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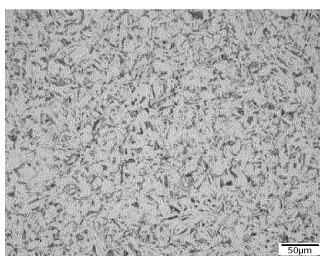
(54) **STEEL MATERIAL USED AS MATERIAL FOR FASTENING MEMBER, AND FASTENING MEMBER**

(57) A steel material having excellent corrosion resistance and hydrogen embrittlement resistance is provided. A steel material according to present disclosure consists of, in mass%, C: 0.15 to 0.45%, Si: 0.01 to 1.00%, Mn: 0.01 to 1.50%, P: 0.050% or less, S: 0.050% or less, Al: 0.100% or less, Sn: 0.02 to 0.30%, Cr: 0.20% or less, Cu: 0.010 to 0.500%, Ni: 0.01 to 0.50%, Mo: 0.01 to 0.50%, Ti: 0.001 to 0.100%, one or more kind of elements selected from a group consisting of Co, Sb, Ge, and In: 0.0013 to less than 0.0065% in total, N: 0.010% or less, O: 0.015% or less, and the balance: Fe and impurities, and satisfies Formula (1).

$$\begin{aligned} &23 < 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) \\ &+ 10 < 39 \end{aligned} \quad (1)$$

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FIG.1



Description

TECHNICAL FIELD

[0001] The present disclosure relates to a steel material and a fastening member, and more particularly relates to a steel material that is used as a starting material for a fastening member such as a bolt, a nut, or a washer, and a fastening member composed of the steel material.

BACKGROUND ART

[0002] A fastening member such as a bolt, a nut, or a washer is used for fastening in industrial machinery, automobiles, bridges, and architectural structures and the like. Among these uses, bridges or architectural structures or the like are sometimes built in coastal regions. Coastal regions are corrosive environments in which there is a large amount of chloride ions. Therefore, even if the aforementioned fastening members are coated with paint or the like, in some cases the paint or the like peels off and corrosion progresses. Accordingly, fastening members used in the aforementioned corrosive environments containing chloride ions are required to have excellent corrosion resistance.

[0003] In addition, hydrogen embrittlement is likely to occur in a corrosive environment containing chloride ions. Therefore, fastening members used in corrosive environments containing chloride ions are required to also have excellent hydrogen embrittlement resistance, and not just excellent corrosion resistance.

[0004] Technology relating to improving corrosion resistance is proposed in Japanese Patent Application Publication No. 2020-180325 (Patent Literature 1) and Japanese Patent Application Publication No. 2017-226878 (Patent Literature 2).

[0005] Patent Literature 1 discloses a steel material having a chemical composition consisting of, in mass%, C: 0.15% or more to 0.25% or less, Si: 0.05% or more to 0.30% or less, Mn: 0.50% or more to 1.80% or less, P: 0.002% or more to 0.030% or less, S: 0.0005% or more to 0.0200% or less, Al: 0.010% or more to 0.065% or less, Cu: 0.01% or more to 0.48% or less, Nb: 0.005% or more to 0.030% or less, Sn: 0.005% or more to 0.200% or less, Ti: 0.005% or more to 0.200% or less, B: 0.0001% or more to 0.0050% or less, N: 0.0020% or more to 0.0100% or less, and O: 0.0025% or less, with the balance being Fe and unavoidable impurities. Patent Literature 1 describes that the corrosion resistance of the steel material in a corrosive environment is increased by containing Cu, Nb, and Sn.

[0006] Patent Literature 2 discloses a steel material having a chemical composition consisting of, in mass%, C: 0.15% or more to less than 0.30%, Si: 0.05% or more to 1.00% or less, Mn: 0.20% or more to 2.00% or less, P: 0.001% or more to 0.030% or less, S: 0.0001% or more to 0.0100% or less, Al: 0.010% or more to 0.100% or less, Cu: 0.010% or more to 1.000% or less, Nb: 0.005% or more to 0.200% or less, Sn: 0.005% or more to 0.200% or less, and N: 0.0010% or more to 0.0100% or less, with the balance being Fe and unavoidable impurities. Patent Literature 2 describes that the corrosion resistance of the steel material in a corrosive environment is increased by containing Cu, Nb, Sn, and Ni.

CITATION LIST

PATENT LITERATURE

[0007]

Patent Literature 1: Japanese Patent Application Publication No. 2020-180325

Patent Literature 2: Japanese Patent Application Publication No. 2017-226878

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0008] However, corrosion resistance and hydrogen embrittlement resistance may also be increased by means that is different from the means employed in the steel materials disclosed in Patent Literature 1 and Patent Literature 2.

[0009] An objective of the present disclosure is to provide a steel material and a fastening member that have excellent corrosion resistance and excellent hydrogen embrittlement resistance.

SOLUTION TO PROBLEM

[0010] A steel material according to the present disclosure is as follows.

[0011] A steel material consisting of, in mass%,

C: 0.15 to 0.45%,
 Si: 0.01 to 1.00%,
 Mn: 0.01 to 1.50%,
 P: 0.050% or less,
 S: 0.050% or less,
 Al: 0.100% or less,
 Sn: 0.02 to 0.30%,
 Cr: 0.20% or less,
 Cu: 0.010 to 0.500%,
 Ni: 0.01 to 0.50%,
 Mo: 0.01 to 0.50%,
 Ti: 0.001 to 0.100%,
 one or more kind of elements selected from a group consisting of Co, Sb, Ge, and In: 0.0013 to less than 0.0065% in total,
 N: 0.010% or less,
 O: 0.015% or less,
 W: 0 to 0.50%,
 B: 0 to 0.0050%,
 Nb: 0 to 0.300%,
 Ca: 0 to 0.0050%,
 Mg: 0 to 0.0050%,
 rare earth metal: 0 to 0.0200%, and
 the balance: Fe and impurities; and
 satisfying Formula (1);

$$23 < 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10 < 39 \quad (1)$$

where, a content in mass of a corresponding element is substituted for each symbol of an element in Formula (1), and a total content in mass of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is substituted for Tx. LN in Formula (1) means "natural logarithm".

[0012] A fastening member according to the present disclosure is composed of the steel material described above.

ADVANTAGEOUS EFFECTS OF INVENTION

[0013] A steel material and a fastening member according to the present disclosure have excellent corrosion resistance and excellent hydrogen embrittlement resistance.

BRIEF DESCRIPTION OF DRAWINGS

[0014]

[FIG. 1] FIG. 1 is an example of a photographic image of the microstructure of the steel material of the present embodiment.

[FIG. 2] FIG. 2 is a schematic diagram of one example of a graph illustrating the relation between an amount of hydrogen penetration and a rupture load obtained by an SSRT test performed under hydrogen charging.

DESCRIPTION OF EMBODIMENTS

[0015] The present inventors carried out studies and investigations regarding a steel material having excellent corrosion resistance and excellent hydrogen embrittlement resistance. As a result, the present inventors obtained the following findings.

[0016] In order to increase the corrosion resistance and hydrogen embrittlement resistance of a steel material, it is effective to decrease the content of Cr in the steel material as much as possible. In addition, Cu, Ni, and Sn markedly increase the corrosion resistance of a steel material. Based on studies from the viewpoint of the chemical composition described above, the present inventors conducted a study regarding the chemical composition of a steel material that has

excellent corrosion resistance and excellent hydrogen embrittlement resistance. As a result, the present inventors considered that if a steel material has a chemical composition consisting of, in mass%, C: 0.15 to 0.45%, Si: 0.01 to 1.00%, Mn: 0.01 to 1.50%, P: 0.050% or less, S: 0.050% or less, Al: 0.100% or less, Sn: 0.02 to 0.30%, Cr: 0.20% or less, Cu: 0.010 to 0.500%, Ni: 0.01 to 0.50%, Mo: 0.01 to 0.50%, Ti: 0.001 to 0.100%, N: 0.010% or less, O: 0.015% or less, W: 0 to 0.50%, B: 0 to 0.0050%, Nb: 0 to 0.300%, Ca: 0 to 0.0050%, Mg: 0 to 0.0050%, rare earth metal: 0 to 0.0200%, and the balance: Fe and impurities, the corrosion resistance and the hydrogen embrittlement resistance will be increased even in a corrosive environment containing chloride ions.

[0017] However, even when steel materials had the chemical composition described above, there were cases where sufficient corrosion resistance and sufficient hydrogen embrittlement resistance were not obtained in a corrosive environment containing chloride ions. Therefore, the present inventors conducted studies and investigations regarding the reason why the corrosion resistance and hydrogen embrittlement resistance of a steel material having the aforementioned chemical composition decreased. As a result, the present inventors have considered that, in a corrosive environment containing chloride ions, corrosion progresses due to the following mechanism.

[0018] In a case where a fastening member such as a bolt, a nut, or a washer is used in an architectural structure such as a bridge in a coastal region, as mentioned above, chloride ions fly through the air and land on the surface of the steel material constituting the fastening member. In addition, water containing chloride ions that comes flying in due to fog or rainfall or the like adheres to the surface of the steel material. As a result, a state is entered in which the steel material surface becomes wet (wetting process), and thereafter a state is entered in which the water containing chloride ions dries off from the steel material surface (drying process).

[0019] Under such an environment, dissolution of Fe on the steel material surface is promoted, in particular, in the drying process. The dissolved Fe makes the steel material surface an acidic environment. That is, the pH at the steel material surface decreases as the dissolution of Fe progresses. The lower the pH becomes, the greater the degree to which dissolution of Fe progresses. In other words, corrosion progresses.

[0020] Based on the results of the above studies, the present inventors have considered that if a decrease in pH at the steel material surface can be suppressed, dissolution of Fe can be suppressed. Therefore, the present inventors conducted investigations regarding elements which are capable of suppressing a decrease in pH in the acidic range of pH 0 to 7. As a result, the present inventors have discovered that if any one or more kind of elements among Co, Sb, Ge, and In is contained in addition to the aforementioned Cu, Ni, and Sn, a decrease in pH can be suppressed over a wide range within the acidic range, and as a result the dissolution of Fe can be suppressed in the drying process.

[0021] The present inventors conducted further studies regarding the chemical composition of the steel material taking into consideration the results of the above investigations. As a result, the present inventors have discovered that if the chemical composition described above further contains one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In within a range of 0.0013 to less than 0.0065% in total, corrosion resistance and hydrogen embrittlement resistance are further increased in a corrosive environment containing chloride ions. In other words, the present inventors have discovered that, by the steel material satisfying the following Feature 1, corrosion resistance and hydrogen embrittlement resistance are further increased in a corrosive environment containing chloride ions.

