be obtained while maintaining excellent low-temperature toughness and excellent pitting resistance.

[0076] A preferable lower limit of the number density of fine Cu precipitates in austenite in the duplex stainless steel material according to the present embodiment is 156 /μm³, and more preferably is 160 /μm³. A preferable upper limit of the number density of fine Cu precipitates in austenite in the duplex stainless steel material according to the present embodiment is 1200 /μm³, more preferably is 900 /μm³, and further preferably is 600 /μm³.

[0077] In the duplex stainless steel material according to the present embodiment, the number density of fine Cu precipitates in austenite can be determined by the following method. A thin film test specimen for observation of fine Cu precipitates is prepared from the steel material according to the present embodiment. If the steel material is a steel plate, the thin film test specimen is prepared from a center portion of the thickness. If the steel material is a steel pipe, the thin film test specimen is prepared from a center portion of the wall thickness. If the steel material is a round steel bar, the thin film test specimen is prepared from an R/2 position. Note that, the thin film test specimen is prepared by electropolishing using a twin-jet method. Further, a size of the thin film test specimen is not particularly limited as long as an observation visual field to be described later can be obtained.

[0078] On the observation surface of the obtained thin film test specimen, an arbitrary four visual fields are specified from the austenite. The austenite in the observation surface can be identified by identification of a crystal structure by electron diffraction. The specified four visual fields are subjected to microstructure observation using a transmission electron microscope (hereinafter, also referred to as a "TEM"). Specifically, the arbitrary four visual fields are specified as observation visual fields. Although not particularly limited, an area of each observation visual field is set to, for example, 800 nm × 800 nm. The microstructure observation for each observation visual field is conducted using an accelerating voltage of 200 kV and a diffraction condition that is set to a condition suitable for observation of precipitates (for example, a diffraction vector $g = 11\text{-}1$ at 011 incidence). In addition, precipitates are photographed by performing exposure for an appropriate time. In generated photographic images, precipitates are identified based on contrast. Among the identified precipitates, precipitates having a major axis of 50 nm or less are identified by performing a comparison with a scale bar in the images. Note that, identification of precipitates having a major axis of 50 nm or less in the observation visual

fields can be, as a matter of course, performed by a person skilled in the art.

[0079] The precipitates having a major axis of 50 nm or less in austenite as identified in the manner described above are subjected to elementary analysis by the EDS. Note that, element concentrations are determined for Fe, Cr, Ni, Cu, Mn, Mo, and Si as elements to be analyzed. Here, in the EDS, due to the characteristics of the apparatus, elementary analysis is performed with respect to a range that has a certain volume. That is, even when precipitates are present at the observation surface, elementary analysis of only the precipitates cannot be performed, and the base metal is also simultaneously subjected to elementary analysis. Accordingly, when elementary analysis by the EDS is performed in a region in which Cu precipitates are present at the observation surface, elements (Fe and the like) derived from the base metal are also simultaneously detected in addition to Cu.

[0080] On the other hand, in the present embodiment the content of Cu in the base metal is, as mentioned above, 1.50 to 4.00%. Therefore, in elementary analysis by the EDS, if a precipitate has a Cu concentration of 15.0% by mass or more, it can be determined that the precipitate is a Cu precipitate. In each observation visual field, the number of precipitates which have a major axis of 50 nm or less and which have a Cu concentration of 15.0% by mass or more (fine Cu precipitates) is counted. In addition, the volume (μm^3) of each observation region is determined based on the area of each observation visual field and the thickness of the observation region. Note that, the thickness of the observation region can be determined based on, with respect to the thin film test specimen, the total integrated intensity of an electron energy loss spectrum (EELS) and the integrated intensity of a zero-loss spectrum.

[0081] The number density of fine Cu precipitates ($/\mu\text{m}^3$) in each observation visual field is determined based on the obtained number (pieces) of Cu precipitates having a major axis of 50 nm or less in each observation visual field and the volume (μm^3) of each observation visual field. An arithmetic average value of the number densities of fine Cu precipitates obtained in the four visual fields is defined as the number density of fine Cu precipitates ($/\mu\text{m}^3$) in austenite. In the present embodiment, a value obtained by rounding off to first decimal place of the obtained numerical value is adopted as the number density of fine Cu precipitates ($/\mu\text{m}^3$) in austenite.

[Yield strength]

[0082] The yield strength of the duplex stainless steel material according to the present embodiment is 586 MPa or more. The duplex stainless steel material according to the present embodiment has the chemical composition described above and also satisfies Formula (1), and has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite, and furthermore, the number density of Cu precipitates having a major axis of 50 nm or less in austenite in the duplex stainless steel material is 150 to 1500 $/\mu\text{m}^3$. As a result, even though the yield strength is 586 MPa or more, the duplex stainless steel material according to the present embodiment has excellent low-temperature toughness and excellent pitting resistance.

[0083] A preferable lower limit of the yield strength of the duplex stainless steel material according to the present embodiment is 590 MPa, more preferably is 592 MPa, and further preferably is 594 MPa. Although the upper limit of the yield strength of the duplex stainless steel material according to the present embodiment is not particularly limited, for example the upper limit is 724 MPa.

[0084] 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 tensile test specimen is prepared from a center portion of the thickness. In this case, a longitudinal direction of the tensile test specimen is to be made parallel to the rolling direction of the steel plate. 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. In this case, a longitudinal direction of the arc-shaped test specimen is to be made parallel to the pipe axis direction. If the steel material is a round steel bar, a tensile test specimen is prepared from an R/2 position. In this case, a longitudinal direction of the tensile test specimen is to be made parallel to the axial direction of the round steel bar. When preparing the tensile test specimen, the tensile test specimen is prepared so as to be a size with, for example, a parallel portion diameter of 6 mm and a gage length of 24 mm. A tensile test is carried out at normal temperature (25°C) in atmospheric air using the test specimen. In the present embodiment, a 0.2% offset yield stress obtained in the tensile test is defined as the yield strength (MPa). In the present embodiment, a value obtained by rounding off decimals of the obtained numerical value is adopted as the yield strength (MPa).

[Low-temperature toughness]

[0085] The duplex stainless steel material according to the present embodiment has the chemical composition described above, satisfies Formula (1), and has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite, and in addition, in austenite in the duplex stainless steel material, the

number density of Cu precipitates having a major axis of 50 nm or less is 150 to 1500 / μm^3 . As a result, even though the yield strength is 586 MPa or more, the duplex stainless steel material according to the present embodiment has excellent low-temperature toughness and excellent pitting resistance. In the present embodiment, the phrase "excellent low-temperature toughness" is defined as follows.

