(19) Europäisches Patentamt / European Patent Office / Office européen des brevets

(11) EP 4 461 838 A1

(12) EUROPEAN PATENT APPLICATION
published in accordance with Art. 153(4) EPC

(43) Date of publication:
13.11.2024 Bulletin 2024/46

(21) Application number: **23749474.5**

(22) Date of filing: **06.01.2023**

(51) International Patent Classification (IPC):
C22C 38/00 *(2006.01)* ***C21D 8/02*** *(2006.01)*
C22C 38/14 *(2006.01)* ***C22C 38/58*** *(2006.01)*

(52) Cooperative Patent Classification (CPC):
C21D 8/02; C22C 38/00; C22C 38/14; C22C 38/58

(86) International application number:
PCT/JP2023/000227

(87) International publication number:
WO 2023/149157 (10.08.2023 Gazette 2023/32)

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
KH MA MD TN

(30) Priority: **03.02.2022 JP 2022015943**

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(54) STEEL SHEET AND METHOD FOR MANUFACTURING SAME

(57) Provided is a steel plate having high strength and excellent multilayer-fill-welded joint CTOD properties even when thickness exceeds 100 mm. The steel plate has a defined chemical composition and values for Ti/N, Ceq, and Pcm within specific ranges, where the average effective crystal grain size in a mid-thickness part is 20 μm or less, and the number of pores in the steel plate having a circle equivalent diameter of 180 μm or more per mm^2 is 0.10 or less.

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Description

TECHNICAL FIELD

[0001] The present disclosure relates to steel material suitable for steel structures such as ships, marine structures, pressure vessels, line pipes, and offshore wind power generators. In particular, with respect to steel plates having thicknesses exceeding 100 mm, the present disclosure relates to a thick, high tensile strength steel plate that not only has excellent base metal strength and toughness but also has excellent joint CTOD properties in multilayer fill welded portions, and a method of producing same.

BACKGROUND

[0002] Conventionally, mainly Charpy tests have been used to evaluate steel toughness. In recent years, crack tip opening displacement tests (hereinafter also referred to as CTOD test) have been increasingly applied to steel plates used in steel structures as a method to evaluate fracture resistance with higher precision.

[0003] The CTOD test evaluates resistance to occurrence of brittle cracks by introducing a fatigue precrack into a test piece at the location to be evaluated for toughness, subjecting the test piece to three-point bending at low temperature, and measuring the amount of crack opening (plastic deformation) immediately before fracture.

[0004] When steel plates are applied to steel structures such as ships, marine structures, pressure vessels, line pipes, wind power generators, and the like, as mentioned above, multilayer fill welding is used. In the multilayer fill weld heat-affected zone (hereinafter also referred to as "multilayer fill weld HAZ"), a zone in the vicinity of the weld line where microstructure has become coarse-grained due to the preceding welding pass (hereinafter also referred to as coarse grain heat-affected zone, or "CGHAZ") is reheated to a two-phase region of ferrite and austenite by a subsequent welding pass, resulting in martensite austenite constituent (hereinafter also referred to as "MA") being mixed into a coarse matrix, resulting in a zone of significantly reduced toughness (hereinafter also referred to as inter-critically reheated coarse grain heat-affected zone, or "ICCGHAZ").

[0005] Here, CTOD testing of welded joints is basically performed on the full plate thickness, and therefore when a multilayer fill weld HAZ is the target of evaluation, the region where a fatigue precrack is introduced includes ICCGHAZ microstructure. Further, joint CTOD properties obtained by a joint CTOD test depend on toughness of the most brittle microstructure in the evaluation region, and therefore joint CTOD properties of a multilayer fill weld HAZ reflect the toughness of ICCGHAZ microstructure as well as CGHAZ microstructure.

[0006] Therefore, to improve joint CTOD properties of a multilayer fill weld HAZ, it is necessary to improve not only toughness of CGHAZ microstructure but also ICCGHAZ microstructure.

[0007] Conventional toughness improvement techniques for the heat-affected zone (HAZ) have been suppression of austenite grain coarsening in the CGHAZ by fine particle distribution of TiN and the use of TiN as a ferrite nucleation site. Here, TiN is sometimes heated to a temperature range where TiN melts in a bonded portion, and therefore when low-temperature toughness requirements for a welded portion are strict, satisfying such requirements has become difficult with only the effect of using TiN.

[0008] Further, a technique to suppress austenite grain growth through adding rare earth metals (REM) and dispersing resulting REM acid sulfide, a technique to suppress austenite grain growth through adding Ca and dispersing resulting Ca acid sulfide, and a technique combining the ferrite nucleation capability of BN with oxide dispersion have been used.

[0009] For example, Patent Literature (PTL) 1 and PTL 2 describe techniques to suppress austenite grain growth and improve toughness of welded portions by adding REM in combination with Ti and dispersing the fine particles in steel.

[0010] Further, PTL 3 proposes a technique for improving toughness of HAZ by using CaS and a technique for improving toughness of base metal by hot rolling.

[0011] Further, as a measure for countering toughness decrease at the ICCGHAZ, a technique to increase base metal strength by adding Cu after suppressing the formation of MA by reducing C and Si is proposed in PTL 4.

[0012] In addition, in PTL 5, a technique is proposed using BN as a ferrite nucleation site in the heat-affected zone of large-heat input welding to refine HAZ microstructure and improve HAZ toughness.

[0013] In recent years, steel structures such as ships, marine structures, pressure vessels, line pipes, and offshore wind power generators have tended to become larger, and steel plates used in steel structures have become thicker and stronger accordingly. Increasing the amount of alloying elements is necessary to achieve steel plates that are both thicker and stronger, but adding large amounts of alloying elements makes securing the toughness of multilayer fill weld HAZ more difficult. To address this problem, PTL 6 describes a technique to improve low-temperature toughness by controlling hardness of a central segregation area.

CITATION LIST

Patent Literature

[0014]

PTL 1: JP S60-152626 A
PTL 2: JP S60-184663 A
PTL 3: JP 2012-184500 A
PTL 4: JP H05-186823 A
PTL 5: JP S61-253344 A
PTL 6: WO 2014/038200 A1

SUMMARY

(Technical Problem)

[0015] CTOD specification temperature in standards that specify joint CTOD properties (for example, American Petroleum Institute (API) Recommended Practice RP-2Z) is typically -10 °C.

[0016] However, to secure new resources in response to growing energy demand in recent years, the construction range of marine structures and the like has shifted to cold regions and deep-sea regions where resource development has not previously been possible. As a result, there is increasing demand for steel plates that are high-strength, thick-walled, and capable of meeting CTOD specification temperatures that are even lower than those specified by the API standard (for example, -40 °C).