(Feature 1)

[0022] The chemical composition consists of, in mass%, C: 0.15 to 0.45%, Si: 0.01 to 1.00%, Mn: 0.01 to 1.50%, P: 0.050% or less, S: 0.050% or less, Al: 0.100% or less, Sn: 0.02 to 0.30%, Cr: 0.20% or less, Cu: 0.010 to 0.500%, Ni: 0.01 to 0.50%, Mo: 0.01 to 0.50%, Ti: 0.001 to 0.100%, one or more kind of elements selected from a group consisting of Co, Sb, Ge, and In: 0.0013 to less than 0.0065% in total, N: 0.010% or less, O: 0.015% or less, W: 0 to 0.50%, B: 0 to 0.0050%, Nb: 0 to 0.300%, Ca: 0 to 0.0050%, Mg: 0 to 0.0050%, rare earth metal: 0 to 0.0200%, and the balance: Fe and impurities.

[0023] However, in a steel material having the above chemical composition, it was not possible to sufficiently obtain both excellent corrosion resistance and excellent hydrogen embrittlement resistance in a corrosive environment containing chloride ions. Therefore, the present inventors carried out further studies regarding means for obtaining excellent corrosion resistance and excellent hydrogen embrittlement resistance in a steel material having the above chemical composition.

[0024] As a result of such studies, the present inventors have discovered that in a steel material that satisfies the aforementioned Feature 1, when the steel material also satisfies the following Feature 2, excellent corrosion resistance and excellent hydrogen embrittlement resistance are obtained.

(Feature 2)

[0025] The chemical composition of the steel material also satisfies Formula (1):

$$23 < 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo})$$

$$+10 < 39 \quad (1)$$

where, a content in mass of a corresponding element is substituted for each symbol of an element in Formula (1), and a total content in mass of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is substituted for Tx. LN in Formula (1) means "natural logarithm".

[0026] Let F1 be defined as $F1 = 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10$. Among the elements in the chemical composition satisfying Feature 1, the elements Cu, Sn, Co, Sb, Ge, and In are elements which, in an environment containing chloride ions, increase corrosion resistance and also suppress the generation of hydrogen caused by a reduction reaction due to corrosion. When the generation of hydrogen is suppressed, the amount of hydrogen that comes into contact with the steel material surface decreases. Therefore, the amount of hydrogen penetrating into the steel material from the steel material surface also decreases. As a result, the hydrogen embrittlement resistance increases. Thus, Cu, Sn, Co, Sb, Ge, and In are a group of elements which increase corrosion resistance and also suppress the generation of hydrogen and increase hydrogen embrittlement resistance.

[0027] On the other hand, among the elements in the chemical composition satisfying Feature 1, Ni and Mo are elements which, depending on their contents, either increase or decrease the corrosion resistance and hydrogen embrittlement resistance by a synergistic action with Sn in the chemical composition satisfying Feature 1. Specifically, in the chemical composition that satisfies Feature 1, although the corrosion resistance and hydrogen embrittlement resistance increase when the contents of Ni and Mo are within a certain range, on the other hand, the corrosion resistance and hydrogen embrittlement resistance decrease when the contents of Ni and Mo are within a range that is different to the aforementioned certain range. It is considered that such an increase or decrease in the corrosion resistance and hydrogen embrittlement resistance caused by Ni and Mo is influenced by a synergistic action between Ni and Mo and Sn. In F1, " $100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10$ " is a cubic polynomial. This cubic polynomial shows the relation between the contents of Ni and Mo and the corrosion resistance and hydrogen embrittlement resistance in a chemical composition satisfying Feature 1 that contains Sn.

[0028] When F1 is more than 23 and less than 39, in a chemical composition satisfying Feature 1, the relation between the contents of Cu, Sn, Co, Sb, Ge, and In and the contents of Ni and Mo is appropriate. Therefore, in a corrosive environment containing chloride ions, excellent corrosion resistance and excellent hydrogen embrittlement resistance can both be achieved.

[0029] A steel material according to the present embodiment, which has been completed based on the above findings, is as follows.

[1] A steel material consisting of, in mass%,

C: 0.15 to 0.45%,
 Si: 0.01 to 1.00%,
 Mn: 0.01 to 1.50%,
 P: 0.050% or less,
 S: 0.050% or less,
 Al: 0.100% or less,
 Sn: 0.02 to 0.30%,
 Cr: 0.20% or less,
 Cu: 0.010 to 0.500%,
 Ni: 0.01 to 0.50%,
 Mo: 0.01 to 0.50%,
 Ti: 0.001 to 0.100%,
 one or more kind of elements selected from a group consisting of Co, Sb, Ge, and In: 0.0013 to less than 0.0065% in total,
 N: 0.010% or less,
 O: 0.015% or less,
 W: 0 to 0.50%,
 B: 0 to 0.0050%,
 Nb: 0 to 0.300%,
 Ca: 0 to 0.0050%,
 Mg: 0 to 0.0050%, rare earth metal: 0 to 0.0200%, and
 the balance: Fe and impurities; and
 satisfying Formula (1);

$$23 < 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2$$

$$+30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10 < 39 \quad (1)$$

where, a content in mass of a corresponding element is substituted for each symbol of an element in Formula (1), and a total content in mass of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is substituted for Tx. LN in Formula (1) means "natural logarithm".

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

W: 0.01 to 0.50%,
B: 0.0001 to 0.0050%,
Nb: 0.001 to 0.300%,
Ca: 0.0001 to 0.0050%,
Mg: 0.0001 to 0.0050%, and
rare earth metal: 0.0001 to 0.0200%.

[3] A fastening member composed of the steel material according to [1] or [2].

[0030] Hereunder, the steel material and fastening member according to the present embodiment are described in detail. Note that, the symbol "%" in relation to elements means "mass percent" unless specifically stated otherwise.

[Features of steel material of present embodiment]

[0031] The steel material of the present embodiment satisfies the following Features 1 and 2.

(Feature 1)

[0032] The chemical composition consists of, in mass%, C: 0.15 to 0.45%, Si: 0.01 to 1.00%, Mn: 0.01 to 1.50%, P: 0.050% or less, S: 0.050% or less, Al: 0.100% or less, Sn: 0.02 to 0.30%, Cr: 0.20% or less, Cu: 0.010 to 0.500%, Ni: 0.01 to 0.50%, Mo: 0.01 to 0.50%, Ti: 0.001 to 0.100%, one or more kind of elements selected from a group consisting of Co, Sb, Ge, and In: 0.0013 to less than 0.0065% in total, N: 0.010% or less, O: 0.015% or less, W: 0 to 0.50%, B: 0 to 0.0050%, Nb: 0 to 0.300%, Ca: 0 to 0.0050%, Mg: 0 to 0.0050%, rare earth metal: 0 to 0.0200%, and the balance: Fe and impurities.

(Feature 2)

[0033] The chemical composition of the steel material also satisfies Formula (1):

$$23 < 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10 < 39 \quad (1)$$

where, a content in mass of a corresponding element is substituted for each symbol of an element in Formula (1), and a total content in mass of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is substituted for Tx. LN in Formula (1) means "natural logarithm".

[0034] Hereunder, Feature 1 and Feature 2 are described.

[(Feature 1) Regarding content of each element in chemical composition]

[0035] The chemical composition of the steel material according to the present embodiment contains the following elements.

C: 0.15 to 0.45%

[0036] Carbon (C) increases hardenability of the steel material and increases the strength of the fastening member composed of the steel material. If the content of C is less than 0.15%, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment.

[0037] On the other hand, if the content of C is more than 0.45%, even if the contents of other elements are within the range of the present embodiment, the cold forgeability of the steel material will decrease.

[0038] Therefore, the content of C is 0.15 to 0.45%.

[0039] A preferable lower limit of the content of C is 0.18%, more preferably is 0.20%, and further preferably is 0.22%.

[0040] A preferable upper limit of the content of C is 0.43%, more preferably is 0.41%, and further preferably is 0.39%.

Si: 0.01 to 1.00%

5 **[0041]** Silicon (Si) increases the strength of the fastening member composed of the steel material by solid-solution strengthening. If the content of Si is less than 0.01%, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment.

[0042] On the other hand, if the content of Si is more than 1.00%, even if the contents of other elements are within the range of the present embodiment, the cold forgeability of the steel material will decrease.

10 **[0043]** Therefore, the content of Si is 0.01 to 1.00%.

[0044] A preferable lower limit of the content of Si is 0.02%, more preferably is 0.03%, and further preferably is 0.05%.

[0045] A preferable upper limit of the content of Si is 0.90%, more preferably is 0.80%, further preferably is 0.70%, further preferably is 0.60%, and further preferably is 0.50%.

15 Mn: 0.01 to 1.50%

[0046] Manganese (Mn) increases hardenability of the steel material and increases the strength of the fastening member composed of the steel material. If the content of Mn is less than 0.01%, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment.

20 **[0047]** On the other hand, if the content of Mn is more than 1.50%, the cold forgeability of the steel material will decrease even if the contents of other elements are within the range of the present embodiment.

[0048] Therefore, the content of Mn is 0.01 to 1.50%.

[0049] A preferable lower limit of the content of Mn is 0.05%, more preferably is 0.10%, and further preferably is 0.15%.

[0050] A preferable upper limit of the content of Mn is 1.40%, more preferably is 1.30%, and further preferably is 1.20%.

25 P: 0.050% or less

[0051] Phosphorus (P) is an impurity. That is, the lower limit of the content of P is more than 0%.

30 **[0052]** If the content of P is more than 0.050%, P will segregate to grain boundaries even if the contents of other elements are within the range of the present embodiment. As a result, the hydrogen embrittlement resistance of the steel material will decrease.

[0053] Therefore, the content of P is 0.050% or less.

[0054] 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 production is taken into consideration, a preferable lower limit of the content of P is 0.001%, more preferably is 0.002%, and further preferably is 0.003%.

35 **[0055]** A preferable upper limit of the content of P is 0.040%, more preferably is 0.030%, and further preferably is 0.020%.

S: 0.050% or less

40 **[0056]** Sulfur (S) is an impurity. That is, the lower limit of the content of S is more than 0%.

[0057] If the content of S is more than 0.050%, S will segregate to grain boundaries even if the contents of other elements are within the range of the present embodiment. As a result, the hydrogen embrittlement resistance of the steel material will decrease.

45 **[0058]** Therefore, the content of S is 0.050% or less.

[0059] 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 production is taken into consideration, a preferable lower limit of the content of S is 0.001%, more preferably is 0.002%, and further preferably is 0.003%.