[0086] The low-temperature toughness of the duplex stainless steel material according to the present embodiment can be 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, the V-notch test specimen is prepared from a center portion of the thickness. In this case, in the V-notch test specimen, a notched surfaces are made parallel to the thickness direction and the rolling direction of the steel plate, and a longitudinal direction is made parallel to the rolling direction of the steel plate. If the steel material is a steel pipe, the V-notch test specimen is prepared from a center portion of the wall thickness. In this case, in the V-notch test specimen, the notched surfaces are made parallel to the wall thickness direction and the pipe axis direction, and a longitudinal direction is made parallel to the pipe axis direction. If the steel material is a round steel bar, the V-notch test specimen is prepared from an R/2 position. In this case, in the V-notch test specimen, the notched surfaces are made parallel to the radial direction and the axial direction of the round steel bar, and a longitudinal direction is made parallel to the axial direction of the round steel bar.

[0087] The prepared V-notch test specimen is subjected to the Charpy impact test in accordance with ASTM E23 (2018) to determine absorbed energy (J) at -10°C . The determined absorbed energy (J) is divided by a cross-sectional area (cm^2) of the V-notch test specimen to determine the absorbed energy (J/cm^2) per unit area at -10°C . Note that, the 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 a 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 of 0.8 cm^2 (width of $0.8 \text{ cm} \times$ thickness of 1.0 cm) of the V-notch test specimen. In the present embodiment, a value obtained by rounding off to first decimal place of the obtained numerical value is adopted as the absorbed energy (J/cm^2) per unit area at -10°C .

[0088] In the present embodiment, if the absorbed energy per unit area at -10°C is $60.0 \text{ J}/\text{cm}^2$ or more, 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 at -10°C is also referred to simply as "absorbed energy".

[Pitting resistance]

[0089] The duplex stainless steel material according to the present embodiment has the chemical composition described above and also satisfies Formula (1), and has the microstructure consisting of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite, and in addition, the number density of Cu precipitates having a major axis of 50 nm or less in austenite in the duplex stainless steel material is 150 to 1500 / μm^3 . As a result, even though the yield strength is 586 MPa or more, the duplex stainless steel material according to the present embodiment has excellent low-temperature toughness and excellent pitting resistance. In the present embodiment, the phrase "excellent pitting resistance" is defined as follows.

[0090] The pitting resistance of the duplex stainless steel material according to the present embodiment can be evaluated by a corrosion test in accordance with "Method E" specified in ASTM G48 (2011). A test specimen for the corrosion test is prepared from the steel material according to the present embodiment. Regarding a size of the test specimen, for example, the test specimen has a thickness of 3 mm, a width of 25 mm, and a length of 50 mm. Further, if the steel material is a steel plate, the test specimen is prepared from a center portion of the thickness. In this case, a longitudinal direction of the test specimen is to be made parallel to the rolling direction of the steel plate. If the steel material is a steel pipe, the test specimen is prepared from a center portion of the wall thickness. In this case, a longitudinal direction of the test specimen is to be made parallel to the pipe axis direction. If the steel material is a round steel bar, the test specimen is prepared from an R/2 position. In this case, a longitudinal direction of the test specimen is to be made parallel to the axial direction of the round steel bar.

[0091] A solution of $6\% \text{FeCl}_3 + 1\% \text{HCl}$ is adopted as a test solution. The test specimen is immersed in the test solution so that the solution volume to specimen area ratio is $5 \text{ mL}/\text{cm}^2$ or more. A temperature at a start of the test is set to 15°C , and the temperature of the test solution is increased by 5°C every 24 hours. The temperature when pitting occurs on the test specimen is defined as a critical pitting temperature (CPT). In the present embodiment, if the obtained CPT is higher than 15°C , it is determined that the duplex stainless steel material exhibits excellent pitting resistance.

[Shape of duplex stainless steel material]

[0092] As mentioned above, a shape of the duplex stainless steel material according to the present embodiment is not particularly limited. Preferably, the duplex stainless steel material according to the present embodiment is a seamless

steel pipe. In the case where the duplex stainless steel material according to the present embodiment is a seamless steel pipe, even when a wall thickness is 5 mm or more, the duplex stainless steel material has a yield strength of 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance.

[Production method]

[0093] One example of a method for producing the duplex stainless steel material according to the present embodiment that is constituted as described above will now be described. Note that, the 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 the method for producing the duplex stainless steel material according to the present embodiment includes a starting material preparation process, a hot working process, and a solution treatment process. Hereunder, each production process is described in detail.

[Starting material preparation process]

[0094] 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.

[0095] 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]

[0096] 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 will be a steel plate, refers to a hollow shell in a case where the end product will be a steel pipe, refers to a bar-shaped steel material in which a cross section perpendicular to the axial direction is a circular shape in a case where the end product will be a round steel bar, and refers to a wire-shaped steel material in a case where the end product will be a wire rod. The hot working may be hot forging, may be hot extrusion, or may be hot rolling. The method of hot working is not particularly limited, and it suffices to use a well-known method.

[0097] If the intermediate steel material is a hollow shell (seamless steel pipe), in the hot working process, for example, the Ugine-Sejournet 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, drawing and rolling 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 a desired shape.

[Solution treatment process]

[0098] In the solution treatment process according to the present embodiment, the intermediate steel material produced in the aforementioned hot working process is subjected to a solution treatment to produce a duplex stainless steel material. The term "solution treatment" refers to a heat treatment which dissolves compounds in the intermediate steel material. That is, the solution treatment process includes a process that subjects the intermediate steel material to a heat treatment at a desired temperature (heat treatment process), and a process that rapidly cools the intermediate steel material subjected to the heat treatment (rapid cooling process). On the other hand, in the present embodiment, as mentioned above, the yield strength of the steel material is increased by causing fine Cu precipitates to precipitate in austenite. Therefore, the solution treatment process according to the present embodiment includes a process of maintaining the temperature of the intermediate steel material (maintaining process) between the heat treatment process and the rapid cooling process. Each process is described in detail hereunder.

[Heat treatment process]

[0099] In the heat treatment process according to the present embodiment, the intermediate steel material produced by the aforementioned hot working process is subjected to a heat treatment. Specifically, preferably the intermediate steel material is subjected to a heat treatment in which a heat treatment temperature is set in a range of 960 to 1100°C and a heat treatment time is set in a range of 5 to 180 minutes. In the present description, the term "heat treatment temperature" means a temperature (°C) of a heat treatment furnace for performing the solution treatment. In the present description, the term "heat treatment time" means a time period from when the starting material is charged into the heat treatment furnace for performing the solution treatment until the starting material is taken out from the heat treatment furnace.

[0100] In the heat treatment process, if the heat treatment temperature is too low, precipitates may sometimes remain in the duplex stainless steel material after the solution treatment process. In such a case, the pitting resistance of the duplex stainless steel material will decrease. On the other hand, in the heat treatment process, if the heat treatment temperature is too high, in some cases the volume ratio of ferrite may increase to more than 70.0%. In such a case, the pitting resistance of the duplex stainless steel material will decrease. Therefore, in the heat treatment process according to the present embodiment, preferably the heat treatment temperature is set in the range of 960 to 1100°C. A more preferable lower limit of the heat treatment temperature is 965°C. A more preferable upper limit of the heat treatment temperature is 1080°C.