[0017] According to investigation by the inventors, the conventional techniques described in PTL 1 to PTL 6 are unable to fully satisfy joint CTOD properties required for multilayer-fill-welded joints for low-temperature specifications in high-strength, thick-walled steel plates having a thickness exceeding 100 mm, which are in high demand in recent years.

[0018] For example, PTL 1 and PTL 2 propose techniques for suppressing coarsening of austenite microstructure in the HAZ by adding REM in combination with Ti and dispersing the fine particles in steel. These techniques are intended for steels having relatively low strength and low alloying element content, and therefore cannot be applied to steel material having higher strength and higher alloying element content, because such HAZ microstructure does not include ferrite.

[0019] The REM acid sulfide and the Ca acid sulfide in PTL 1 and PTL 2 are effective in inhibiting austenite grain growth. However, the effect of improving toughness by inhibiting austenite grain coarsening of the HAZ cannot alone achieve the joint CTOD properties at the temperatures of low-temperature specifications.

[0020] Further, the technique proposed in PTL 3 can satisfy the joint CTOD properties at normal operating temperatures (-10 °C). However, PTL 3 does not consider the joint CTOD properties at the temperatures of low-temperature specifications as described above.

[0021] Similarly, PTL 4 does not consider the joint CTOD properties at the temperatures of low-temperature specifications, and it is conceivable that only improving toughness of the ICCGHAZ by decreasing component content of the base metal cannot satisfy low-temperature CTOD specifications. Further, decreasing the alloying element content of the base metal to improve the toughness of the ICCGHAZ is a technical concept that conflicts with securing strength for thicker walls, making it difficult to apply to steel plates used in marine structures and the like.

[0022] The technique proposed in PTL 5 is effective when HAZ microstructure is mainly composed of ferrite and a cooling rate of a heat-affected zone is slow, as in large-heat input welding. However, in the case of steel plates exceeding 100 mm in thickness, the amount of alloy components contained in the base metal is relatively high and the heat input in multilayer fill welding is relatively small. Therefore, in multilayer fill welding of steel plates, HAZ microstructure is mainly bainite, and therefore the effect, mentioned above, of improving joint CTOD properties cannot be achieved.

[0023] Although PTL 6 proposes a technique for satisfying joint CTOD properties in a low temperature range for steel plates having a thickness of 100 mm or less, equivalent mechanical properties for ultra-thick steel plates having a thickness exceeding 100 mm has not been achieved.

[0024] As described above, it is difficult to say that a technique has been established to improve the toughness of the CGHAZ and the ICCGHAZ in the heat-affected zone of multilayer fill welding of high-strength steel plates having a thickness of more than 100 mm. In other words, there was a problem to be solved in improving the CTOD properties of the joint CTOD where a notch position is a bonded portion where the CGHAZ and the ICCGHAZ are mixed.

[0025] The present disclosure is made in view of the above problems faced by conventional technologies, and it would be helpful to provide a steel plate having a thickness exceeding 100 mm and high strength, as well as excellent CTOD properties at a joint where multilayer fill welding is applied (hereinafter also referred to as multilayer-fill-welded joint CTOD properties), and a method of producing same.

[0026] Hereinafter, high strength refers to a yield stress of 320 MPa or more at the mid-thickness position in a tensile test, and excellent multilayer-fill-welded joint CTOD properties refers to a crack opening displacement of 0.30 mm or more at each of a notch position CGHAZ and a sub-critically reheated / inter-critically reheated HAZ (SC/ICHAZ) boundary, at a test temperature of -40 °C.

(Solution to Problem)

[0027] To solve the technical problems described, the inventors have conducted extensive studies to improve joint CTOD properties. As a result, the inventors made the following discoveries.

(1) When pores generated in slab production remain without being closed during rolling, the pores may become defects in the steel plate and become fracture origins. In particular, in order to close pores of a mid-thickness part, it is necessary to appropriately introduce strain into the mid-thickness part during rolling, but this becomes difficult for steel plates having a thickness of more than 100 mm, and therefore remaining pores are a problem. However, the inventors and others have found that when rolling is performed at a high mid-thickness temperature of 950 °C or more, with an average deformation resistance ratio between the mid-thickness part and the surface of a steel plate of 0.70 or less, a rolling reduction ratio of 3 % or more per pass, and a cumulative rolling reduction ratio of 30 % or more, sufficient strain can be introduced into the mid-thickness part, and pores can be sufficiently closed.
Hereinafter, the mid-thickness part is a region from the center in the thickness direction to a thickness of 10 % of the slab or plate toward both main surfaces of the steel slab or plate.
(2) Further, the mid-thickness part of the slab has element segregation regions, and concentration of alloying elements in these regions causes coarse inclusions to be dispersed at low density. However, as described above, when rolling is performed at a mid-thickness temperature of 950 °C or more, with an average deformation resistance ratio between the mid-thickness part and the surface of the steel plate of 0.70 or less, a rolling reduction ratio of 3 % or more per pass, and a cumulative rolling reduction ratio of 30 % or more, the strain applied to the mid-thickness can be increased. As a result, it was found that coarse inclusions could be elongated and broken up, and fine inclusions could be dispersed to a high density. In addition, as a result of such dispersion, it was found that the HAZ toughness-improving effect of inclusions could be secured.
(3) Further, in order to precipitate and finely disperse TiN in the steel, which is effective in suppressing austenite grain growth, the inventors found that when the composition of the steel plate contains Ti and N satisfying the relationship of $1.50 \leq Ti/N \leq 5.00$, and, in addition, the equivalent carbon content Ceq is controlled to $[C] + [Mn] / 6 + ([Cu] + [Ni]) / 15 + ([Cr] + [Mo] + [V]) / 5 \leq 0.540$ %, and the weld cracking parameter Pcm is controlled to $[C] + [Si] / 30 + ([Mn] + [Cu] + [Cr]) / 20 + [Ni] / 60 + [Mo] / 15 + [V] / 10 + 5[B] \leq 0.250$ %, toughness of the matrix of HAZ with multilayer fill welding (hereinafter also referred to as multilayer-fill-welded joint HAZ) can be improved and good joint CTOD properties that can satisfy low-temperature CTOD specifications can be obtained.
In addition, the inventors and others also studied joint CTOD properties at the sub-critically reheated / inter-critically reheated HAZ (SC/ICHAZ) boundary, which is the boundary between the transformed and untransformed regions of the base metal during welding, as required by the British Standards (BS) EN10225 (2019) and API RP-2Z (2005), which specify the joint CTOD test method. As a result, the inventors made the following discoveries.
(4) In order to satisfy the joint CTOD property requirements at the SC/ICHAZ boundary at a test temperature of -40 °C, the toughness of base metal is dominant over the joint CTOD properties at the SC/ICHAZ boundary, and therefore the inventors found that crystal grain refinement so that the effective crystal grain size of the base metal microstructure is 20 μm or less is required to improve toughness of the base metal.
(5) In steel plates having a thickness exceeding 100 mm, the cooling rate of the mid-thickness part is smaller, resulting in coarsening of the crystal grains at this location. However, the inventors found that by rolling so that the cumulative rolling reduction ratio is 40 % or more under a set of conditions including an average deformation resistance ratio between the mid-thickness part and the surface of the steel plate of 0.70 or less at a mid-thickness temperature of less than 950 °C, sufficient strain can be introduced to the mid-thickness part and crystal grain refinement to the crystal grain size described above can be achieved.