50 **[0060]** A preferable upper limit of the content of S is 0.040%, more preferably is 0.030%, and further preferably is 0.020%.

Al: 0.100% or less

[0061] Aluminum (Al) is unavoidably contained. That is, the content of Al is more than 0%.

55 **[0062]** Al deoxidizes the steel. If the chemical composition includes even a small content of Al, the aforementioned advantageous effect will be obtained to a certain extent.

[0063] However, if the content of Al is more than 0.100%, even if the contents of other elements are within the range of the present embodiment, coarse Al nitrides will form. The coarse Al nitrides will act as starting points for fractures.

Consequently, the workability of the steel material will decrease.

[0064] Therefore, the content of Al is 0.100% or less.

[0065] A preferable lower limit of the content of Al is 0.001%, more preferably is 0.010%, and further preferably is 0.015%.

5 **[0066]** A preferable upper limit of the content of Al is 0.090%, more preferably is 0.080%, and further preferably is 0.070%.

[0067] In the chemical composition of the steel material of the present embodiment, the content of Al means the total Al content.

10 Sn: 0.02 to 0.30%

[0068] Tin (Sn) increases the corrosion resistance and hydrogen embrittlement resistance of the steel material in a corrosive environment. If the content of Sn is less than 0.02%, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment.

15 **[0069]** On the other hand, if the content of Sn is more than 0.30%, Sn will segregate to grain boundaries even if the contents of other elements are within the range of the present embodiment. In such case, the hot workability of the steel material will decrease.

[0070] Therefore, the content of Sn is 0.02 to 0.30%.

[0071] A preferable lower limit of the content of Sn is 0.03%, more preferably is 0.05%, and further preferably is 0.10%.

20 **[0072]** A preferable upper limit of the content of Sn is 0.25%, more preferably is 0.20%, further preferably is 0.15%, and further preferably is 0.10%.

Cr: 0.20% or less

25 **[0073]** In the steel material of the present embodiment, the content of Cr is more than 0%. Cr increases hardenability of the steel material. Cr decreases the corrosion resistance and hydrogen embrittlement resistance of the steel material in a corrosive environment. If the content of Cr is more than 0.20%, the corrosion resistance and hydrogen embrittlement resistance of the steel material will decrease even if the contents of other elements are within the range of the present embodiment.

30 **[0074]** Therefore, the content of Cr is 0.20% or less.

[0075] The content of Cr is preferably as low as possible. However, extremely reducing the content of Cr will significantly increase the production cost. Therefore, when industrial production is taken into consideration, a preferable lower limit of the content of Cr is 0.01%, more preferably is 0.02%, and further preferably is 0.03%.

35 **[0076]** A preferable upper limit of the content of Cr is 0.15%, more preferably is 0.10%, and further preferably is 0.07%. A preferable upper limit of a more effective content of Cr for further increasing the corrosion resistance and hydrogen embrittlement resistance of the steel material is less than 0.05%.

Cu: 0.010 to 0.500%

40 **[0077]** Copper (Cu) increases the corrosion resistance and hydrogen embrittlement resistance of the steel material in a corrosive environment. If the content of Cu is less than 0.010%, the aforementioned advantageous effect will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment.

[0078] On the other hand, if the content of Cu is more than 0.500%, the steel material will be susceptible to red shortness. In addition, the corrosion resistance and hydrogen embrittlement resistance of the steel material will, on the contrary, decrease.

45 **[0079]** Therefore, the content of Cu is 0.010 to 0.500%.

[0080] A preferable lower limit of the content of Cu is 0.050%, more preferably is 0.100%, further preferably is 0.150%, further preferably is 0.200%, and further preferably is 0.250%.

50 **[0081]** A preferable upper limit of the content of Cu is 0.450%, and more preferably is 0.400%.

Ni: 0.01 to 0.50%

55 **[0082]** Nickel (Ni) increases hardenability of the steel material and increases the strength of the fastening member composed of the steel material. Ni also increases the corrosion resistance and hydrogen embrittlement resistance of the steel material. If the content of Ni is less than 0.01%, the aforementioned advantageous effects will not be sufficiently obtained even if the contents of other elements are within the range of the present embodiment.

[0083] On the other hand, if the content of Ni is more than 0.50%, the corrosion resistance and hydrogen embrittlement resistance of the steel material will, on the contrary, decrease.

[0084] Therefore, the content of Ni is 0.01 to 0.50%.

[0085] A preferable lower limit of the content of Ni is 0.05%, more preferably is 0.10%, further preferably is 0.15%, further preferably is 0.20%, and further preferably is 0.25%.

[0086] A preferable upper limit of the content of Ni is 0.45%, and more preferably is 0.40%.

Mo: 0.01 to 0.50%

[0087] Molybdenum (Mo) increases hardenability of the steel, and increases the strength of the fastening member composed of the steel material. Fastening members for civil engineering and architectural applications may sometimes have a diameter of more than 20 mm. In order to increase the strength of such thick fastening members, it is necessary to increase the hardenability of the steel material that serves as the starting material of the fastening member. Mo is an element that easily increases the hardenability of the steel material.

[0088] On the other hand, if the content of Mo is more than 0.50%, the corrosion resistance and hydrogen embrittlement resistance of the steel material will decrease even if the contents of other elements are within the range of the present embodiment.

[0089] Therefore, the content of Mo is 0.01 to 0.50%.

[0090] A preferable lower limit of the content of Mo is 0.05%, more preferably is 0.10%, further preferably is 0.15%, and further preferably is 0.20%.

[0091] A preferable upper limit of the content of Mo is 0.45%, more preferably is 0.40%, and further preferably is 0.35%.

Ti: 0.001 to 0.100%

[0092] Titanium (Ti) combines with N to form Ti nitrides, and thereby increases the strength of the fastening member composed of the steel material. If the content of Ti is less than 0.001%, the aforementioned advantageous effect will not be sufficiently obtained.

[0093] On the other hand, if the content of Ti is more than 0.100%, even if the contents of other elements are within the range of the present embodiment, an excessively large amount of Ti precipitates such as carbides and carbo-nitrides will form. In such case, the corrosion resistance and hydrogen embrittlement resistance of the steel material will decrease.

[0094] Therefore, the content of Ti is 0.001 to 0.100%.

[0095] A preferable lower limit of the content of Ti is 0.005%, more preferably is 0.010%, further preferably is 0.015%, and further preferably is 0.018%.

[0096] A preferable upper limit of the content of Ti is 0.080%, more preferably is 0.060%, further preferably is 0.040%, and further preferably is 0.030%.

[0097] One or more kind of elements selected from the group consisting of Co, Sb, Ge, and In: 0.0013 to less than 0.0065% in total

[0098] Cobalt (Co), antimony (Sb), germanium (Ge), and indium (In) each suppress dissolution of Fe in the steel material in an acidic environment. More specifically, these elements dissolve preferentially over Fe in an acidic environment. These dissolved elements adhere to the steel material surface as oxides or metals. Thus, dissolution of Fe in the steel material is suppressed. As a result, the corrosion resistance and hydrogen embrittlement resistance of the steel material increase. If the total content of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is less than 0.0013%, the aforementioned advantageous effect will not be sufficiently obtained.

[0099] On the other hand, if the total content of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is 0.0065% or more, the corrosion resistance and hydrogen embrittlement resistance of the steel material will, on the contrary, decrease.

[0100] Therefore, the total content of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is 0.0013 to less than 0.0065%.

[0101] A preferable lower limit of the total content of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is 0.0015%, more preferably is 0.0017%, further preferably is 0.0020%, and further preferably is 0.0022%.

[0102] A preferable upper limit of the total content of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is 0.0063%, more preferably is 0.0061%, further preferably is 0.0059%, and further preferably is 0.0057%.

N: 0.010% or less

[0103] Nitrogen (N) is unavoidably contained. That is, the content of N is more than 0%.

[0104] N combines with Al or Ti to form nitrides or carbo-nitrides. These nitrides and carbo-nitrides suppress coarsening of grains by a pinning effect. As a result, the cold forgeability of the steel material increases.

[0105] However, if the content of N is more than 0.010%, coarse nitrides will form even if the contents of other elements are within the range of the present embodiment. The coarse nitrides will act as starting points for fractures and will reduce the cold forgeability of the steel material. In addition, the hydrogen embrittlement resistance of the bolt will decrease.

[0106] Therefore, the content of N is 0.010% or less.

[0107] A preferable lower limit of the content of N is 0.001%, more preferably is 0.002%, and further preferably is 0.003%.

[0108] A preferable upper limit of the content of N is 0.009%, more preferably is 0.008%, further preferably is 0.007%, and further preferably is 0.006%.

O: 0.015% or less

[0109] Oxygen (O) is an impurity that is unavoidably contained. That is, the content of O is more than 0%.

[0110] O forms oxides in the steel material. If the content of O is more than 0.015%, coarse oxides will reduce the hydrogen embrittlement resistance of the bolt even if the contents of other elements are within the range of the present embodiment.

[0111] Therefore, the content of O is 0.015% or less.

[0112] A preferable lower limit of the content of O is 0.001%, more preferably is 0.002%, further preferably is 0.003%, and further preferably is 0.004%.

[0113] A preferable upper limit of the content of O is 0.013%, more preferably is 0.011%, and further preferably is 0.009%.

[0114] The balance of the chemical composition of the steel material according to the present embodiment is Fe and impurities. Here, the term "impurities" in the chemical composition means substances which are mixed in from ore and scrap used as the raw material or from the production environment or the like when industrially producing the steel material, and which are permitted within a range that does not adversely affect the steel material according to the present embodiment.

[Optional Elements]

[0115] The steel material of the present embodiment may further contain one or more elements selected from the following group of elements in lieu of a part of Fe.

W: 0 to 0.50%,

B: 0 to 0.0050%,

Nb: 0 to 0.300%,

Ca: 0 to 0.0050%,

Mg: 0 to 0.0050%, and

rare earth metal: 0 to 0.0200%.

[0116] These elements are described hereunder.

W: 0 to 0.50%

[0117] Tungsten (W) is an optional element, and does not have to be contained. That is, the content of W may be 0%. When contained, similarly to Co, Sb, Ge, and In, W suppresses dissolution of Fe in the steel material in a corrosive environment containing chloride ions. As a result, the corrosion resistance and hydrogen embrittlement resistance of the steel material increase. If even a small amount of W is contained, the aforementioned advantageous effect will be obtained to a certain extent.

[0118] However, if the content of W is more than 0.50%, even if the contents of other elements are within the range of the present embodiment, the corrosion resistance and hydrogen embrittlement resistance of the steel material will, on the contrary, decrease.

[0119] Therefore, the content of W is 0 to 0.50%.