[0101] In the heat treatment process, if the heat treatment time is too short, in some cases precipitates which reduce the pitting resistance may remain in the duplex stainless steel material after the solution treatment process. In such a case, the pitting resistance of the duplex stainless steel material will decrease. On the other hand, in the heat treatment process, if the heat treatment time is too long, the effect of dissolving precipitates will be saturated. Therefore, in the heat treatment process according to the present embodiment, preferably the heat treatment time is set within the range of 5 to 180 minutes.

[Maintaining process]

[0102] In the maintaining process according to the present embodiment, the temperature of the intermediate steel material subjected to the heat treatment in the aforementioned heat treatment process is maintained. Specifically, preferably the intermediate steel material is maintained at a temperature of 900 to 950°C for 20 to 180 seconds. In the present description, the phrase "the temperature of the intermediate steel material is maintained" is not limited to a case where the temperature of the intermediate steel material is held at a constant temperature. For example, the intermediate steel material may be cooled at a cooling rate (by allowing cooling or by slow cooling or the like) that is not more than the cooling rate of allowing cooling to keep the temperature of the intermediate steel material within a range of 900 to 950°C. In addition, for example, the intermediate steel material may be heated using a supplementary heating furnace or a high-frequency heating furnace to keep the temperature of the intermediate steel material within a range of 900 to 950°C. That is, in the maintaining process according to the present embodiment, the intermediate steel material may be held at a constant temperature, the intermediate steel material may be allowed to cool or may be slow-cooled, or the intermediate steel material may be heated.

[0103] If the temperature at which the intermediate steel material is maintained (maintaining temperature) is too high, Cu precipitates will not precipitate sufficiently in austenite. As a result, in some cases the number density of fine Cu precipitates in austenite will decrease, and the yield strength of the steel material will become less than 586 MPa. On the other hand, if the maintaining temperature is too low, in some cases the σ -phase in the steel material will precipitate. As a result, the pitting resistance of the steel material will decrease. Therefore, in the maintaining process according to the present embodiment, preferably the maintaining temperature is set in the range of 900 to 950°C.

[0104] If the time for which the intermediate steel material is maintained (maintaining time) is too short, Cu precipitates will not precipitate sufficiently in austenite. As a result, in some cases the number density of fine Cu precipitates in austenite will decrease, and the yield strength of the steel material will become less than 586 MPa. On the other hand, if the maintaining time is too long, Cu precipitates will coarsen. As a result, in some cases the low-temperature toughness of the steel material will decrease. Therefore, in the maintaining process according to the present embodiment, preferably the maintaining time is set in the range of 20 to 180 seconds.

[Rapid cooling process]

[0105] In the rapid cooling process according to the present embodiment, the intermediate steel material whose temperature was maintained in the aforementioned maintaining process is rapidly cooled to produce a duplex stainless steel material. The temperature at which the rapid cooling is started (rapid cooling start temperature) is the temperature of the intermediate steel material at the time when the aforementioned maintaining process is completed. If the rapid

cooling start temperature is too low, in some cases too many fine Cu precipitates will precipitate in austenite. In such a case, the low-temperature toughness of the steel material will decrease. Therefore, in the rapid cooling process according to the present embodiment, preferably the rapid cooling is performed without delay after maintaining the intermediate steel material at 900 to 950°C in the aforementioned maintaining process.

[0106] In the rapid cooling process according to the present embodiment, the method of rapid cooling is not particularly limited, and it suffices to perform a well-known method. For example, the intermediate steel material can be cooled by shower water cooling, mist water cooling, oil cooling, or the like. Note that, although a cooling rate in the rapid cooling process is not particularly limited, for example, the cooling rate from 900°C to 400°C is 3°C/sec or more.

[0107] 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, if the duplex stainless steel material on which the solution treatment was performed is subjected to cold working, the strength of the steel material will become too high and the toughness of the steel material will decrease extremely. Therefore, it is preferable not to perform cold working on the duplex stainless steel material according to the present embodiment.

[0108] 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 that is described above is one example, and the duplex stainless steel material may be produced by another method. Hereunder, the present invention is described in more detail by way of examples.

EXAMPLES

[0109] Molten steels having the chemical compositions shown in Table 1 were melted using a 50 kg vacuum furnace, and ingots were produced by an ingot-making process. Note that, the symbol "-" in Table 1 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 rare earth metal (REM) of Test No. 1 were each 0% when rounded off to third decimal places. Further, Fn1 which was determined based on the chemical composition described in Table 1 and the definition described above is shown in Table 1.

[Table 1]