[0028] The present disclosure is based on these findings and further studies. Primary features of the present disclosure are as follows.

1. A steel plate comprising a chemical composition containing (consisting of), in mass%, C: 0.02 % to 0.12 %, Si: 0.70 % or less, Mn: 0.3 % to 3.0 %, P: 0.050 % or less, S: 0.0050 % or less, Al: 0.002 % to 0.100%, Ti: 0.002 % to 0.060 %, N: 0.0130 % or less, and O: 0.0100 % or less, the balance being Fe and inevitable impurity, wherein the chemical composition satisfies Expressions (1) to (3) below,

average effective crystal grain size in a mid-thickness part is 20 μm or less, and the number of pores in the steel plate having a circle equivalent diameter of 180 μm or more is 0.10 or less per mm^2,

$$1.50 \leq Ti/N \leq 5.00 \quad \ldots (1)$$

$$0.280\ \% \leq Ceq\ (= [C] + [Mn] / 6 + ([Cu] + [Ni]) / 15 + ([Cr] + [Mo] + [V]) / 5) \leq 0.540\ \% \quad (2)$$

$$Pcm\ (= [C] + [Si] / 30 + ([Mn] + [Cu] + [Cr]) / 20 + [Ni] / 60 + [Mo] / 15 + [V] / 10 + 5[B]) \leq 0.250\ \% \quad (3)$$

where the square brackets in Expressions (1) to (3) indicate content in mass% of an element enclosed in the brackets and have a value of 0 when the element is not contained.

2. The steel plate according to 1, above, wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of Ni: 2.0 % or less, Ca: 0.0180 % or less, Cu: 2.00 % or less, Cr: 2.00 % or less, Mo: 2.00 % or less, Nb: 0.070 % or less, V: 0.20 % or less, W: 0.50 % or less, B: 0.0050 % or less, REM: 0.030 % or less, and Mg: 0.0150 % or less.

3. A method of producing the steel plate according to 1 or 2, above, the method comprising:

heating a slab having the chemical composition according to 1 or 2, above, to a temperature range from 990 °C or more to 1200 °C or less; hot rolling the under a set of conditions satisfying Expression (4) below, with a mid-thickness temperature of 950 °C or more, a rolling reduction ratio of 3 % or more per pass, and a cumulative rolling reduction ratio of 30 % or more; hot rolling at a mid-thickness temperature of less than 950 °C and a cumulative rolling reduction ratio of 40 % or more; then, when cooling to a cooling stop temperature of 600 °C or less at an average cooling rate at mid-thickness of 1.0 °C/s or more, when the cooling stop temperature is 500 °C or less, the average value from 700 °C to 500 °C is the average cooling rate, and when the cooling stop temperature is higher than 500 °C, the average value from 700 °C to the cooling stop temperature that is higher than 500 °C is the average cooling rate,

$$k_{fm}(\text{mid-thickness}) / k_{fm}(\text{surface}) \leq 0.70 \quad \ldots (4)$$

where k_{fm} is derived from Expression (5),
[Math. 1]

$$k_{fm} = e^{\left(0.126 - 1.75[C] + 0.594[C]^2 + \frac{2851 + 2968[C] - 1120[C]^2}{T_k}\right)} \times \varepsilon^{0.21} \times \dot{\varepsilon}^{0.13} \quad \cdots (5)$$

where ε is derived from Expression (6) and $\dot{\varepsilon}$ is derived from Expression (7)
[Math. 2]

$$\varepsilon = \ln\frac{h_1}{h_0} \quad \cdots (6)$$

[Math. 3]

$$\dot{\varepsilon} = \frac{2\pi n}{60\sqrt{r}} \times \sqrt{\frac{R}{h_0}} \times \ln\left(\frac{1}{1-r}\right) \quad \cdots (7)$$

where, in Expressions (5) to (7), [C] is mass% of C, T_k is absolute temperature (K) at mid-thickness or steel plate surface, h_0 is thickness on rolling entry, h_1 is thickness on rolling delivery, n is the roller rotational speed (rpm), r is rolling reduction, and R is roller radius (mm).

4. The method of producing a steel plate according to 3, above, wherein, after the cooling to the cooling stop temperature, a tempering treatment is performed at a temperature of 700 °C or less.

(Advantageous Effect)

[0029] According to the present disclosure, a steel plate having high strength and excellent multilayer-fill-welded joint CTOD properties may be provided, even when thickness exceeds 100 mm.

DETAILED DESCRIPTION

[0030] The reasons for limitations placed on the features of the present disclosure are explained below.

[Chemical composition]

[0031] First, the reasons for limiting the chemical composition of the steel plate and the slab to the ranges of the present disclosure are described. Hereinafter, "%" of each component means mass percentage unless otherwise specified.

C: 0.02 % to 0.12 %

[0032] C is an element that increases hardenability and improves strength of steel. C content needs to be 0.02 % or more. However, the C content exceeding 0.12 % increases the hardness of C-enriched portions and degrades joint CTOD properties. The C content is therefore in the range from 0.02 % to 0.12 %. The lower limit is preferably 0.04 %. The upper limit is preferably 0.09 %.

Si: 0.70 % or less

[0033] Si is an element inevitably contained as an impurity and has an action of improving strength. However, Si content exceeding 0.70 % degrades joint CTOD properties. The Si content is therefore limited to an upper limit of 0.70 %. The upper limit is preferably 0.50 % or less. A lower limit is not particularly limited. The lower limit is preferably about 0.04 %.