[0120] A preferable lower limit of the content of W is 0.01%, more preferably is 0.03%, and further preferably is 0.05%.

[0121] A preferable upper limit of the content of W is 0.40%, more preferably is 0.35%, further preferably is 0.30%, and further preferably is 0.25%.

B: 0 to 0.0050%

[0122] 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 increases the hardenability of the steel material, and thus increases the strength of the fastening member

composed of the steel material. In the steel material of the present embodiment, in order to suppress penetration of hydrogen into the steel material in a corrosive environment, the content of Cr is suppressed. Together with Mo, B increases the hardenability of the steel material as a substitute for Cr, and thus increases the strength of the fastening member composed of the steel material. If even a small amount of B is contained, the aforementioned advantageous effect will be obtained to a certain extent.

[0123] However, if the content of B is more than 0.0050%, coarse B nitrides will form even if the contents of other elements are within the range of the present embodiment. The coarse B nitrides will act as starting points for fractures. As a result, the cold forgeability of the steel material will decrease.

[0124] Therefore, the content of B is 0 to 0.0050%.

[0125] A preferable lower limit of the content of B is 0.0001%, more preferably is 0.0005%, and further preferably is 0.0007%.

[0126] A preferable upper limit of the content of B is 0.0045%, more preferably is 0.0040%, further preferably is 0.0030%, and further preferably is 0.0025%.

Nb: 0 to 0.300%

[0127] 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 Nb precipitates such as carbides and carbo-nitrides. The Nb precipitates increase the strength of the fastening member composed of the steel material. If the chemical composition includes even a small content of Nb, the aforementioned advantageous effect will be obtained to a certain extent.

[0128] However, if the content of Nb is more than 0.300%, an excessively large amount of Nb precipitates will form even if the contents of other elements are within the range of the present embodiment. In such case, the amount of hydrogen penetration into the steel material will be large. As a result, the corrosion resistance and hydrogen embrittlement resistance of the steel material will decrease.

[0129] Therefore, the content of Nb is 0 to 0.300%.

[0130] A preferable lower limit of the content of Nb is 0.001%, more preferably is 0.003%, further preferably is 0.005%, further preferably is 0.010%, and further preferably is 0.020%.

[0131] A preferable upper limit of the content of Nb is 0.250%, more preferably is 0.200%, and further preferably is 0.150%.

Ca: 0 to 0.0050%

[0132] Calcium (Ca) is an optional element, and does not have to be contained. That is, the content of Ca may be 0%. When Ca is contained, that is, when the content of Ca is more than 0%, Ca refines MnS. Consequently, the corrosion resistance and hydrogen embrittlement resistance of the steel material increase. If even a small amount of Ca is contained, the aforementioned advantageous effect will be obtained to a certain extent.

[0133] However, if the content of Ca is more than 0.0050%, even if the contents of other elements are within the range of the present embodiment, coarse Ca oxides will form. In such case, the corrosion resistance and hydrogen embrittlement resistance of the steel material will decrease.

[0134] Therefore, the content of Ca is 0 to 0.0050%.

[0135] A preferable lower limit of the content of Ca is 0.0001%, more preferably is 0.0002%, and further preferably is 0.0005%.

[0136] A preferable upper limit of the content of Ca is 0.0040%, and more preferably is 0.0030%.

Mg: 0 to 0.0050%

[0137] Magnesium (Mg) is an optional element, and does not have to be contained. That is, the content of Mg may be 0%. When Mg is contained, that is, when the content of Mg is more than 0%, Mg refines MnS. Consequently, the corrosion resistance and hydrogen embrittlement resistance of the steel material increase. If even a small amount of Mg is contained, the aforementioned advantageous effect will be obtained to a certain extent.

[0138] However, if the content of Mg is more than 0.0050%, even if the contents of other elements are within the range of the present embodiment, coarse Mg oxides will form. In such case, the corrosion resistance and hydrogen embrittlement resistance of the steel material will decrease.

[0139] Therefore, the content of Mg is 0 to 0.0050%.

[0140] A preferable lower limit of the content of Mg is 0.0001%, more preferably is 0.0002%, and further preferably is 0.0005%.

[0141] A preferable upper limit of the content of Mg is 0.0040%, and more preferably is 0.0030%.

[0142] Rare earth metal (REM): 0 to 0.0200%

[0143] 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 REM is contained, that is, when the content of REM is more than 0%, REM refines MnS. Consequently, the corrosion resistance and hydrogen embrittlement resistance of the steel material increase. If even a small amount of REM is contained, the aforementioned advantageous effect will be obtained to a certain extent.

[0144] However, if the content of REM is more than 0.0200%, coarse oxides will form even if the contents of other elements are within the range of the present embodiment. In such case, the corrosion resistance and hydrogen embrittlement resistance of the steel material will decrease.

[0145] Therefore, the content of REM is 0 to 0.0200%.

[0146] A preferable lower limit of the content of REM is 0.0001%, more preferably is 0.0005%, further preferably is 0.0010%, further preferably is 0.0020%, and further preferably is 0.0050%.

[0147] A preferable upper limit of the content of REM is 0.0150%, and more preferably is 0.0100%.

[0148] In the present description the term "REM" means one or more elements selected from the group consisting of scandium (Sc) which is the element with atomic number 21, yttrium (Y) which is the element with atomic number 39, and the elements from lanthanum (La) with atomic number 57 to lutetium (Lu) with atomic number 71 that are lanthanoids. In the present description, the term "content of REM" means the total content of these elements.

[Method for measuring chemical composition of steel material]

[0149] The chemical composition of the steel material of the present embodiment can be measured by a well-known composition analysis method in accordance with JIS G0321: 2017. Specifically, a drill is used to collect a machined chip from a position at or more than a depth of 1 mm on the inner side from the surface of the steel material. The collected machined chip is dissolved in acid to obtain a liquid solution. The liquid solution is subjected to ICP-AES (Inductively Coupled Plasma Atomic Emission Spectrometry) to perform elementary analysis of the chemical composition. The content of C and the content of S are determined by a well-known high-frequency combustion method (combustion-infrared absorption method). The content of N and the content of O are determined using a well-known inert gas fusion-thermal conductivity method.

[0150] Note that, the content of each element is taken as a numerical value up to the least significant digit of the content of each element defined in the present embodiment that is obtained by rounding off a fraction of the measured numerical value based on the significant figures defined in the present embodiment. For example, the content of C in the steel material of the present embodiment is defined as a numerical value up to the second decimal place. Therefore, the content of C is taken as a numerical value up to the second decimal place that is obtained by rounding off the third decimal place of the measured numerical value.

[0151] Similarly, for the content of each element other than the content of C in the steel material of the present embodiment also, a value obtained by rounding off a fraction of the numerical value of the measured value up to the least significant digit defined in the present embodiment is taken as the content of the relevant element.

[0152] Note that, the term "rounding off" means rounding down if the fraction is less than 5, and rounding up if the fraction is 5 or more.

[(Feature 2) Regarding Formula (1)]

[0153] On the precondition that the content of each element is within the range of the present embodiment, the chemical composition of the steel material of the present embodiment also satisfies Formula (1):

$$23 < 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10 < 39 \quad (1)$$

where, a content in mass of a corresponding element is substituted for each symbol of an element in Formula (1), and a total content in mass of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is substituted for Tx. LN in Formula (1) means "natural logarithm". The term "natural logarithm" refers to a logarithm whose base is Napier's constant e.

[0154] Let F1 be defined as $F1 = 10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10$. F1 is an index of the corrosion resistance and hydrogen embrittlement resistance of the steel material.

[0155] Among the elements in the chemical composition satisfying Feature 1, the elements Cu, Sn, Co, Sb, Ge, and In are elements which, in an environment containing chloride ions, increase corrosion resistance and also suppress the generation of hydrogen due to a reduction reaction caused by corrosion. When generation of hydrogen is suppressed, the amount of hydrogen that comes into contact with the steel material surface decreases. Therefore, the amount of hydrogen penetrating into the steel material from the steel material surface also decreases. As a result, the hydrogen embrittlement

resistance increases. Thus, Cu, Sn, Co, Sb, Ge, and In are a group of elements that increase corrosion resistance, and also suppress generation of hydrogen and increase the hydrogen embrittlement resistance.

[0156] In addition, among the elements in the chemical composition satisfying Feature 1, Ni and Mo are elements which, depending on their contents, either increase or decrease the corrosion resistance and hydrogen embrittlement resistance by a synergistic action with Sn in the chemical composition satisfying Feature 1. Specifically, in the chemical composition that satisfies Feature 1, although the corrosion resistance and hydrogen embrittlement resistance increase when the contents of Ni and Mo are within a certain range, on the other hand, the corrosion resistance and hydrogen embrittlement resistance decrease when the contents of Ni and Mo are within a range that is different to the aforementioned certain range. It is considered that such an increase or decrease in the corrosion resistance and hydrogen embrittlement resistance caused by Ni and Mo is influenced by a synergistic action between Ni and Mo and Sn.

[0157] In F1, $100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2 + 30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10$ is a cubic polynomial. This cubic polynomial shows the relation between the contents of Ni and Mo and the corrosion resistance and hydrogen embrittlement resistance in a chemical composition satisfying Feature 1 that contains Sn.

[0158] When F1 is more than 23 and less than 39, in a chemical composition satisfying Feature 1, the relation between the contents of Cu, Sn, Co, Sb, Ge, and In and the contents of Ni and Mo is appropriate. Therefore, in a corrosive environment containing chloride ions, excellent corrosion resistance and excellent hydrogen embrittlement resistance can both be achieved.

[0159] Therefore, F1 is more than 23 and less than 39.

[0160] A preferable lower limit of F1 is 24, more preferably is 25, and further preferably is 26.

[0161] A preferable upper limit of F1 is 38, more preferably is 36, and further preferably is 34.

[0162] The F1 value is to be an integer. That is, the F1 value is a value obtained by rounding off the first decimal place of the determined value.

[Regarding microstructure of steel material of present embodiment]

[0163] The microstructure of the steel material of the present embodiment is not particularly limited. In a case where the steel material of the present embodiment is to be used as a fastening member, an annealing treatment is performed if the hardness of the steel material is too high. The cold forgeability of an annealed steel material increases. Hence, it is possible to produce a fastening member by performing cold forging using the steel material of the present embodiment as a starting material. Accordingly, the microstructure of the steel material of the present embodiment is not particularly limited.