TABLE 1

Steel	Chemical Composition (Unit Is Mass%; Balance Is Fe and Impurities)																								Fn1	
	C	Si	Mn	P	S	Al	Ni	Cr	Mo	Cu	N	V	Nb	Ta	Ti	Zr	Hf	W	Co	Sn	Sb	Ca	Mg	B		REM
A	0.016	0.51	4.83	0.021	0.001	0.039	4.89	25.43	1.01	2.53	0.223	0.09	-	-	-	-	-	-	-	-	-	-	-	-	-	32.3
B	0.014	0.49	1.03	0.022	0.001	0.017	4.99	25.35	1.03	2.51	0.191	0.10	0.028	-	-	-	-	-	-	-	-	-	-	-	-	31.8
C	0.025	0.60	6.18	0.029	0.012	0.064	6.93	26.85	0.94	2.71	0.210	0.93	-	0.023	-	-	-	-	-	-	-	-	-	-	-	33.3
D	0.020	0.55	3.20	0.011	0.012	0.074	5.12	27.71	1.28	3.38	0.246	0.80	-	-	0.076	-	-	-	-	-	-	-	-	-	-	35.9
E	0.006	0.44	5.28	0.018	0.016	0.047	4.51	26.81	1.16	3.50	0.195	0.43	-	-	-	0.064	-	-	-	-	-	-	-	-	-	33.8
F	0.005	0.31	4.69	0.030	0.016	0.085	5.31	22.50	1.50	3.25	0.327	0.99	-	-	-	-	0.044	-	-	-	-	-	-	-	-	32.7
G	0.020	0.37	1.61	0.020	0.006	0.059	7.68	27.90	1.22	2.61	0.274	0.36	-	-	-	-	-	0.142	-	-	-	-	-	-	-	36.5
H	0.015	0.50	4.90	0.022	0.001	0.033	4.90	25.61	1.03	2.51	0.220	0.11	-	-	-	-	-	-	0.325	-	-	-	-	-	-	32.5
I	0.016	0.51	4.85	0.023	0.001	0.039	4.96	25.22	1.02	2.49	0.224	0.20	-	-	-	-	-	-	-	0.012	-	-	-	-	-	32.2
J	0.017	0.49	4.83	0.021	0.001	0.036	4.89	25.88	1.01	2.55	0.221	0.15	-	-	-	-	-	-	-	-	0.001	-	-	-	-	32.7
K	0.007	0.32	1.74	0.011	0.009	0.035	4.91	26.61	1.47	3.13	0.205	0.19	-	-	-	-	-	-	-	-	-	0.016	-	-	-	34.7
L	0.008	0.38	3.25	0.013	0.005	0.079	4.74	27.01	0.81	2.55	0.240	0.67	-	-	-	-	-	-	-	-	-	-	0.019	-	-	33.5
M	0.022	0.53	1.10	0.029	0.002	0.054	5.19	27.07	1.39	2.78	0.328	0.51	-	-	-	-	-	-	-	-	-	-	-	0.009	-	36.9
N	0.023	0.37	2.84	0.028	0.007	0.084	5.80	25.62	0.80	3.36	0.239	0.77	-	-	-	-	-	-	-	-	-	-	-	-	0.155	32.1
O	0.009	0.47	6.00	0.015	0.009	0.078	6.45	24.75	1.25	2.88	0.310	0.33	0.043	0.021	-	-	-	-	-	-	-	0.010	-	-	-	33.8
P	0.022	0.45	3.95	0.013	0.001	0.056	5.91	28.00	1.42	2.67	0.259	0.33	-	-	0.051	-	-	-	-	-	-	0.011	0.014	-	-	36.8
Q	0.021	0.55	4.14	0.027	0.015	0.076	5.23	24.78	1.13	2.56	0.202	0.25	-	-	0.061	0.063	-	-	-	-	-	-	0.015	0.010	-	31.7
R	0.013	0.54	3.91	0.013	0.008	0.019	6.10	23.10	1.01	3.47	0.318	0.40	-	-	-	0.061	0.045	-	-	-	-	-	-	-	-	31.5
S	0.008	0.31	1.77	0.015	0.012	0.021	7.05	26.03	0.91	2.73	0.199	0.50	-	-	-	-	0.047	0.132	-	-	-	-	-	-	-	32.4
T	0.025	0.58	1.03	0.030	0.001	0.046	5.03	25.02	1.50	3.40	0.252	0.05	0.033	-	-	-	-	0.138	-	-	-	-	-	-	-	34.2

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U	0.029	0.85	6.78	0.034	0.017	0.009	7.80	25.85	0.76	1.65	0.153	1.03	-	0.022	-	0.059	-	-	-	-	-	0.013	-	-	0.154	30.8
V	0.030	0.87	6.65	0.001	0.012	0.074	5.12	20.30	1.60	3.38	0.333	1.30	-	-	0.077	-	-	-	-	-	-	0.017	-	-	0.152	30.9
W	0.004	0.22	0.98	0.035	0.020	0.097	4.48	28.10	0.51	3.93	0.153	0.04	-	-	-	0.063	-	-	-	-	-	-	0.011	-	0.149	32.5
X	0.015	0.50	0.55	0.021	0.001	0.040	8.40	29.30	1.91	2.10	0.310	0.10	0.003	-	-	-	0.010	-	-	-	-	-	-	-	0.030	40.6
Y	0.023	0.45	3.28	0.004	0.010	0.046	6.59	21.34	0.55	3.04	0.189	0.69	-	-	-	-	-	-	-	-	-	-	-	-	-	26.2
Z	0.018	0.70	5.54	0.005	0.012	0.070	7.67	19.93	1.80	3.88	0.343	0.83	-	-	-	-	-	-	-	-	-	-	-	-	-	31.4
AA	0.002	0.86	3.40	0.029	0.009	0.081	4.50	29.40	1.95	1.10	0.349	0.81	-	-	-	-	-	-	-	-	-	-	-	-	-	41.4

[0110] The obtained ingots were heated to the rolling temperatures (°C) shown in Table 2 and Table 3, and thereafter hot rolling was performed to produce intermediate steel materials having shapes described in Table 2 and Table 3. Note that, in the present Examples, the temperature (°C) of the reheating furnace used for heating was adopted as the rolling temperature (°C). The steel material shapes described in the column "Shape" in Table 2 and Table 3 were as follows.

The term "Pipe A" refers to a seamless steel pipe shape having an outer diameter of 177.8 mm and a wall thickness of 12.65 mm. The term "Pipe B" refers to a seamless steel pipe shape having an outer diameter of 139.7 mm and a wall thickness of 9.2 mm. The term "Pipe C" refers to a seamless steel pipe shape having an outer diameter of 114.3 mm and a wall thickness of 7.4 mm. The term "Pipe D" refers to a seamless steel pipe shape having an outer diameter of 198.2 mm and a wall thickness of 21.2 mm. The term "Steel Plate" refers to a steel plate shape with a plate thickness of 13 mm and in which a cross section perpendicular to the thickness direction is a rectangle of 15 mm × 60 mm. The term "Round steel bar" refers to a cylindrical shape that is a 500 mm in length in the axial direction and in which a cross section perpendicular to the axial direction is a circular shape with a diameter of 50 mm.

[Table 2]

[0111]

TABLE 2

Test Number	Steel	Shape	Rolling Temperature (°C)	Solution Treatment					Ferrite Volume Ratio (%)	Number Density of Fine Cu Precipitates (/μm ³)	YS (MPa)	CPT (°C)	E (-10°C) (J/cm ²)
				Heat Treatment Temperature (°C)	Heat Treatment Time (min)	Maintaining Temperature (°C)	Maintaining Time (sec)	Rapid Cooling Start Temperature (°C)					
1	A	Pipe A	1285	1050	40	930	30	930	42.9	266	594	25	83.0
2	A	Pipe A	1285	1050	40	940	30	940	43.2	160	590	25	110.0
3	A	Pipe A	1285	1050	40	920	30	920	43.3	524	604	25	81.0
4	A	Pipe A	1285	1050	40	920	60	920	43.3	650	610	25	77.0
5	A	Pipe A	1285	1050	40	920	90	920	41.8	780	617	25	73.0
6	A	Pipe A	1285	1050	40	920	170	920	42.2	918	620	25	70.0
7	A	Pipe A	1285	1050	40	910	30	910	42.0	810	618	25	72.0
8	A	Pipe A	1285	1050	40	910	60	910	41.7	1080	624	25	68.0
9	A	Pipe A	1285	1050	40	910	120	910	41.9	1330	629	25	66.0
10	A	Pipe A	1285	1050	40	910	170	910	42.5	1470	633	25	61.0
11	A	Pipe B	1285	1050	40	930	160	930	42.6	422	602	25	72.0
12	A	Pipe B	1285	980	40	SC	21	900	42.8	422	603	25	73.0
13	A	Pipe B	1285	1050	40	910	160	910	41.8	1410	620	25	63.0
14	A	Pipe B	1285	1050	40	920	160	910	41.8	1170	619	25	71.0
15	A	Pipe D	1285	1050	120	SC	167	900	42.3	453	620	25	74.0
16	B	Pipe A	1285	1000	40	950	30	950	41.4	203	590	35	82.0
17	C	Pipe A	1285	1050	40	900	160	900	43.9	406	611	25	71.0
18	D	Pipe A	1285	1050	40	930	100	930	44.2	359	604	30	96.0
19	E	Pipe A	1285	1050	40	930	90	930	41.8	281	599	25	84.0
20	F	Pipe A	1285	1050	40	930	80	930	45.9	313	601	25	92.0
21	G	Pipe A	1285	1050	40	930	70	930	44.9	328	607	25	78.0
22	H	Pipe A	1285	1050	40	930	30	930	43.1	272	599	25	84.0