Mn: 0.3 % to 3.0 %

[0034] Mn is an element that has the effect of improving strength of the base metal and welded portion through improvement of hardenability of steel. To obtain this effect, addition of 0.3 % or more is required. Mn content is preferably 0.5 % or more. However, addition exceeding 3.0 % not only decreases weldability, but also causes excessive hardenability, which reduces toughness of the base metal and welded portion, resulting in degradation of joint CTOD properties. The Mn content is therefore in the range from 0.3 % to 3.0 %. The Mn content is preferably 2.8 % or less.

P: 0.050 % or less

[0035] P is an element that has a large effect of embrittling grain boundaries, and when added in large amounts decreases HAZ toughness and degrades joint CTOD properties. P content is therefore limited to 0.050 % or less. The P content is preferably 0.030 % or less. Decreasing P content as much as possible is desirable, and therefore a lower limit of the P content is not particularly limited. However, excessively low P content leads to increased refining time and higher costs. The P content is therefore preferably 0.001 % or more.

S: 0.0050 % or less

[0036] S is an element that degrades joint CTOD properties, and therefore an upper limit of S content is limited to 0.0050 %. The upper limit is preferably 0.0030 % or less. Decreasing S content as much as possible is desirable, and therefore a lower limit of the S content is not limited. However, excessively low S content leads to increased refining time and higher costs. The S content is therefore preferably 0.0001 % or more.

Al: 0.002 % to 0.100 %

[0037] Al is an element required for formation of inclusions to improve toughness of multilayer fill weld HAZ and to improve joint CTOD properties, and needs to be added at 0.002 % or more. Al content is preferably 0.005 % or more. However, excessive addition of more than 0.100 % degrades joint CTOD properties in a low temperature range. The Al content is therefore in the range from 0.002 % to 0.100 %. The Al content is preferably 0.075 % or less.

Ti: 0.002 % to 0.060 %

[0038] Ti precipitates in steel as TiN. Precipitated TiN has an effect of inhibiting coarsening of austenite grains in the base metal and HAZ, refining HAZ microstructure and improving joint CTOD properties. To obtain these effects, addition of 0.002 % or more is required. Ti content is preferably 0.005 % or more. However, when the Ti content exceeds 0.060 %, precipitation of solute Ti and coarse TiC decreases toughness of the heat-affected zone and degrades joint CTOD properties. The Ti content is therefore in the range from 0.002 % to 0.060 %. The Ti content is preferably 0.050 % or less.

N: 0.0130 % or less

[0039] N is an element that reduces HAZ toughness and degrades joint CTOD properties, and therefore an upper limit of N content is limited to 0.0130 %. Decreasing N content as much as possible is desirable, and therefore a lower limit of the N content is not limited. However, excessively low N content leads to increased refining time and higher costs. The N content is therefore preferably 0.0005 % or more.

O: 0.0100 % or less

[0040] O is an element that reduces HAZ toughness and degrades joint CTOD properties, and therefore an upper limit of O content is limited to 0.0100 %. Decreasing O content as much as possible is desirable, and therefore a lower limit of the O content is not limited. However, excessively low O content leads to increased refining time and higher costs. The O content is therefore preferably 0.0005 % or more.

[0041] The chemical composition of the steel plate according to an embodiment consists of the elements described above, with the balance being Fe and inevitable impurity.

[0042] Further, according to another embodiment, for the purpose of further improving strength, toughness of base metal, joint toughness, and the like, the chemical composition may further optionally contain at least one element selected from the group consisting of Ni, Ca, Cu, Cr, Mo, Nb, V, W, B, REM, and Mg, in a quantity indicated below.

Ni: 2.0 % or less

[0043] Ni is an element that can increase strength of steel plates without significantly degrading toughness of either the base metal or joints, but Ni addition increases production costs and environmental impact. Conventionally, Ni content was required to secure toughness of base metal and joint toughness. However, rolling with a controlled deformation resistance ratio makes it possible to produce high strength steel plates having a thickness of more than 100 mm and excellent multilayer-fill-welded joint CTOD properties without Ni content. On the other hand, Ni may be included to further improve toughness. In such a case, Ni content exceeding 2.0 % increases production costs and environmental impact. The Ni content is therefore limited to 2.0 % or less. The Ni content is more preferably 1.8 % or less. On the other hand, when Ni is added, 0.1 % or more is desirable.

Ca: 0.0180 % or less

[0044] Ca is an element that improves toughness of multilayer fill weld HAZ by forming acid sulfides having high stability at high temperatures, but content exceeding 0.0180 % instead degrades joint CTOD properties. The upper limit of Ca content is therefore limited to 0.0180 %. The Ca content is more preferably 0.0160 % or less. On the other hand, when Ca is added, 0.0002 % or more is desirable.

Cu: 2.00 % or less

[0045] Cu is an element that can increase strength of steel plates without significantly degrading toughness of the base metal and joints. However, when Cu content exceeds 2.00 %, surface cracks caused by a Cu-enriched layer that forms just below scale become a problem. The Cu content is therefore limited to 2.00 % or less. The Cu content is more preferably 1.50 % or less. On the other hand, when Cu is added, 0.05 % or more is desirable.

Cr: 2.00 % or less

[0046] Cr is an element that has an effect of increasing strength of steel through improving hardenability. However, Cr content exceeding 2.00 % degrades joint CTOD properties, and therefore the Cr content is limited to 2.00 % or less. The Cr content is more preferably 1.50 % or less. On the other hand, when Cr is added, 0.05 % or more is desirable.

Mo: 2.00 % or less

[0047] Mo is an element that has an effect of increasing strength of steel through improving hardenability. However, Mo content exceeding 2.00 % degrades joint CTOD properties, and therefore the Mo content is limited to 2.00 % or less. The Mo content is more preferably 1.50 % or less. On the other hand, when Mo is added, 0.05 % or more is desirable.

Nb: 0.070 % or less

[0048] Nb is an element that widens a non-recrystallization temperature range of austenite phase. Therefore, the addition of Nb is effective for efficiently rolling a non-recrystallized region to obtain a fine grain microstructure. When Nb is added, 0.005 % or more is desirable. On the other hand, Nb addition exceeding 0.070 % reduces joint CTOD properties, and therefore Nb content is limited to 0.070 % or less. The Nb content is more preferably 0.050 % or less.

V: 0.20 % or less

[0049] V is an element that improves strength of the base metal, and when V is added, 0.01 % or more is desirable. On the other hand, V content exceeding 0.20 % decreases HAZ toughness and degrades joint CTOD properties, and therefore the V content is limited to 0.20 % or less. The V content is more preferably 0.15 % or less.

W: 0.50 % or less

[0050] W is an element that improves strength of the base metal, and when W is added, 0.05 % or more is desirable. On the other hand, W content exceeding 0.50 % decreases HAZ toughness and degrades joint CTOD properties, and therefore the W content is limited to 0.50 % or less. The W content is more preferably 0.40 % or less.