[0164] For example, when the diameter of the steel material is taken as "D", in a cross section perpendicular to the longitudinal direction of the steel material, in the microstructure at a D/4 depth position in the radial direction from the surface of the steel material, the area fraction of pearlite is 10% or less and portions other than pearlite are composed of one or more kinds selected from the group consisting of polygonal ferrite, bainitic ferrite, acicular ferrite, and martensite. Note that, in the present description, the term "pearlite" includes pseudo-pearlite. FIG. 1 illustrates an example of a photographic image of the microstructure at the D/4 depth position of the steel material of the present embodiment. Portions with low brightness in FIG. 1 are pearlite, and the portions other than pearlite are composed of one or more kinds selected from the group consisting of polygonal ferrite, bainitic ferrite, acicular ferrite, and martensite. However, the microstructure of the steel material of the present embodiment is not limited to microstructure described above.

[Microstructure observation method]

[0165] The microstructure of the steel material can be observed by the following method.

[0166] In a cross section perpendicular to the longitudinal direction of the steel material, a surface including a D/4 depth position in the radial direction from the surface of the steel material is defined as an observation surface. Here, as mentioned above, "D" means the diameter of the steel material. A sample including the observation surface is taken. The observation surface of the sample is mirror polished. The mirror-polished observation surface is subjected to etching using a 3% nitric acid-alcohol solution (nital etching reagent). On the etched observation surface, an arbitrary observation visual field (0.5 mm × 0.5 mm) is observed with an optical microscope at a magnification of 500x. In the observation visual field, the respective microstructures are identified, and the area fractions (%) are determined.

[Uses of steel material of present embodiment]

[0167] The steel material of the present embodiment can be applied as a starting material for a fastening member for industrial machinery, automobiles, bridges and architectural structures and the like. Here, the meaning of the term "fastening member" includes bolts, nuts, and washers. The shape of the steel material of the present embodiment is not particularly limited. The shape of the steel material may be a steel bar or a wire rod, or may be a steel plate.

[Method for producing steel material]

[0168] An example of a method for producing the steel material of the present embodiment will now be described. The method for producing the steel material described hereunder is one example for producing the steel material of the present embodiment. Accordingly, a steel material composed as described above may also be produced by a production method other than the production method described hereunder. However, the production method described hereunder is a preferable example of a method for producing the steel material of the present embodiment.

[0169] One example of a method for producing the steel material of the present embodiment includes the following processes.

(Process 1) Process of preparing starting material (starting material preparation process)

(Process 2) Process of subjecting starting material to hot working to produce steel material (hot working process)

[0170] Each of these processes is described hereunder.

[(Process 1) Starting material preparation process]

[0171] In the starting material preparation process, a starting material for the steel material of the present embodiment is prepared. Specifically, a molten steel in which the content of each element in the chemical composition is within the range of the present embodiment is produced. The refining method is not particularly limited, and it suffices to use a well-known method. For example, molten iron produced by a well-known method is subjected to refining (primary refining) using a converter. Molten steel tapped from the converter is subjected to a well-known secondary refining. In the secondary refining, the content of alloying elements in the molten steel is adjusted to thereby produce a molten steel having a chemical composition in which the content of each element is within the range of the present embodiment.

[0172] The molten steel produced by the aforementioned refining method is used to produce a starting material by a well-known casting process. For example, an ingot may be produced by an ingot-making process using the molten steel. Further, a bloom or a billet may be produced by a continuous casting process using the molten steel. A starting material (ingot, bloom, or billet) is produced by the above method.

[(Process 2) Hot working process]

[0173] In the hot working process, the starting material (ingot, bloom, or billet) prepared in the starting material preparation process is subjected to hot working to produce the steel material of the present embodiment. The shape of the steel material is not particularly limited, and for example the steel material is formed in the shape of a steel bar or a wire rod. In the following description, a case where the steel material is a steel bar or a wire rod is described as one example. However, even if the steel material is a steel plate, the steel material can be produced by a similar hot working process.

[0174] The hot working process includes the following processes. The principal conditions in the respective processes are as described hereunder.

(Process 21) Blooming process

(Process 22) Finish rolling process

(Process 23) Cooling process

[0175] Hereunder, each process is described.

[(Process 21) Blooming process]

[0176] In the blooming process, the starting material is subjected to hot rolling to produce a billet.

[0177] Specifically, in the blooming process, the starting material is subjected to hot rolling (blooming) by a blooming mill to produce a billet. In a case where a continuous mill is arranged downstream of the blooming mill, the continuous mill may be used to further perform hot rolling on the billet obtained after performing the blooming, to thereby produce a billet of an even smaller size. In the continuous mill, horizontal stands having a pair of horizontal rolls and vertical stands having a pair of vertical rolls are alternately arranged in a row. As described above, in the blooming process the starting material is produced into a billet using a blooming mill or using a blooming mill and a continuous mill.

[0178] It suffices that the heating temperature in the blooming process is within a well-known temperature range. The heating temperature is, for example, 1100 to 1300°C. The billet produced by the blooming process is allowed to cool (air-cooling) to normal temperature before the finish rolling process.

[(Process 22) Finish rolling process]

[0179] In the finish rolling process, first, the billet cooled to normal temperature is heated using a reheating furnace. After being heated, the billet is subjected to hot rolling using a continuous mill to produce a steel bar or a wire rod as the steel material.

[0180] It suffices that the heating temperature in the reheating furnace in the finish rolling process is within a well-known range. The heating temperature is, for example, 900 to 1050°C. In the finish rolling process, hot rolling (finish rolling) is performed by a continuous mill equipped with a plurality of rolling stands arranged in a row. In the hot rolling using a continuous mill, the steel material temperature on the exit side of the stand which last rolls the steel material is defined as the finishing temperature (°C). It suffices that the finishing temperature is within a well-known range. The finishing temperature is, for example, 800 to less than 900°C.

[(Process 23) Cooling process]

[0181] In the cooling process, the steel material after the finish rolling process is cooled. Here, the arithmetic average value (°C/sec) of the cooling rate from the finishing temperature FT to 300°C is defined as an average cooling rate. It suffices that the average cooling rate is within a well-known range. The average cooling rate CR1 is, for example, 0.6 to 1.8°C/sec.

[0182] Note that, in the hot working process of the production process described above, the finish rolling process may be performed without performing the blooming process. That is, the blooming process is an optional process. For example, in a case where a billet has been prepared in the starting material preparation process, the blooming process may be omitted and the finish rolling process may be performed.

[Regarding fastening member of present embodiment]

[0183] The fastening member of the present embodiment is composed of the steel material of the present embodiment that is described above. That is, the fastening member of the present embodiment satisfies Feature 1 and Feature 2. As mentioned above, examples of the fastening member include a bolt, a nut, a washer and the like.

[Method for producing fastening member composed of steel material of present embodiment]

[0184] A method for producing a fastening member composed of the steel material of the present embodiment is a well-known production method. The method for producing the fastening member, for example, includes the following processes.

- (Process 31) Wire drawing process
- (Process 32) Cold forging process
- (Process 33) Quenching and tempering process

[0185] Hereunder, each process is described.

[(Process 31) Wire drawing process]

[0186] In the wire drawing process, the aforementioned steel material is subjected to well-known wire drawing to produce a steel wire. The wire drawing may be only primary wire drawing, or may be carried out multiple times, for example, including a secondary wire drawing and the like.

[(Process 32) Cold forging process]

[0187] In the cold forging process, the steel wire after the wire drawing process is subjected to well-known cold forging to produce an intermediate product having the shape of the fastening member.

[(Process 33) Quenching and tempering process]

[0188] In the quenching and tempering process, the intermediate product is subjected to quenching and tempering.

[Quenching]

[0189] Quenching is performed by a well-known method. It suffices that the quenching temperature and the holding time at the quenching temperature are within a well-known range. The quenching temperature is, for example, 840 to 970°C. The holding time at the quenching temperature is, for example, 15 mins to 360 mins (6 hours). After the holding time elapses, the intermediate product is rapidly cooled. Specifically, the intermediate product is subjected to water cooling or oil cooling.

[Tempering]

[0190] The intermediate product after quenching is subjected to tempering. It suffices that the tempering temperature and the holding time at the tempering temperature are within a well-known range. The tempering temperature is, for example, 400 to 550°C. The holding time at the tempering temperature is 0.5 to 6.0 hours.

[0191] A fastening member composed of the steel material of the present embodiment can be produced by the production method described above.

Sufficient corrosion resistance and sufficient hydrogen embrittlement resistance in a corrosive environment containing chloride ions are obtained in the produced fastening member.

EXAMPLES

[0192] The advantageous effects of the steel material of the present embodiment are described more specifically hereunder by way of examples. The conditions adopted in the following examples are one example of conditions adopted for confirming the feasibility and advantageous effects of the steel material of the present embodiment. Accordingly, the steel material of the present embodiment is not limited to this one example of conditions.

[Starting material preparation process]

[0193] Molten steels having the chemical compositions shown in Table 1-1 and Table 1-2 were produced. Starting materials (cast pieces) were produced by a continuous casting process using the molten steels.

[Table 1-1]

[0194]

TABLE1-1

Test Number	Chemical Composition (unit is mass percent; balance is Fe and impurities)													
	C	Si	Mn	P	S	Al	Sn	Cr	Cu	Ni	Mo	Ti	N	O
1	0.22	0.20	0.01	0.020	0.020	0.100	0.12	0.01	0.400	0.40	0.30	0.010	0.002	0.002
2	0.35	0.50	0.80	0.020	0.010	0.030	0.15	0.07	0.300	0.30	0.03	0.100	0.003	0.004
3	0.22	0.01	0.80	0.050	0.030	0.020	0.15	0.10	0.400	0.40	0.30	0.020	0.005	0.006
4	0.35	0.30	1.20	0.020	0.020	0.010	0.30	0.08	0.400	0.40	0.01	0.030	0.003	0.004
5	0.45	0.30	0.80	0.030	0.030	0.001	0.15	0.08	0.010	0.01	0.30	0.020	0.008	0.010
6	0.22	0.20	0.01	0.020	0.020	0.100	0.12	0.01	0.400	0.40	0.30	0.010	0.002	0.002
7	0.22	0.01	0.80	0.050	0.030	0.020	0.30	0.10	0.400	0.40	0.30	0.020	0.005	0.006
8	0.18	0.30	1.50	0.010	0.010	0.020	0.12	0.20	0.200	0.10	0.30	0.020	0.003	0.004
9	0.22	0.01	0.80	0.050	0.030	0.020	0.30	0.10	0.400	0.40	0.30	0.020	0.005	0.006
10	0.22	0.30	1.50	0.010	0.010	0.020	0.12	0.20	0.200	0.10	0.30	0.020	0.003	0.004
11	0.22	0.20	0.01	0.020	0.020	0.100	0.12	0.01	0.400	0.40	0.30	0.010	0.002	0.002
12	0.22	0.30	1.00	0.030	0.050	0.030	0.20	0.10	0.400	0.40	0.30	0.050	0.003	0.004
13	0.22	0.01	0.80	0.050	0.030	0.020	0.15	0.10	0.400	0.40	0.30	0.020	0.005	0.006
14	0.35	0.30	1.20	0.020	0.020	0.010	0.30	0.08	0.400	0.40	0.01	0.030	0.003	0.004