(continued)

Test Number	Steel	Shape	Rolling Temperature (°C)	Solution Treatment					Ferrite Volume Ratio (%)	Number Density of Fine Cu Precipitates (/μm ³)	YS (MPa)	CPT (°C)	E (-10°C) (J/cm ²)
				Heat Treatment Temperature (°C)	Heat Treatment Time (min)	Maintaining Temperature (°C)	Maintaining Time (sec)	Rapid Cooling Start Temperature (°C)					
23	I	Pipe A	1285	1050	40	930	30	930	43.2	278	600	25	86.0
24	J	Pipe A	1285	1050	40	930	30	930	43.4	281	601	25	85.0
25	K	Pipe A	1285	1050	40	930	60	930	43.6	453	612	25	89.0

[Table 3]

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[0112]

TABLE 3

Test Number	Steel	Shape	Rolling Temperature (°C)	Solution Treatment					Ferrite Volume Ratio (%)	Number Density of Fine Cu Precipitates (/μm ³)	YS (MPa)	CPT (°C)	E(-10°C) (J/cm ²)
				Heat Treatment Temperature (°C)	Heat Treatment Time (min)	Maintaining Temperature (°C)	Maintaining Time (sec)	Rapid Cooling Start Temperature (°C)					
26	L	Pipe A	1285	1050	40	930	50	930	43.3	391	623	25	99.0
27	M	Pipe A	1285	1050	40	930	40	930	47.1	422	620	40	91.0
28	N	Pipe A	1285	1050	40	930	30	930	42.1	297	606	25	90.0
29	O	Pipe A	1285	1050	40	930	30	930	43.0	281	620	25	94.0
30	P	Pipe A	1285	1050	40	930	30	930	40.3	203	621	25	95.0
31	Q	Pipe A	1285	1050	40	930	30	930	54.0	172	589	25	77.0
32	R	Pipe A	1285	1050	40	930	60	930	59.9	375	607	40	75.0
33	S	Pipe A	1285	1050	40	930	30	930	50.3	297	596	25	90.0
34	T	Pipe A	1285	1050	40	930	40	930	52.1	344	598	25	93.0
35	U	Pipe A	1285	1050	40	930	20	930	33.1	234	589	20	87.0
36	V	Pipe A	1285	1050	40	930	30	930	42.7	266	602	20	78.0
37	W	Pipe A	1285	1050	40	930	180	930	67.9	1210	633	25	61.0
38	X	Pipe A	1285	1050	40	930	40	930	44.4	330	611	40	88.0
39	A	Steel Plate	1250	1050	40	910	30	910	46.5	784	608	25	80.0
40	A	Steel Plate	1250	1050	40	910	100	910	46.1	1213	610	25	74.0
41	A	Round Steel Bar	1250	1050	40	910	30	910	48.1	510	597	25	91.0
42	A	Round Steel Bar	1250	1050	40	910	100	910	47.3	1035	611	25	75.0

(continued)

Test Number	Steel	Shape	Rolling Temperature (°C)	Solution Treatment					Ferrite Volume Ratio (%)	Number Density of Fine Cu Precipitates (/μm ³)	YS (MPa)	CPT (°C)	E(-10°C) (J/cm ²)
				Heat Treatment Temperature (°C)	Heat Treatment Time (min)	Maintaining Temperature (°C)	Maintaining Time (sec)	Rapid Cooling Start Temperature (°C)					
43	A	Pipe C	1285	940	40	930	160	930	40.2	1670	625	25	32.0
44	A	Pipe B	1285	980	40	970	20	970	41.9	37	563	25	169.0
45	A	Pipe A	1285	1050	40	-	-	1050	43.0	0	570	25	143.0
46	A	Pipe A	1285	1050	40	930	10	930	42.7	125	581	25	137.0
47	A	Pipe A	1285	1050	40	SC	17	900	42.6	109	569	25	139.0
48	A	Pipe A	1285	980	40	SC	100	880	44.3	1540	604	25	54.0
49	Y	Pipe A	1285	1050	40	930	30	930	35.9	344	604	15	93.0
50	Z	Pipe A	1285	1050	40	930	30	930	28.1	234	572	20	87.0
51	AA	Pipe A	1285	980	40	930	30	930	48.6	94	575	25	98.0

[0113] The intermediate steel material of each test number produced by the hot rolling was subjected to a solution treatment under conditions described in Table 2 and Table 3 to produce a steel material of each test number. Specifically, the intermediate steel material of each test number was subjected to a heat treatment under the heat treatment temperature (°C) for the heat treatment time (min) described in Table 2 and Table 3. Note that, in the present Examples, the furnace temperature of the heat treatment furnace used to perform the solution treatment was taken as the heat treatment temperature (°C). In addition, the time period from when the intermediate steel material was charged into the heat treatment furnace for performing the solution treatment until the intermediate steel material was taken out from the heat treatment furnace was taken as the heat treatment time (min). The heat treatment temperature (°C) and the heat treatment time (min) for the heat treatment performed on the intermediate steel material of the respective test numbers are shown in Table 2 and Table 3.

[0114] The intermediate steel material of each test number on which the heat treatment had been performed was maintained at the maintaining temperature (°C) shown in Table 2 and Table 3 for the maintaining time (sec) shown in Table 2 and Table 3, and thereafter was water-cooled from the rapid cooling start temperature (°C) to thereby produce the steel material of each test number. Note that, "SC" (slow cooling) in the column "Maintaining Temperature" in Table 2 and Table 3 means that, the relevant intermediate steel material was water-cooled from the rapid cooling start temperature (°C) after being maintained at a temperature in the range of 950 to 900°C for the maintaining time (sec) described in Table 2 and Table 3 by performing slow cooling, and without the temperature of the steel material being held at a constant temperature. In addition, the symbol "-" in the column "Maintaining Temperature" in Table 2 means that the maintaining process was not performed. The maintaining temperature (°C), the maintaining time (sec), and the rapid cooling start temperature (°C) for each test number are shown in Table 2 and Table 3. The steel material of each test number was obtained by the above process. Note that, the shape of the intermediate steel material of each test number and the shape of the steel material of the corresponding test number were the same.