B: 0.0050 % or less

[0051] B is an element that can improve hardenability and thereby strength of steel plates with only a very small amount of B. When B is added, 0.0005 % or more is desirable. On the other hand, B content exceeding 0.0050 % decreases HAZ toughness and degrades joint CTOD properties, and therefore the B content is limited to 0.0050 % or less. The B content is more preferably 0.0040 % or less.

REM: 0.030 % or less

[0052] Rare earth metals (REM) are elements that inhibit austenite grain growth in the HAZ and improve HAZ toughness by forming acid sulfide inclusions. When REM is added, 0.001 % or more is desirable. On the other hand, REM content exceeding 0.030 % decreases base metal toughness and HAZ toughness and degrades joint CTOD properties. The REM content is therefore limited to 0.030 % or less. The REM content is more preferably 0.025 % or less.

Mg: 0.0150 % or less

[0053] Mg is an element that inhibits growth of austenite grains in the heat-affected zone by forming oxide-based inclusions, improving toughness of the heat-affected zone. When Mg is added, 0.0002 % or more is desirable. On the other hand, when the Mg content exceeds 0.0150 %, the addition effect becomes saturated, and thus an effect commensurate with the content cannot be expected, which becomes economically disadvantageous. The Mg content is therefore limited to 0.0150 % or less. The Mg content is more preferably 0.0100 % or less.

[0054] According to the present disclosure, the chemical composition of the steel plate and the slab is required to further satisfy the Ti/N, Ceq, and Pcm conditions, respectively, as described below.

$$1.50 \leq \mathrm{Ti/N} \leq 5.00 \qquad \ldots (1)$$

[0055] Ti/N controls the amount of solute N and the precipitation state of TiN in the HAZ. When Ti/N is less than 1.50, HAZ toughness degrades due to the presence of solute N that is not fixed as TiN, and joint CTOD properties degrade. On the other hand, when Ti/N is more than 5.00, HAZ toughness degrades due to precipitation of coarse TiN, and joint CTOD properties degrade. The Ti/N range is therefore 1.50 to 5.00. The lower limit is preferably 1.80. The upper limit is preferably 4.50.

Ceq: 0.280 % or more and 0.540 % or less

[0056] When the equivalent carbon content Ceq, defined by the following Expression (2), is increased, microstructure having poor toughness such as martensite austenite constituent and bainite increases in HAZ microstructure, and therefore HAZ toughness degrades. That is, when Ceq is more than 0.540 %, the HAZ matrix itself suffers toughness degradation, and therefore even with HAZ toughness enhancement techniques through inclusions, the required joint CTOD properties cannot be satisfied. On the other hand, when Ceq is less than 0.280 %, the target strength cannot be secured. The Ceq range is therefore 0.280 % to 0.540 %. The lower limit is preferably 0.300 %. The upper limit is preferably 0.500 %.

$$\text{Ceq}\ (\%) = [\text{C}] + [\text{Mn}] / 6 + ([\text{Cu}] + [\text{Ni}]) / 15 + ([\text{Cr}] + [\text{Mo}] + [\text{V}]) / 5 \quad (2)$$

Pcm: 0.250 % or less

[0057] When the weld cracking parameter Pcm defined by the following Expression (3) is increased, microstructure having poor toughness such as martensite austenite constituent and bainite increases in HAZ microstructure, and therefore HAZ toughness degrades. When Pcm exceeds 0.250 %, the HAZ matrix itself suffers toughness degradation, and therefore the required joint CTOD properties cannot be obtained. Pcm is therefore 0.250 % or less. Pcm is preferably 0.240 % or less. A lower limit is not particularly limited, but excessive attempts to reduce Pcm result in too low a Ceq value, and therefore about 0.140 % is preferred.

$$\text{Pcm}\ (\%) = [\text{C}] + [\text{Si}] / 30 + ([\text{Mn}] + [\text{Cu}] + [\text{Cr}]) / 20 + [\text{Ni}] / 60 + [\text{Mo}] / 15 + [\text{V}] / 10 + 5[\text{B}] \quad (3)$$

[0058] The square brackets in Expressions (1) to (3) indicate content in mass% of an element enclosed in the brackets and have a value of 0 when the element is not contained.

[Average effective crystal grain size]

[0059] Average effective crystal grain size at mid-thickness part: 20 μm or less

[0060] According to the present disclosure, average effective crystal grain size of microstructure in the mid-thickness part of the steel plate having a thickness exceeding 100 mm is 20 μm or less. Crystal grains in the mid-thickness part in which segregation is easily caused are refined as described above to improve toughness of the base metal, thereby increasing joint CTOD properties at SC/ICHAZ boundaries. The smaller the average effective crystal grain size, the more advantageous, and therefore the average effective crystal grain size is not particularly limited. Typically, a lower limit is about 1 μm.

[0061] Here, "effective crystal grain size" is defined as the circle equivalent diameter of a crystal grain surrounded by grain boundaries of crystal grains having an orientation difference of 15° or more, that is, large-angle grain boundaries. Further, the average effective crystal grain size in the mid-thickness part can be measured by a method described in the following EXAMPLES section.

[Pore number density]

Pore number density: 0.10/mm^2 or less

[0062] As mentioned above, residual pores in the steel plates become fracture origins, which degrade joint CTOD properties. In particular, when the number of pores having a circle equivalent diameter of 180 μm or more per mm^2 (hereinafter also referred to simply as "pore number density") in the steel plate exceeds 0.10, the possibility of insufficient crack opening displacement (δ) in the joint CTOD test becomes extremely high. Further, as the pore number density increases, the yield stress at the mid-thickness part of the base material decreases. Accordingly, limiting the pore number density to 0.10/mm^2 or less is important.

[0063] Hereinafter, the pore number density means an average number density across full thickness × full width in a cross-section parallel to the transverse direction of a steel plate (cross section perpendicular to the rolling direction). The pore number density may be measured by the method described in the EXAMPLES section below, but the measurement method is not limited to the method described in the EXAMPLES section and any known measurement method may be used for measurement.

[0064] Further, measurement frequency of the pore number density may be measuring one or two cross-sections of any one steel plate among steel plates prepared from steel slabs under the same steelmaking and rolling conditions. As long as the slab steelmaking method and rolling conditions are not changed, the pore number density is highly reproducible, and therefore measurement results at the above measurement frequency are representative of the whole.