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(continued)

	Test Number	Chemical Composition (unit is mass percent; balance is Fe and impurities)													
		C	Si	Mn	P	S	Al	Sn	Cr	Cu	Ni	Mo	Ti	N	O
5	15	0.22	0.30	1.50	0.010	0.010	0.020	0.12	0.20	0.200	0.10	0.30	0.020	0.003	0.004
	16	0.35	0.50	0.80	0.020	0.010	0.030	0.15	0.07	0.300	0.30	0.03	0.100	0.003	0.004
	17	0.18	0.30	1.50	0.010	0.010	0.020	0.12	0.20	0.200	0.10	0.30	0.020	0.003	0.004
10	18	0.15	0.50	0.80	0.010	0.001	0.020	0.30	0.10	0.300	0.30	0.05	0.020	0.003	0.004
	19	0.22	0.01	0.80	0.050	0.030	0.020	0.30	0.10	0.400	0.40	0.30	0.020	0.005	0.006
	20	0.35	0.50	0.80	0.020	0.010	0.030	0.15	0.07	0.300	0.30	0.03	0.100	0.003	0.004
15	21	0.35	0.30	1.20	0.020	0.020	0.010	0.30	0.08	0.400	0.40	0.01	0.030	0.003	0.004
	22	0.45	0.30	0.80	0.030	0.030	0.001	0.15	0.08	0.010	0.01	0.30	0.020	0.008	0.010
	23	0.22	0.20	0.80	0.010	0.010	0.030	0.02	0.05	0.400	0.40	0.30	0.010	0.002	0.002
20	24	0.22	0.50	1.00	0.020	0.010	0.030	0.20	0.08	0.500	0.50	0.30	0.010	0.005	0.006
	25	0.35	0.30	0.80	0.001	0.020	0.030	0.20	0.02	0.400	0.40	0.30	0.040	0.006	0.007
	26	0.35	0.30	0.80	0.020	0.010	0.030	0.06	0.08	0.300	0.30	0.07	0.020	0.003	0.004
25	27	0.22	0.30	0.80	0.010	0.010	0.030	0.01	0.20	0.050	0.05	0.05	0.030	0.003	0.004
	28	0.35	0.20	0.70	0.020	0.020	0.050	0.40	0.10	0.100	0.10	0.10	0.030	0.004	0.005
	29	0.33	0.30	0.70	0.030	0.030	0.030	0.05	0.30	0.030	0.06	0.30	0.030	0.005	0.006
30	30	0.22	0.50	0.80	0.020	0.010	0.050	0.12	0.10	0.005	0.50	0.40	0.020	0.003	0.004
	31	0.35	0.30	0.80	0.010	0.010	0.030	0.02	0.02	0.600	0.40	0.40	0.030	0.003	0.004
	32	0.22	0.20	0.80	0.020	0.020	0.030	0.30	0.08	0.400	0.01	0.30	0.040	0.001	0.001
35	33	0.22	0.20	0.80	0.010	0.010	0.030	0.02	0.05	0.400	0.40	0.30	0.010	0.002	0.002
	34	0.22	0.20	0.01	0.020	0.020	0.100	0.12	0.01	0.400	0.40	0.30	0.010	0.002	0.002
	35	0.22	0.01	0.80	0.030	0.030	0.010	0.20	0.20	0.300	0.60	0.30	0.050	0.002	0.002
40	36	0.35	0.30	0.70	0.030	0.030	0.050	0.06	0.20	0.300	0.30	0.60	0.030	0.005	0.006
	37	0.22	0.50	0.80	0.020	0.010	0.020	0.20	0.01	0.400	0.40	0.40	0.030	0.004	0.005
	38	0.22	0.30	0.70	0.030	0.050	0.060	0.20	0.20	0.500	0.50	0.50	0.030	0.002	0.002
	39	0.35	0.30	0.80	0.001	0.020	0.030	0.20	0.02	0.200	0.30	0.50	0.040	0.006	0.007
	40	0.22	0.01	0.80	0.020	0.030	0.050	0.10	0.05	0.100	0.10	0.01	0.030	0.003	0.004
	41	0.22	0.50	0.80	0.020	0.010	0.020	0.05	0.01	0.100	0.05	0.01	0.030	0.004	0.005

[Table 1-2]

[0195]

TABLE1-2

50	Test Number	Chemical Composition (unit is mass percent; balance is Fe and impurities)										F1	
		Co	Sb	Ge	In	Tx	W	B	Nb	Ca	Mg		REM
55	1	0.0050	-	-	-	0.0050	-	-	-	-	-	-	36
	2	-	0.0050	-	-	0.0050	-	-	-	-	-	-	36
	3	-	-	0.0030	-	0.0030	-	-	-	-	-	-	31
	4	-	-	-	0.0015	0.0015	-	-	-	-	-	-	25
	5	0.0030	-	-	0.0010	0.0040	-	-	-	-	-	-	34

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(continued)

	Test Number	Chemical Composition (unit is mass percent; balance is Fe and impurities)											F1
		Co	Sb	Ge	In	Tx	W	B	Nb	Ca	Mg	REM	
5	6	0.0020	0.0010	-	-	0.0030	-	-	-	-	-	-	31
	7	0.0030	0.0010	-	0.0010	0.0050	-	-	-	-	-	-	36
	8	0.0020	-	0.0010	0.0020	0.0050	-	-	-	-	-	-	36
10	9	0.0033	-	-	-	0.0033	0.10	0.0020	0.030	0.0030		0.0100	32
	10	-	0.0015	-	-	0.0015	-	-	0.040	-	-	-	24
	11	-	-	0.0014	-	0.0014	-	0.0020	0.100	-	-	-	24
	12	-	-	-	0.0033	0.0033	0.08	-	0.050	-	-	-	32
15	13	0.0015	0.0030	0.0008	0.0007	0.0060	-	-	-	-	-	-	38
	14	0.0014	0.0010	0.0010	0.0005	0.0039	-	-	-	-	-	-	34
	15	0.0010	0.0020	0.0000	0.0003	0.0033	-	-	-	0.0030	-	-	32
20	16	0.0015	0.0030	0.0008	0.0007	0.0060	-	-	-	-	0.0030	-	38
	17	0.0014	0.0010	0.0010	0.0005	0.0039	-	-	-	-	-	0.0100	33
	18	0.0015	0.0020	0.0008	0.0010	0.0053	-	-	0.030	-	-	-	37
	19	0.0015	0.0030	0.0008	0.0007	0.0060	-	-	0.050	-	-	-	38
25	20	0.0014	0.0010	0.0010	0.0005	0.0039	0.05	-	0.020	-	-	-	34
	21	0.0025	0.0010	0.0008	0.0004	0.0047	-	0.0010	0.200	-	-	-	36
	22	0.0010	0.0000	0.0002	0.0005	0.0017	-	0.0020	0.010	-	-	-	25
30	23	0.0015	0.0002	0.0008	0.0001	0.0026	0.01	0.0020	0.300	-	-	-	30
	24	0.0010	0.0010	0.0010	0.0008	0.0038	0.30	0.0008	0.020	-	-	-	34
	25	0.0015	0.0003	0.0000	0.0002	0.0020	0.30	0.0020	0.100	-	-	-	27
	26	0.0014	0.0020	0.0008	0.0020	0.0062	0.07	0.0020	0.060	-	-	-	38
35	27	0.0010	0.0000	0.0003	0.0001	0.0014	0.07	0.0020	0.050	-	-	-	22
	28	0.0020	0.0020	0.0001	0.0010	0.0051	0.05	-	0.200	-	-	-	36
	29	0.0002	0.0020	0.0000	0.0000	0.0022	0.05	-	0.060	-	-	-	28
40	30	0.0002	0.0020	0.0010	0.0030	0.0062	-	-	0.040	-	-	-	40
	31	0.0020	0.0020	0.0010	0.0010	0.0060	0.50	-	0.050	-	-	-	39
	32	0.0025	0.0030	0.0010	0.0010	0.0075	-	-	0.040	-	-	-	40
	33	0.0002	-	0.0005	0.0002	0.0009	-	-	0.040	-	-	-	20
45	34	0.0005	0.0002	-	-	0.0007	-	-	0.050	-	-	-	19
	35	0.0030	0.0020	0.0010	0.0000	0.0060	0.08	0.0020	0.050	-	-	-	39
	36	0.0030	0.0010	0.0020	0.0010	0.0070	0.07	-	0.040	-	-	-	45
50	37	0.0032	0.0010	0.0010	0.0010	0.0062	0.60	-	0.020	-	-	-	39
	38	0.0030	0.0010	0.0010	0.0010	0.0060	0.05	-	0.080	-	-	-	44
	39	0.0030	0.0010	0.0010	0.0010	0.0060	0.05	-	0.060	-	-	-	40
	40	0.0004	0.0000	0.0000	0.0010	0.0014	0.07	0.0020	0.020	-	-	-	22
55	41	0.0003	0.0000	0.0000	0.0010	0.0013	0.07	0.0020	0.020	-	-	-	21

[Hot working process]

[0196] Each of the produced starting materials was subjected to a blooming process to produce a billet. In the blooming process, each starting material was heated to 1100 to 1300°C, and thereafter subjected to hot rolling using a blooming mill and a continuous mill. The billets produced by the blooming process were allowed to cool to normal temperature.

[0197] Each of the produced billets was subjected to a finish rolling process. In the finish rolling process, the billet was heated to 900 to 1050°C. After being heated, the billet was subjected to hot rolling using a continuous mill to produce a steel material (steel bar) with a diameter of 22 mm. The finishing temperature in the hot rolling was within the range of 800 to less than 900°C. The steel material (steel bar) after hot rolling was subjected to cooling. At such time, the average cooling rate from the finishing temperature to 300°C was 0.6 to 1.8°C/sec.