[Evaluation tests]

[0115] The steel material of each test number after the solution treatment was subjected to microstructure observation, a fine Cu precipitates number density measurement test, a tensile test, a Charpy impact test, and a corrosion test.

[Microstructure observation]

[0116] The microstructure of the steel material of each test number was observed by the aforementioned method in accordance with ASTM E562 (2019), and the ferrite volume ratio (%) was determined. First, a test specimen having a cross section perpendicular to the rolling direction of the steel material as an observation surface was prepared from the steel material of each test number. Specifically, if the shape of the steel material was a steel pipe, the test specimen was prepared from a center portion of the wall thickness. If the shape of the steel material was a steel plate, the test specimen was prepared from a center portion of the thickness. Further, if the shape of the steel material was a round steel bar, a test specimen was prepared from an R/2 position. The prepared test specimen was used to determine the ferrite volume ratio by the aforementioned method. The obtained ferrite volume ratio (%) of each test number is shown in Table 2 and Table 3.

[Fine Cu precipitates number density measurement test]

[0117] The number density of fine Cu precipitates in austenite in the steel material of each test number was determined. The number density of fine Cu precipitates in austenite was determined using the method described above. First, a test specimen was prepared from the steel material of each test number. Specifically, if the shape of the steel material was a steel pipe, a test specimen having an observation surface with dimensions of 5 mm in the pipe axis direction and 5 mm in the pipe diameter direction was prepared from a center portion of the wall thickness. If the shape of the steel material was a steel plate, a test specimen having an observation surface with dimensions of 5 mm in the thickness direction and 5 mm in the width direction was prepared from a center portion of the thickness. If the shape of the steel material was a round steel bar, a test specimen having an observation surface with dimensions of 5 mm in the axial direction and 5 mm in the radial direction was prepared from an R/2 position. The prepared test specimen was used to determine the number density of fine Cu precipitates in austenite by the method described above. The obtained number density of fine Cu precipitates in austenite ($/\mu\text{m}^3$) of each test number is shown as "Number Density of Fine Cu Precipitates ($/\mu\text{m}^3$)" in Table 2 and Table 3.

[Tensile test]

[0118] The steel material of each test number was subjected to a tensile test by the method described above in

accordance with ASTM E8/E8M (2021) to determine yield strength (MPa). First, a test specimen for a tensile test was prepared from the steel material of each test number. Specifically, if the shape of the steel material was a steel pipe, an arc-shaped test specimen having the same thickness as the wall thickness of the pipe, and having a width of 25.4 mm and a gage length of 50.8 mm was prepared. If the steel material was a steel plate, a tensile test specimen was prepared from a center portion of the thickness. If the steel material was a round steel bar, a tensile test specimen was prepared from an R/2 position. Regarding the size of the tensile test specimen, the tensile test specimen was prepared so as to have a parallel portion diameter of 6 mm, and a gage length of 24 mm. Note that, the longitudinal direction of the tensile test specimen and of the arc-shaped test specimen was parallel to the rolling direction of the steel material. A tensile test in accordance with ASTM E8/E8M (2021) was carried out on the prepared test specimen of each test number. The 0.2% offset yield stress obtained in the tensile test was defined as the yield strength. The obtained yield strength (MPa) of each test number is shown as "YS (MPa)" in Table 2 and Table 3.

[Charpy impact test]

[0119] The steel material of each test number was subjected to the Charpy impact test in accordance with ASTM E23 (2018) to evaluate the low-temperature toughness. First, a V-notch test specimen for the Charpy impact test was prepared from the steel material of each test number in accordance with ASTM E23 (2018). If the shape of the steel material was a steel pipe, a V-notch test specimen having notched surfaces parallel to the wall thickness direction and the pipe axis direction was prepared from a center portion of the wall thickness. If the shape of the steel material was a steel plate, a V-notch test specimen having notched surfaces parallel to the thickness direction and the rolling direction was prepared from a center portion of the thickness. If the shape of the steel material was a round steel bar, a V-notch test specimen having notched surfaces parallel to the radial direction and the axial direction was prepared from an R/2 position. Note that, the longitudinal direction of the V-notch test specimen was parallel to the rolling direction of the steel material.

[0120] Note that, for the steel materials having the shape of pipe A, pipe D, a steel plate, or a round steel bar, a full-size V-notch test specimen (having a width of 10 mm, a thickness of 10 mm, and a length of 55 mm) was prepared. For the steel materials having the shape of pipe B, a sub-size V-notch test specimen (having a width of 10 mm, a thickness of 7.5 mm, and a length of 55 mm) was prepared. For the steel material having the shape of pipe C, a sub-size V-notch test specimen (having a width of 10 mm, a thickness of 5 mm, and a length of 55 mm) was prepared. Here, the width of the V-notch test specimen means a distance between a face where the V-notch was formed and a face on an opposite side thereto in the V-notch test specimen.

[0121] The Charpy impact test was carried out in accordance with ASTM E23 (2018) on the prepared V-notch test specimen of each test number. Specifically, three test specimens of each test number that were prepared in accordance with ASTM E23 (2018) were cooled to -10°C , and the absorbed energy (J) was determined. The thus-determined absorbed energy was divided by the cross-sectional area (cm^2) perpendicular to the longitudinal direction of the V-notch test specimen that was used, to thereby determine the absorbed energy (J/cm^2) per unit area at -10°C . Note that, the cross-sectional area (cm^2) in the longitudinal direction of the V-notch test specimen was defined in accordance with the method described above. The obtained absorbed energy (J/cm^2) per unit area at -10°C of each test number is shown as "E (-10°C) (J/cm^2)" in Table 2 and Table 3.

[Corrosion test]

[0122] The steel material of each test number was subjected to a corrosion test by the method described above in accordance with "Method E" specified in ASTM G48 (2011), and the pitting resistance was evaluated. First, a test specimen for a corrosion test was prepared from the steel material of each test number.

Specifically, if the shape of the steel material was a steel pipe, a test specimen was prepared from a center portion of the wall thickness. If the shape of the steel material was a steel plate, a test specimen was prepared from a center portion of the thickness. If the shape of the steel material was a round steel bar, a test specimen was prepared from an R/2 position. Note that, regarding the size of the test specimen for the corrosion test, the test specimen had a thickness of 3 mm, a width of 25 mm, and a length of 50 mm, and the longitudinal direction of the test specimen was parallel to the rolling direction of the steel material.

[0123] The prepared test specimen of each test number was immersed in a test solution ($6\%\text{FeCl}_3 + 1\%\text{HCl}$) at 15°C so that the solution volume to specimen area ratio was $5 \text{ mL}/\text{cm}^2$ or more. The temperature of the test solution was increased by 5°C every 24 hours from the time at which the test specimen was immersed in the test solution, and whether or not pitting had occurred was confirmed with the naked eye. The temperature when pitting occurred was defined as the CPT ($^{\circ}\text{C}$). The CPT ($^{\circ}\text{C}$) obtained for each test number is shown in Table 2 and Table 3.