[Production method]

[0065] Next, the reasons for limiting each condition in the method of producing the steel plate according to the present disclosure are explained below. In the following description, "temperature" means temperature at the mid-thickness part, unless otherwise noted. Temperature at the mid-thickness part may be measured as described in the following EXAMPLES section. However, for example, on an actual production line, temperature at a surface of a steel plate may be measured using a radiation thermometer and temperature at the mid-thickness part may be determined by heat transfer calculation.

• Slab heating conditions

[0066] According to the present disclosure, a method of preparing the slab is not particularly limited, and any known steelmaking method may be applied, such as a converter, an electric furnace, a vacuum melting furnace, and the like. The slab may be produced, for example, by a continuous casting method. Further, molten steel from which the slab is produced may be further subjected to secondary refining such as ladle refining.

[0067] The slab produced as described above is heated to a temperature of 990 °C or more and 1200 °C or less. When the heating temperature is lower than 990 °C, the following conditions of hot rolling cannot be met, and a sufficient effect cannot be obtained. On the other hand, when the heating temperature is higher than 1200 °C, austenite grains become coarse and the desired fine grain microstructure cannot be obtained after controlled rolling. For these reasons, the range of the heating temperature is 990 °C or more to 1200 °C or less. The lower limit of temperature is preferably 990 °C, and the upper limit of temperature is preferably 1180 °C.

• Hot rolling conditions

[0068] During the hot rolling, it is important to control hot rolling conditions in both a recrystallization temperature range and a non-recrystallization temperature range.

[0069] In the recrystallization temperature range, rolling is performed at 950 °C or more, the rolling reduction ratio is 3 % or more per pass, and the cumulative rolling reduction ratio is 30 % or more, under a set of conditions including the average deformation resistance ratio between the mid-thickness part and the surface of the steel plate being 0.70 or less.

[Deformation resistance ratio between mid-thickness part and surface of steel plate: 0.70 or less]

[0070] According to the present disclosure, the average value of the ratio of the deformation resistance k_{fm} (mid-thickness) of the mid-thickness part to the deformation resistance k_{fm} (surface) of the surface of the steel plate, as defined by the following Expressions (5) to (7), is 0.70 or less (Expression (4)). Specifically, the average deformation resistance ratio between the mid-thickness part and the surface made to be 0.70 or less by rolling at the timing when the temperature difference between mid-thickness and surface is at an appropriate value according to the mass% of C, while adjusting roller rotational speed, roller radius, and roll gap to appropriate values.

$$k_{fm}(\text{mid-thickness}) \;/\; k_{fm}(\text{surface}) \leq 0.70 \qquad \ldots (4)$$

(Here, k_{fm} is derived from Expression (5))
[Math. 1]

$$k_{fm} = e^{\left(0.126-1.75[C]+0.594[C]^{2}+\frac{2851+2968[C]-1120[C]^{2}}{T_k}\right)} \times \varepsilon^{0.21} \times \dot{\varepsilon}^{0.13} \qquad \cdots (5)$$

where ε is derived from Expression (6) and $\dot{\varepsilon}$ is derived from Expression (7)
[Math. 2]

$$\varepsilon = \ln\frac{h_1}{h_0} \qquad \cdots (6)$$

[Math. 3]

$$\dot{\varepsilon} = \frac{2\pi n}{60\sqrt{r}} \times \sqrt{\frac{R}{h_0}} \times \ln\left(\frac{1}{1-r}\right) \quad \cdots (7)$$

[0071] In Expressions (5) to (7), [C] is mass% of C, T_k is absolute temperature (K) at the point where k_{fm} is determined, that is, the mid-thickness or steel plate surface, h_0 is thickness on rolling entry, h_1 is thickness on rolling delivery, n is the roller rotational speed (rpm), r is rolling reduction, and R is roller radius (mm).

[0072] Temperature at the surface may be measured by a radiation thermometer, and temperature at the mid-thickness part may be measured as described in the following EXAMPLES section. However, for example, on an actual production line, temperature at a surface of a steel plate may be measured using a radiation thermometer and temperature at the mid-thickness part may be determined by heat transfer calculation.

[0073] Under conditions where the average value of the deformation resistance ratio between the mid-thickness part and the surface of a steel plate according to Expression (4) exceeds 0.70, sufficient strain cannot be introduced into the mid-thickness part of a steel plate having a thickness exceeding 100 mm, and pores will remain. As a result, the pore number density cannot be made to be 0.10/mm^2 or less. Therefore, the ratio of deformation resistance between the mid-thickness part and the surface of the steel plate is 0.70 or less, the rolling reduction ratio is 3 % or more per pass, and the cumulative rolling reduction ratio is 30 % or more.

[Rolling at 950 °C or more]

[0074] A purpose of rolling at 950 °C or more is to close pores in addition to refining microstructure by recrystallization and refining and dispersing coarse inclusions. That is, rolling at less than 950 °C makes it difficult for recrystallization to occur, resulting in insufficient refinement of austenite grains.

[Rolling reduction ratio of 3 % or more per pass]

[0075] Rolling with a reduction ratio of less than 3 % per pass does not introduce sufficient strain in the mid-thickness part, and even when rolling reduction ratio is 3 % or more per pass, a cumulative rolling reduction ratio of less than 30 % does not sufficiently close pores.

[Rolling at less than 950 °C]

[0076] In rolling at the non-recrystallization temperature range, that is, less than 950 °C, the cumulative rolling reduction ratio is 40 % or more, under the same condition of the average deformation resistance ratio between the mid-thickness part and the surface of the steel plate being 0.70 or less.

[0077] The steel according to the present disclosure is difficult to recrystallize when rolled at temperatures less than 950 °C, and therefore the strain introduced by rolling is not consumed by recrystallization but accumulates and acts as nucleation sites in the subsequent cooling process. As a result, the finally obtained steel plate can have a refined microstructure. However, the crystal grain refinement effect is insufficient under conditions where the cumulative rolling reduction ratio in this temperature range is less than 40 %. Further, in a steel plate having a thickness exceeding 100 mm, under a set of conditions where the average deformation resistance ratio between the mid-thickness part and the surface of the steel plate exceeds 0.70, sufficient strain cannot be introduced into the mid-thickness part, the refinement of the final microstructure in the mid-thickness part becomes insufficient, and the average effective crystal grain size in the mid-thickness part cannot be 20 μm or less.

[0078] Therefore, rolling at the non-recrystallization temperature range has a cumulative rolling reduction ratio of 40 % or more, and the average deformation resistance ratio between the mid-thickness part and the surface of the steel plate is 0.70 or less.

[Cooling]

[0079] After completion of the hot rolling, the obtained hot-rolled steel plate is cooled. The cooling can be performed by any method as long as the following conditions are met. For example, the cooling may be performed by water cooling.