[Table 2]

[0198]

TABLE2

Test Number	Hot Workability	Peeling Area Fraction (%)	Hydrogen Embrittlement Resistance	Remarks
1	E	30	E	Inventive Example
2	E	15	E	Inventive Example
3	E	30	E	Inventive Example
4	E	35	E	Inventive Example
5	E	35	E	Inventive Example
6	E	30	E	Inventive Example
7	E	20	E	Inventive Example
8	E	15	E	Inventive Example
9	E	20	E	Inventive Example
10	E	35	E	Inventive Example
11	E	35	E	Inventive Example
12	E	30	E	Inventive Example
13	E	20	E	Inventive Example
14	E	30	E	Inventive Example
15	E	15	E	Inventive Example
16	E	30	E	Inventive Example
17	E	20	E	Inventive Example
18	E	20	E	Inventive Example
19	E	15	E	Inventive Example
20	E	30	E	Inventive Example
21	E	30	E	Inventive Example
22	E	20	E	Inventive Example
23	E	20	E	Inventive Example
24	E	30	E	Inventive Example
25	E	18	E	Inventive Example
26	E	30	E	Inventive Example
27	E	70	B	Comparative Example
28	B	-	-	Comparative Example

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(continued)

Test Number	Hot Workability	Peeling Area Fraction (%)	Hydrogen Embrittlement Resistance	Remarks
29	E	80	B	Comparative Example
30	E	70	B	Comparative Example
31	E	45	B	Comparative Example
32	E	50	B	Comparative Example
33	E	70	B	Comparative Example
34	E	60	B	Comparative Example
35	E	50	B	Comparative Example
36	E	45	B	Comparative Example
37	E	45	B	Comparative Example
38	E	50	B	Comparative Example
39	E	55	B	Comparative Example
40	E	50	B	Comparative Example
41	E	50	B	Comparative Example

[0199] The steel material of each test number was produced by the above production process.

[Regarding evaluation tests]

[0200] The produced steel material of each test number was subjected to the following steel material evaluation tests (Test 1 to Test 4).

(Test 1) Test to measure chemical composition of steel material

(Test 2) Hot workability evaluation test

(Test 3) Corrosion resistance evaluation test

(Test 4) Hydrogen embrittlement resistance evaluation test

Hereunder, each test is described.

[(Test 1) Test to measure chemical composition of steel material]

[0201] The chemical composition of the steel material (steel bar) of each test number was analyzed based on the method described above in the section [Method for measuring chemical composition of steel material]. As a result, it was found that the chemical composition of each test number was as shown in Table 1-1 and Table 1-2.

[(Test 2) Hot workability evaluation test]

[0202] The steel material (steel bar) of each test number was tested to confirm whether or not a crack occurred during the hot working process. If a crack occurred during hot working, it was determined that the hot workability was low (indicated by "B" (Bad) in the column "Hot Workability" in Table 2). On the other hand, if a crack did not occur in the steel material during the hot working process, it was determined that the steel material was excellent in hot workability (indicated by "E" (Excellent) in the column "Hot Workability" in Table 2).

[(Test 3) Corrosion resistance evaluation test]

[0203] The corrosion resistance of the steel material of each test number was evaluated by the following test.

[0204] In the corrosion resistance evaluation test, in consideration of the ease with which the corrosion resistance could be evaluated, steel bars were not used as the starting materials, and a steel plate of each test number in place of a steel bar was produced by the following method. Specifically, starting materials having the chemical compositions shown in Table 1-1 and Table 1-2 were subjected to a finish rolling process and a cooling process to produce steel plates of the respective

test number with a thickness of 6 mm. The steel plate temperature at the start of the finish rolling was 900 to 1050°C. The finishing temperature was 800 to less than 900°C. The average cooling rate from the finishing temperature to 300°C was 0.6 to 1.8°C/sec.

[0205] Each steel plate was subjected to quenching and tempering that simulated a process for producing a bolt. The quenching was performed using a heat treatment furnace. The quenching temperature was set to 880°C, and the holding time at the quenching temperature was set to 60 minutes. After the holding time elapsed, the steel plate was immersed in oil at a temperature of 60°C to perform quenching. Note that, the inside of the heat treatment furnace was made an atmosphere filled with Ar gas to suppress decarburization of the steel plate. Tempering was performed after the quenching. The tempering was performed using a heat treatment furnace. The tempering temperature was set to 450°C, and the holding time at the tempering temperature was set to 90 minutes.

[0206] A sheet-like test specimen with dimension of 100 mm × 60 mm × 3 mm in thickness was taken from the steel plate subjected to the quenching and tempering. The surface of the sheet-like test specimen taken was subjected to shotblasting so that, on the surface of the sheet-like test specimen, a ten-point average roughness Rzjis in accordance with JIS B0601: 2001 was adjusted to 75 μm.

[0207] Coating of the surface of the sheet-like test specimen after shotblasting was performed to form a coating film composed of an undercoat (trade name: Neo Gose #2300PS, manufactured by Shinto Paint Co., Ltd.) having a thickness of 120 μm, an intermediate coat (trade name: Shinto Flon #100, manufactured by Shinto Paint Co., Ltd.) having a thickness of 30 μm, and an overcoat (trade name: Shinto Flon #100, manufactured by Shinto Paint Co., Ltd.) having a thickness of 25 μm.

[0208] A coating film defect that reached the base metal (steel plate) was formed using a cutter. The total length of the coating film defect was made 500 mm.

[0209] The sheet-like test specimen having the coating film defect was used to perform a corrosion test in accordance with the SAE J2334 standards using a dry-wet cycle testing machine capable of being immersed in salt water. Specifically, a test was performed in which the following three steps (total of 24 hours) were taken as one cycle.

(Step 1: Wetting process)

[0210] The sheet-like test specimen is held for six hours in an environment with a temperature of 50°C and a relative humidity of 100% RH.

(Step 2: Salt water immersion process)

[0211] The sheet-like test specimen after Step 1 is immersed for 15 minutes in an aqueous solution at pH 8 containing 0.5% NaCl, 0.1% CaCl₂, and 0.075% NaHCO₃.

(Step 3: Drying process)

[0212] The sheet-like test specimen after Step 2 is held for 17.75 hours in an environment with a temperature of 60°C and a relative humidity of 50% RH. After being held for 17.75 hours, the sheet-like test specimen is dried.

[0213] The above Step 1 to Step 3 were taken as one cycle, and the test was performed for 80 cycles.

[0214] After performing the test for 80 cycles, in the coating film of the sheet-like test specimen, a coating film portion which was peeling off from the test specimen surface and with respect to which the coating film defect served as a starting point was removed with a cutter (hereunder, referred to as "peeled part of the coating film"). After the peeled part of the coating film was removed, an image of the coating film of the sheet-like test specimen as seen in plan view was generated.

On the surface of the sheet-like test specimen, a region where the coating film remained and a region where the steel plate was exposed (peeled part of the coating film) were distinguished by image processing. The total area of the peeled part of the coating film (peeling area) was then determined. The peeling area fraction (%) of the coating film was determined based on the total area of the peeled part of the coating film, and the area of the surface where the coating film of the sheet-like test specimen was formed. The determined peeling area fraction is shown in the column "Peeling Area Fraction (%)" in Table 2.

[(Test 4) Hydrogen embrittlement resistance evaluation test]

[0215] The hydrogen embrittlement resistance of the steel material of each test number was evaluated by the following test.

[0216] First, the steel material (steel bar) was subjected to quenching and tempering that simulated a process for producing a bolt. The quenching was performed using a heat treatment furnace. The quenching temperature was set to 880°C, and the holding time at the quenching temperature was set to 60 minutes. After the holding time elapsed, the steel

material was immersed in oil at a temperature of 60°C to perform oil quenching. Note that, the inside of the heat treatment furnace was made an atmosphere filled with Ar gas to suppress decarburization of the steel material. Tempering was performed after the quenching. The tempering was performed using a heat treatment furnace. The tempering temperature was set to 450°C, and the holding time at the tempering temperature was set to 90 minutes.

[0217] The amount of hydrogen penetration in the steel material of each test number subjected to the above quenching and tempering was measured by the following method (hydrogen penetration amount investigation test).

[0218] First, a test specimen was taken from the center position in a cross section perpendicular to the axial direction of the steel material (steel bar). The test specimen was a round bar specimen with a diameter of 7 mm and a length of 100 mm. The central axis of the test specimen was coaxial with the steel material. Two test specimens were prepared for each test number.

[0219] A corrosion test in accordance with the American SAE J2334 standards was carried out, and the amount of hydrogen penetration in each test specimen after the corrosion test was measured.

[0220] Specifically, Step 1 to Step 3 of Test 3 were taken as one cycle, and the amount of hydrogen penetration was measured with respect to the test specimen after the test was performed for 56 cycles. To prevent hydrogen penetrated into the test specimen from leaving the test specimen after the corrosion test, the test specimen after the corrosion test was immersed in liquid nitrogen until immediately prior to measuring the amount of hydrogen penetration. Before measuring the amount of hydrogen penetration, corrosion products adhering to the surface of the test specimen were completely removed by sandblasting. In the test specimen from which the corrosion products had been removed, the amount of hydrogen penetration was measured using a thermal desorption spectroscopy apparatus. Specifically, the amount of diffusible hydrogen detected by an elimination reaction from room temperature to 200°C was measured by the thermal desorption spectroscopy apparatus, and the measured amount was taken as the amount of hydrogen penetration. The arithmetic average value of the obtained amounts of hydrogen penetration for the two test specimens was defined as the amount of hydrogen penetration He (ppm) of the steel material of the relevant test number.

[0221] Next, a hydrogen embrittlement resistance evaluation test was performed by the following method.

[0222] A test specimen was taken from the center position in a cross section perpendicular to the axial direction of the steel material (steel bar) which had been subjected to the quenching and tempering described above. A round bar specimen with an annular notch that was 7 mm in diameter and 70 mm in length was taken as the test specimen. The annular notch was formed at a central position in the longitudinal direction of the test specimen. The notch had a shape in which the notch depth was 1.4 mm, the notch angle was 60°, and the radius of curvature of the notch root was 0.175 mm.

[0223] An SSRT (Slow Strain Rate Technique) test was performed using the prepared round bar specimen with an annular notch. Specifically, a hydrogen charging solution was prepared by adding 3 g/L of NH_4SCN to a 3% NaCl aqueous solution. In a state in which the round bar specimen with an annular notch was immersed in the hydrogen charging solution, a current density applied to the test specimen was adjusted to adjust the amount of hydrogen penetrating into the test specimen.

[0224] Each of the round bar specimens with an annular notch that had been charged with hydrogen at various current densities was subjected to a plating treatment to ensure that the hydrogen did not desorb. The round bar specimen with an annular notch after the plating treatment was left to stand at room temperature for eight hours or more. Thereafter, a tensile test was performed at a speed of 0.005 mm/min to cause the round bar specimen with an annular notch to rupture. After rupturing, the amount of hydrogen penetration (ppm) of the round bar specimen with an annular notch was measured using a thermal desorption spectroscopy apparatus.