[Evaluation results]

[0124] Referring to Table 1 to Table 3, for the steel materials of Test Nos. 1 to 42, the chemical composition was appropriate and Fn1 was 30.0 or more. In addition, the production method was the preferred production method described in the present description. As a result, the volume ratio of ferrite was 30.0 to 70.0%, and the number density of fine Cu precipitates in austenite was 150 to 1500 / μm^3 . Consequently, the yield strength was 586 MPa or more, the CPT was more than 15°C, and the absorbed energy per unit area at -10°C was 60.0 J/cm² or more. That is, the steel material of each of Test Nos. 1 to 42 had a yield strength of 586 MPa or more, excellent low-temperature toughness, and excellent pitting resistance.

[0125] On the other hand, for the steel material of Test No. 43, the heat treatment temperature was too low. Consequently, the number density of fine Cu precipitates in austenite was more than 1500 / μm^3 . As a result, the absorbed energy per unit area at -10°C was less than 60.0 J/cm². That is, the steel material of Test No. 43 did not have excellent low-temperature toughness.

[0126] For the steel material of Test No. 44, the maintaining temperature was too high. In addition, for the steel material of Test No. 44, the rapid cooling start temperature was too high. Consequently, the number density of fine Cu precipitates in austenite was less than 150 / μm^3 . As a result, the yield strength was less than 586 MPa. That is, the steel material of Test No. 44 did not have a yield strength of 586 MPa or more.

[0127] For the steel material of Test No. 45, the maintaining process was not performed. In addition, for the steel material of Test No. 45, the rapid cooling start temperature was too high. Consequently, the number density of fine Cu precipitates in austenite was less than 150 / μm^3 . As a result, the yield strength was less than 586 MPa. That is, the steel material of Test No. 45 did not have a yield strength of 586 MPa or more.

[0128] For the steel materials of Test Nos. 46 and 47, the maintaining time was too short. Consequently, the number density of fine Cu precipitates in austenite was less than 150 / μm^3 . As a result, the yield strength was less than 586 MPa. That is, the steel materials of Test Nos. 46 and 47 did not have a yield strength of 586 MPa or more.

[0129] For the steel material of Test No. 48, the rapid cooling start temperature was too low. Consequently, the number density of fine Cu precipitates in austenite was more than 1500 / μm^3 . As a result, the absorbed energy per unit area at -10°C was less than 60.0 J/cm². That is, the steel material of Test No. 48 did not have excellent low-temperature toughness.

[0130] In the steel material of Test No. 49, Fn1 was less than 30.0. As a result, the CPT was 15°C. That is, the steel material of Test No. 49 did not have excellent pitting resistance.

[0131] In the steel material of Test No. 50, the content of Cr was too low. Consequently, the volume ratio of ferrite was less than 30.0%. As a result, the yield strength was less than 586 MPa. That is, the steel material of Test No. 50 did not have a yield strength of 586 MPa or more.

[0132] In the steel material of Test No. 51, the content of Cu was too low. Consequently, the number density of fine Cu precipitates in austenite was less than 150 / μm^3 . As a result, the yield strength was less than 586 MPa. That is, the steel material of Test No. 51 did not have a yield strength of 586 MPa or more.

[0133] 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 not departing from the technical spirit thereof.

[0134] Note that, the gist of the duplex stainless steel material according to the present embodiment can also be described as follows.

[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: 0.020% 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: 1.50 to 4.00%,
N: 0.150 to 0.350%, and
V: 0.01 to 1.50%,
with the balance being Fe and impurities,

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and satisfying Formula (1A),
wherein:

a microstructure consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite;
a yield strength is 586 MPa or more; and
in the austenite, a number density of Cu precipitates having a major axis of 50 nm or less is 150 to 1500 / μm^3 ;

$$\text{Cr} + 3.3\text{Mo} + 16\text{N} \geq 30.0 \quad (1A)$$

where, a content in percent by mass of a corresponding element is substituted for each symbol of an element in Formula (1A).

[2] A duplex stainless steel material containing, 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: 0.020% 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: 1.50 to 4.00%,
N: 0.150 to 0.350%, and
V: 0.01 to 1.50%,

and further containing one or more elements selected from a group consisting of:

Nb: 0.100% or less,
Ta: 0.100% or less,
Ti: 0.100% or less,
Zr: 0.100% or less,
Hf: 0.100% or less,
W: 0.200% or less,
Co: 0.500% or less,
Sn: 0.100% or less,
Sb: 0.100% or less,
Ca: 0.020% or less,
Mg: 0.020% or less,
B: 0.020% or less, and
rare earth metal: 0.200% or less,
with the balance being Fe and impurities,
and satisfying Formula (1B),
wherein:

a microstructure consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite;
a yield strength is 586 MPa or more; and
in the austenite, a number density of Cu precipitates having a major axis of 50 nm or less is 150 to 1500 / μm^3 ;

$$\text{Cr} + 3.3(\text{Mo} + 0.5\text{W}) + 16\text{N} \geq 30.0 \quad (1B)$$

where, a content in percent by mass of a corresponding element is substituted for each symbol of an element in Formula (1B), and if a corresponding element is not contained, "0" is substituted for the

symbol of the corresponding element.

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

Nb: 0.100% or less,
Ta: 0.100% or less,
Ti: 0.100% or less,
Zr: 0.100% or less,
Hf: 0.100% or less, and
W: 0.200% or less.

[4] The duplex stainless steel material according to [2] or [3], containing one or more elements selected from a group consisting of:

Co: 0.500% or less,
Sn: 0.100% or less, and
Sb: 0.100% or less.

[5] The duplex stainless steel material according to any one of [2] to [4], containing one or more elements selected from a group consisting of:

Ca: 0.020% or less,
Mg: 0.020% or less,
B: 0.020% or less, and
rare earth metal: 0.200% or less.

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: 0.020% 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: 1.50 to 4.00%,
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,

and satisfying Formula (1),
wherein:

a microstructure consists of, in volume ratio, ferrite in an amount of 30.0 to 70.0% with the balance being austenite;
a yield strength is 586 MPa or more; and
in the austenite, a number density of Cu precipitates having a major axis of 50 nm or less is 150 to 1500 / μm^3 ;

$$\text{Cr} + 3.3(\text{Mo} + 0.5\text{W}) + 16\text{N} \geq 30.0 \quad (1)$$

where, a content in percent by mass of a corresponding element is substituted for each symbol of an element in Formula (1), and if a corresponding element is not contained, "0" is substituted for the symbol of the corresponding element.