Average cooling rate: 1.0 °C/s or more

[0080] When the average cooling rate at the mid-thickness temperature is less than 1.0 °C/s, coarse ferrite phase occurs in the base metal microstructure, and therefore joint CTOD properties of the SC/ICHAZ degrade. The average cooling rate at the mid-thickness position is therefore 1.0 °C/s or more. On the other hand, when the average cooling rate is greater than 50.0 °C/s, an increase in hard bainite phase increases strength of the base metal and degrades joint CTOD properties of the SC/ICHAZ, and therefore the cooling rate is preferably 50.0 °C/s or less.

[0081] According to the present disclosure, when the cooling stop temperature indicated in the next paragraph is 500 °C or less, the average value from 700 °C to 500 °C is the average cooling rate described above, and when the cooling stop temperature is higher than 500 °C, the average value from 700 °C to the cooling stop temperature higher than 500 °C is the average cooling rate described above.

Cooling stop temperature: 600 °C or less

[0082] In the cooling, the hot-rolled steel plate is cooled to a cooling stop temperature that is 600 °C or less at mid-thickness temperature. When the cooling stop temperature is higher than 600 °C, microstructure after transformation becomes coarse, resulting in insufficient base metal strength and degradation of SC/ICHAZ joint CTOD properties. The cooling stop temperature is therefore 600 °C or less.

[Tempering treatment]

Tempering Temperature: 700 °C or less

[0083] After the cooling stop, the steel plate may be subjected to tempering treatment. Tempering treatment can further improve the toughness of base metal. At this time, a tempering temperature higher than 700 °C generates a coarse ferrite phase, thus degrading toughness of the SCHAZ. The tempering temperature is therefore preferably 700 °C or less. The tempering temperature is more preferably 650 °C or less. A lower limit of the tempering temperature is not particularly limited. The lower limit may be about 300 °C.

[0084] In the method of production according to the present disclosure, anything not described herein may follow a conventional method.

EXAMPLES

[0085] More detailed description is given below based on examples. The following examples merely represent preferred examples, and the present disclosure is not limited to these examples.

[0086] Slabs having a chemical composition listed in Table 1 were used to produce steel plates under the production conditions listed in Table 2. During hot rolling, a thermocouple was attached in a central position in the longitudinal direction, width direction, and thickness direction of each steel material to be hot rolled to measure the temperature of the mid-thickness part. At the same time, surface temperature of the steel material was measured with a radiation thermometer.

[0087] The average effective crystal grain size, the pore number density, and the yield stress of each obtained steel plate were measured by the following methods.

[Average effective crystal grain size]

[0088] A sample was collected from each obtained steel plate so that a measurement position was located at a central position in the longitudinal direction, width direction, and thickness direction of the steel plate. Then, after mirror polishing a surface of the sample, electron backscatter pattern (EBSP) analysis was performed under the following conditions. From an obtained crystal orientation map, a circle equivalent diameter of a microstructure surrounded by a large-angle grain boundary having an orientation difference of 15° or more from adjacent crystal grains was determined, and an average of the circle equivalent diameters in the following analysis region was defined as an average effective crystal grain size.

EBSP Conditions

[0089]

- Analysis region: 1 mm × 1 mm area at mid-thickness
- Step size: 0.4 μm

[Pore number density]

[0090] For detection of defects inside of a steel plate, ultrasonic testing is often used because ultrasonic testing can perform nondestructive inspection. However, to precisely check the state of defects, the inside of the steel plates were directly observed to measure the pore number density. First, a sample was taken in a thickness direction cross-section parallel to the plate transverse direction (cross-section perpendicular to the rolling direction) of the rolled material from a central position of the plate length, for observation where the observation plane is the full thickness × full width size, and finished with mirror polishing. Next, the mirror-polished sample was observed using an optical microscope and image captured. The obtained images were subjected to image analysis to determine the circle equivalent diameter of each pore found in the image. The number of pores having a size of 180 μm or more was divided by the measured area (plate thickness × plate width) to determine the number of pores having a circle equivalent diameter of 180 μm or more per mm^2.

[Yield stress]

[0091] Tensile tests were conducted according to EN 10002-1 to determine yield stress (YS) at 1/4 and 1/2 positions of thickness (t) of each steel plate. For each tensile test, a round bar tensile test piece having a parallel portion diameter of 14 mm and a parallel portion length of 70 mm was used, the test pieces being taken parallel to the plate transverse direction from 1/4 and 1/2 positions of plate thickness. In the tensile test, when an upper yield point appeared, the upper yield point was determined to be yield stress. Further, when an upper yield point did not appear, a 0.2 % proof stress was determined to be yield stress.

[0092] Next, each steel plate was used to produce a multilayer-fill-welded joint. Each obtained multilayer-fill-welded joint was subjected to a joint CTOD test to measure the amount of crack opening displacement in the CGHAZ and the amount of crack opening displacement in the SC/ICHAZ. The conditions for production of the multilayer-fill-welded joints and the conditions of the joint CTOD tests are described below.

[Joint CTOD test]

[0093] Welded joints used for the joint CTOD tests were produced by submerged arc welding (multilayer fill welding) with K groove geometry and heat input of 5.0 kJ/mm. The test method was based on BS EN10225 (2019), and the crack opening displacement [CTOD value (δ)] was evaluated at the test temperature of -40 °C using test pieces each having a square cross-section of t × t (where t is plate thickness).

[0094] In the joint CTOD tests described above, a test where the notch position was set as the CGHAZ on the linear side of the K groove and a test where the notch position was set at the SC/ICHAZ boundary were conducted, and the δ of the CGHAZ and the δ of the SC/ICHAZ boundary were measured, respectively. For each steel plate, the test was performed for three test pieces per notch position and the lowest value measured was taken as δ.

[0095] After the tests, on a fracture surface of the test piece, the end of a fatigue precrack was confirmed to be located both in the CGHAZ and at the SC/ICHAZ boundary specified by EN10225 (2019). In the case of joint CTOD test of multilayer fill welding, even when a notch position is located in the CGHAZ, a certain amount of the ICCGHAZ is also included, and therefore the test result reflects toughness of both the CGHAZ and the ICCGHAZ.

[0096] The measurement results are listed in Table 2.