[0225] By performing the above test, a graph of the amount of hydrogen penetration (ppm) and the rupture load (kN) was created as illustrated in FIG. 2. Based on the created graph, the rupture load ($\sigma_{2\text{He}}$) at a hydrogen amount (2He) that was twice the amount of hydrogen penetration (He) obtained in the hydrogen penetration amount investigation test was determined.

[0226] In addition, a tensile test at a speed of 0.005 mm/min was performed on a round bar specimen with an annular notch that had not been charged with hydrogen of each test number to cause the round bar specimen with an annular notch to rupture, and the rupture load (σ_0) was determined.

[0227] A rupture load ratio ($\sigma_{2\text{He}}/\sigma_0$) was determined by dividing the rupture load $\sigma_{2\text{He}}$ obtained in the case where hydrogen charging was performed by the rupture load (σ_0) obtained in the case where hydrogen charging was not performed.

[0228] The hydrogen embrittlement resistance was evaluated based on the rupture load ratio ($\sigma_{2\text{He}}/\sigma_0$). The evaluation results are shown in the column "Hydrogen Embrittlement Resistance" in Table 2. If the rupture load ratio was 0.8 or more, it was determined that the steel material was excellent in hydrogen embrittlement resistance (indicated by "E" in Table 2). If the rupture load ratio was less than 0.8, it was determined that the hydrogen embrittlement resistance was low (indicated by "B" in Table 2).

[Evaluation results]

[0229] The evaluation results are shown in Table 2.

[0230] In Test Nos. 1 to 26, the chemical composition was appropriate and F1 satisfied Formula (1). Therefore, the peeling area fraction was 40% or less, and sufficient corrosion resistance was obtained. In addition, sufficient hydrogen embrittlement resistance was obtained. Note that, in each of these test numbers, the microstructure was a microstructure in which the pearlite area fraction was 10% or less, and a portion other than pearlite was composed of one kind or more selected from the group consisting of polygonal ferrite, bainitic ferrite, acicular ferrite, and martensite. Therefore, each of these test numbers was excellent in hot workability.

[0231] On the other hand, in Test No. 27, the content of Sn was low. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, sufficient hydrogen embrittlement resistance was not obtained.

[0232] In Test No. 28, the content of Sn was high. Consequently, the hot workability was low.

[0233] In Test No. 29, the content of Cr was too high. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, sufficient hydrogen embrittlement resistance was not obtained.

[0234] In Test No. 30, the content of Cu was too low. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, sufficient hydrogen embrittlement resistance was not obtained.

[0235] In Test No. 31, the content of Cu was too high. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, sufficient hydrogen embrittlement resistance was not obtained.

[0236] In Test No. 32, the total content Tx of Co, Sb, Ge, and In was too high. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, sufficient hydrogen embrittlement resistance was not obtained.

[0237] In Test Nos. 33 and 34, the total content Tx of Co, Sb, Ge, and In was too low. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, sufficient hydrogen embrittlement resistance was not obtained.

[0238] In Test No. 35, the content of Ni was too high. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, sufficient hydrogen embrittlement resistance was not obtained.

[0239] In Test No. 36, the content of Mo was too high. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, the hydrogen embrittlement resistance also decreased.

[0240] In Test No. 37, the content of W was too high. Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, the hydrogen embrittlement resistance also decreased.

[0241] In Test Nos. 38 and 39, F1 was more than the upper limit of Formula (1). Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low. In addition, the hydrogen embrittlement resistance also decreased.

[0242] In Test Nos. 40 and 41, F1 was less than the lower limit of Formula (1). Consequently, the peeling area fraction was more than 40%, and the corrosion resistance was low.

[0243] An embodiment of the present disclosure has been described above. However, the embodiment described above is merely an example for carrying out the present disclosure. Therefore, the present disclosure is not limited to the above-described embodiment, and can be implemented by appropriately modifying the above-described embodiment within a range that does not depart from the gist of the present disclosure.

Claims

1. A steel material consisting of, in mass%,

C: 0.15 to 0.45%,
Si: 0.01 to 1.00%,
Mn: 0.01 to 1.50%,
P: 0.050% or less,
S: 0.050% or less,
Al: 0.100% or less,
Sn: 0.02 to 0.30%,
Cr: 0.20% or less,
Cu: 0.010 to 0.500%,
Ni: 0.01 to 0.50%,
Mo: 0.01 to 0.50%,
Ti: 0.001 to 0.100%,

one or more kind of elements selected from a group consisting of Co, Sb, Ge, and In: 0.0013 to less than 0.0065% in total,

N: 0.010% or less,

O: 0.015% or less,

W: 0 to 0.50%,

B: 0 to 0.0050%,

Nb: 0 to 0.300%,

Ca: 0 to 0.0050%,

Mg: 0 to 0.0050%,

rare earth metal: 0 to 0.0200%, and

the balance: Fe and impurities; and

satisfying Formula (1);

$$\frac{23}{+30 \times (0.5 \times \text{Ni} + \text{Mo}) + 10} < \frac{10 \times \text{LN}(\text{Cu} + 0.5 \times \text{Sn} + 2000 \times \text{Tx}) + 100 \times (0.5 \times \text{Ni} + \text{Mo})^3 - 100 \times (0.5 \times \text{Ni} + \text{Mo})^2}{(1)}$$

where, a content in mass of a corresponding element is substituted for each symbol of an element in Formula (1), a total content in mass of one or more kind of elements selected from the group consisting of Co, Sb, Ge, and In is substituted for Tx, and LN in Formula (1) means "natural logarithm".

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

W: 0.01 to 0.50%,

B: 0.0001 to 0.0050%,

Nb: 0.001 to 0.300%,

Ca: 0.0001 to 0.0050%,

Mg: 0.0001 to 0.0050%, and

rare earth metal: 0.0001 to 0.0200%.

3. A fastening member composed of the steel material according to claim 1 or claim 2.

FIG.1

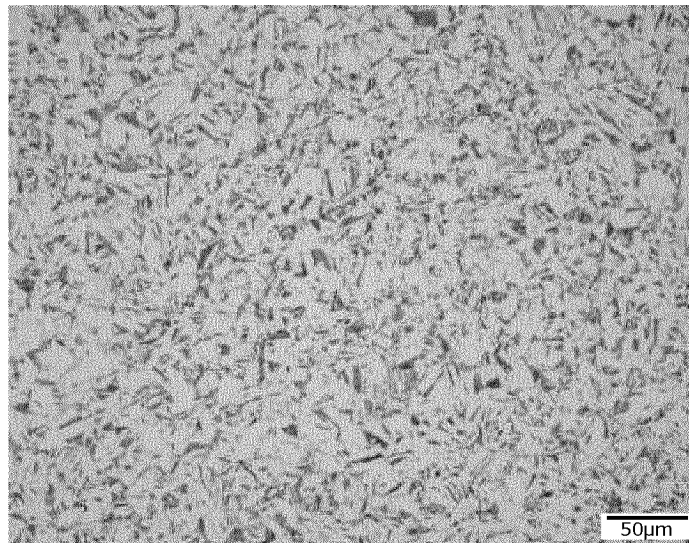
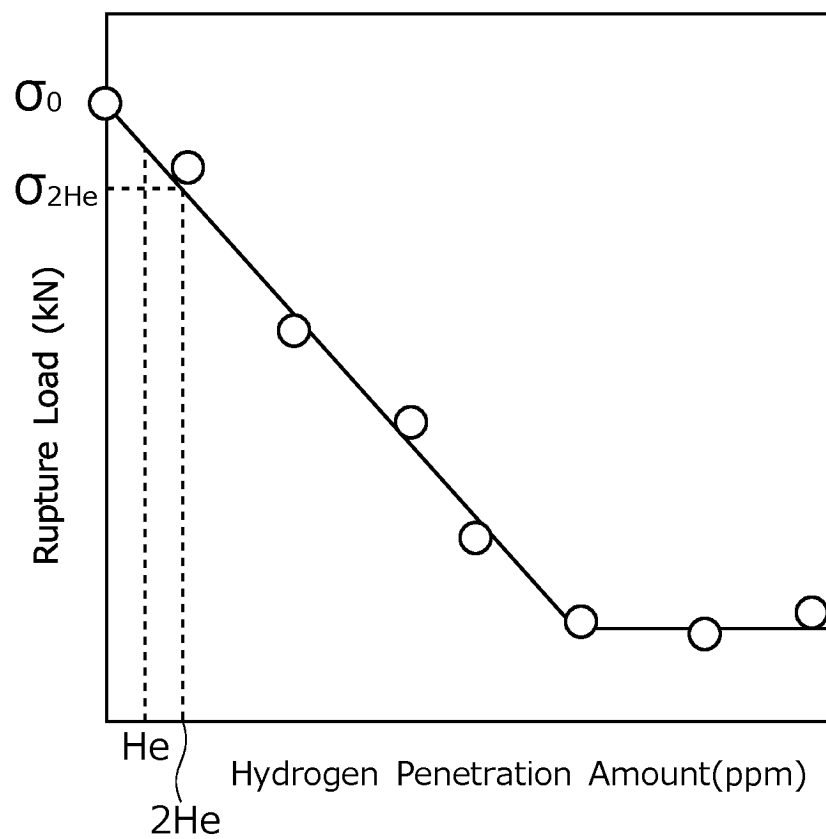


FIG.2



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2022/020477

A. CLASSIFICATION OF SUBJECT MATTER

C21D 9/00(2006.01)i; **C22C 38/00**(2006.01)i; **C22C 38/54**(2006.01)i

FI: C22C38/00 301Z; C22C38/00 301F; C22C38/00 301Y; C22C38/54; C21D9/00 B

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)

C21D9/00; 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 2020/162616 A1 (NIPPON STEEL CORP) 13 August 2020 (2020-08-13) entire text	1-3
A	JP 2019-218584 A (NIPPON STEEL CORP) 26 December 2019 (2019-12-26) entire text	1-3
A	WO 2020/203158 A1 (NIPPON STEEL CORP) 08 October 2020 (2020-10-08) entire text	1-3

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

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“&” document member of the same patent family

Date of the actual completion of the international search

26 July 2022

Date of mailing of the international search report

09 August 2022

Name and mailing address of the ISA/JP

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Telephone No.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/JP2022/020477

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
WO 2020/162616 A1	13 August 2020	US 2022-0064766 A1 entire text KR 10-2021-0104862 A CN 113383094 A	
JP 2019-218584 A	26 December 2019	(Family: none)	
WO 2020/203158 A1	08 October 2020	EP 3950975 A1 entire text KR 10-2021-0091790 A CN 112969804 A	

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

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

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- JP 2017226878 A [0004] [0007]