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

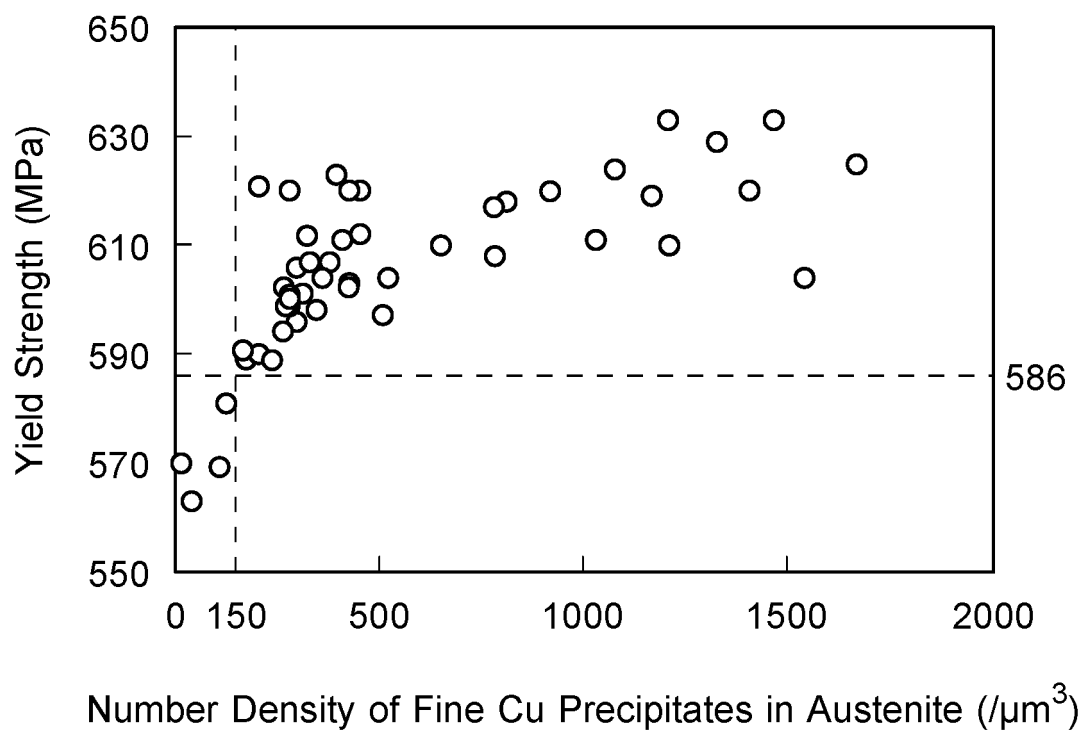
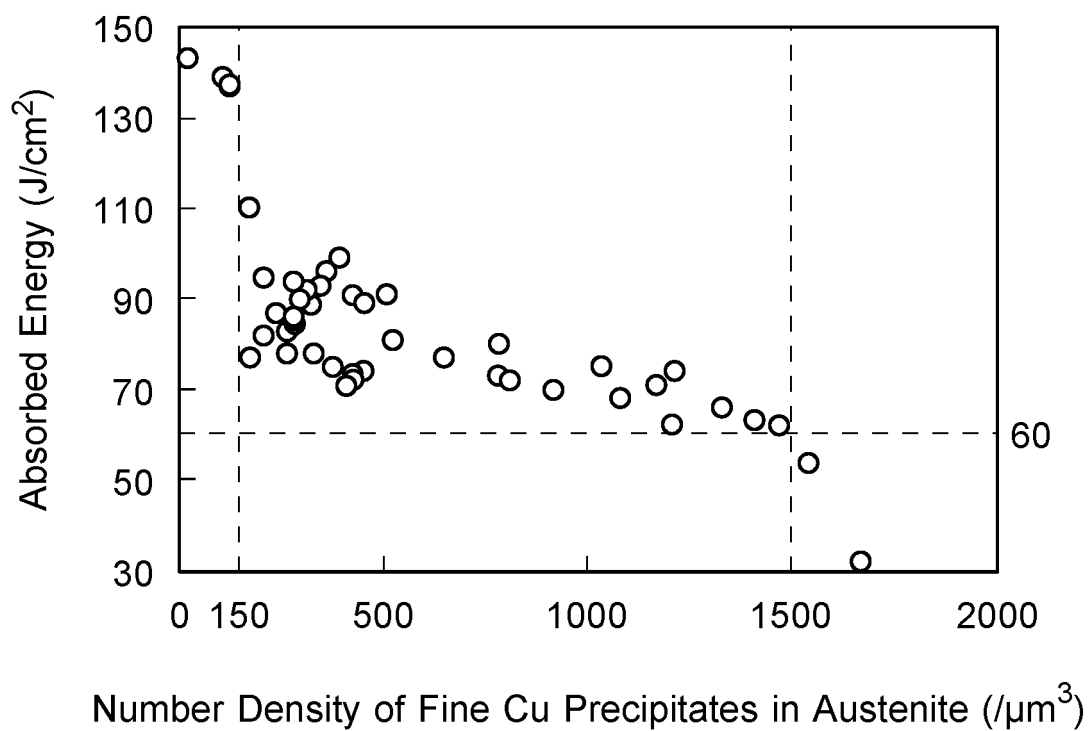


FIG. 2



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2022/035897

A. CLASSIFICATION OF SUBJECT MATTER

C21D 8/02(2006.01)i; *C21D 8/06*(2006.01)i; *C21D 8/10*(2006.01)i; *C21D 9/08*(2006.01)i; *C22C 38/00*(2006.01)i;
C22C 38/60(2006.01)i

FI: C22C38/00 302H; C22C38/60; C21D8/10 D; C21D8/02 D; C21D8/06 B; C21D9/08 E

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C38/00-38/60

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

Published examined utility model applications of Japan 1922-1996
 Published unexamined utility model applications of Japan 1971-2022
 Registered utility model specifications of Japan 1996-2022
 Published registered utility model applications of Japan 1994-2022

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2021/033672 A1 (NIPPON STEEL CORPORATION) 25 February 2021 (2021-02-25) entire text	1-2
A	WO 2020/218426 A1 (NIPPON STEEL CORPORATION) 29 October 2020 (2020-10-29) entire text	1-2
A	JP 2018-193591 A (NIPPON STEEL & SUMITOMO METAL CORP) 06 December 2018 (2018-12-06) entire text	1-2
P, A	JP 2021-167446 A (NIPPON STEEL CORPORATION) 21 October 2021 (2021-10-21) entire text	1-2
P, A	JP 2021-167445 A (NIPPON STEEL CORPORATION) 21 October 2021 (2021-10-21) entire text	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

“E” earlier application or patent but published on or after the international filing date

“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

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

“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&” document member of the same patent family

Date of the actual completion of the international search

18 November 2022

Date of mailing of the international search report

29 November 2022

Name and mailing address of the ISA/JP

Japan Patent Office (ISA/JP)
 3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915
 Japan

Authorized officer

Telephone No.

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Information on patent family members

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