[Table 1]

Table 1

Ref. sign	Chemical composition (mass%)																		Ti/N	Ceq (%)	Pcm (%)	Classification
	C	Si	Mn	P	S	Al	Ni	Ti	N	O	Ca	Cu	Cr	Mo	Nb	V	W	B	REM	Mg			
A	0.04	0.21	0.4	0.011	0.0008	0.092	0.9	0.041	0.0085	0.0041	0.0078	-	1.81	-	0.066	-	-	-	-	0.0044	4.82	0.529	0.173	Conforming steel
B	0.03	0.62	0.6	0.012	0.0041	0.063	1.0	0.037	0.0078	0.0078	-	-	-	1.70	-	-	-	-	-	-	4.74	0.537	0.211	Conforming steel
C	0.10	0.43	1.8	0.020	0.0037	0.021	1.7	0.002	0.0005	0.0070	-	-	-	-	-	-	-	0.0013	0.024	-	4.00	0.513	0.239	Conforming steel
D	0.08	0.31	1.7	0.047	0.0007	0.040	0.9	0.014	0.0039	0.0055	0.0049	-	-	-	-	-	-	-	0.018	0.0131	3.59	0.423	0.190	Conforming steel
E	0.06	0.14	1.9	0.028	0.0020	0.073	1.7	0.004	0.0010	0.0033	-	0.20	-	-	-	-	-	-	-	-	4.00	0.503	0.198	Conforming steel
F	0.09	0.36	0.8	0.040	0.0009	0.053	1.1	0.011	0.0060	0.0087	0.0071	1.51	0.22	-	-	-	-	-	-	-	1.83	0.441	0.247	Conforming steel
G	0.02	0.53	2.1	0.029	0.0010	0.047	-	0.036	0.0095	0.0040	-	-	-	-	-	-	-	-	-	-	3.79	0.370	0.143	Conforming steel
H	0.07	0.68	2.0	0.009	0.0042	0.090	1.6	0.013	0.0039	0.0015	-	-	-	-	0.010	-	0.19	-	-	-	3.33	0.510	0.219	Conforming steel
I	0.04	0.65	1.2	0.020	0.0035	0.074	1.7	0.003	0.0007	0.0075	0.0094	-	-	0.72	-	0.06	-	-	-	-	4.29	0.509	0.204	Conforming steel
J	0.12	0.07	0.3	0.040	0.0041	0.018	2.0	0.054	0.0110	0.0090	0.0068	-	-	-	-	-	-	-	-	-	4.91	0.303	0.171	Conforming steel
K	0.10	0.62	1.3	0.045	0.0045	0.047	1.4	0.054	0.0118	0.0041	-	-	0.40	-	-	-	-	-	-	-	4.58	0.490	0.229	Conforming steel
L	0.02	0.14	2.9	0.045	0.0018	0.049	-	0.029	0.0065	0.0026	0.0075	-	-	-	-	-	0.43	-	-	-	4.46	0.503	0.170	Conforming steel
M	0.11	0.11	0.5	0.031	0.0013	0.033	1.8	0.012	0.0036	0.0083	0.0161	-	-	-	-	0.16	-	0.0044	-	-	3.33	0.345	0.207	Conforming steel
N	0.03	0.08	2.8	0.016	0.0015	0.099	0.2	0.015	0.0039	0.0093	-	-	-	-	-	-	-	-	-	-	3.85	0.510	0.176	Conforming steel
O	0.14	0.25	1.4	0.036	0.0024	0.037	1.5	0.041	0.0115	0.0098	-	-	-	-	-	-	-	-	-	-	3.57	0.473	0.243	Comparative steel
P	0.05	0.52	1.9	0.020	0.0010	0.119	0.8	0.005	0.0019	0.0090	0.0133	-	0.43	-	-	-	-	-	-	0.0052	2.63	0.506	0.197	Comparative steel
Q	0.03	0.24	2.0	0.019	0.0058	0.058	1.2	0.013	0.0039	0.0079	-	-	-	-	-	0.14	-	-	-	-	3.33	0.471	0.172	Comparative steel
R	0.10	0.13	1.5	0.021	0.0033	0.093	1.5	0.042	0.0077	0.0090	-	-	-	-	0.018	-	-	-	-	-	5.45	0.450	0.204	Comparative steel
S	0.11	0.08	1.4	0.055	0.0027	0.027	1.6	0.025	0.0061	0.0019	-	0.30	0.11	-	0.037	-	-	-	-	-	4.10	0.492	0.230	Comparative steel
T	0.11	0.69	0.3	0.030	0.0007	0.025	1.7	0.026	0.0070	0.0062	0.0025	-	0.30	-	-	-	-	0.0033	0.031	-	3.71	0.333	0.208	Comparative steel
U	0.04	0.47	2.0	0.028	0.0039	0.008	1.4	0.062	0.0125	0.0045	0.0046	-	-	-	-	-	-	-	-	-	4.96	0.467	0.179	Comparative steel
V	0.09	0.34	1.6	0.050	0.0027	0.058	0.3	0.043	0.0140	0.0022	-	1.12	-	-	-	-	-	-	-	-	3.07	0.451	0.242	Comparative steel
W	0.03	0.17	1.7	0.042	0.0008	0.036	1.5	0.005	0.0096	0.0015	-	-	-	-	-	-	0.23	0.0016	-	-	0.52	0.413	0.154	Comparative steel
X	0.05	0.72	2.3	0.034	0.0039	0.072	1.0	0.021	0.0050	0.0008	0.0168	-	-	-	-	-	-	-	-	-	4.20	0.500	0.206	Comparative steel
Y	0.02	0.11	3.1	0.031	0.0032	0.052	-	0.045	0.0099	0.0052	0.0050	-	-	-	-	-	-	0.0009	-	-	4.55	0.537	0.183	Comparative steel
Z	0.03	0.15	1.7	0.046	0.0042	0.016	1.9	0.009	0.0052	0.0037	0.0186	-	-	-	-	-	-	-	0.021	-	1.73	0.440	0.152	Comparative steel
AA	0.07	0.46	1.8	0.010	0.0023	0.001	1.3	0.030	0.0063	0.0017	0.0132	-	-	0.21	-	-	-	-	0.004	0.0140	4.76	0.499	0.211	Comparative steel
AB	0.08	0.51	2.2	0.047	0.0035	0.066	1.0	0.020	0.0044	0.0120	-	-	-	-	-	-	-	-	-	-	4.55	0.513	0.224	Comparative steel
AC	0.12	0.55	2.0	0.036	0.0031	0.057	0.9	0.040	0.0095	0.0024	-	-	-	-	0.021	-	-	-	-	-	4.21	0.513	0.253	Comparative steel
AD	0.02	0.55	0.3	0.025	0.0031	0.083	0.1	0.028	0.0063	0.0018	0.0085	-	2.12	-	-	0.09	-	-	-	-	4.44	0.519	0.170	Comparative steel
AE	0.08	0.34	1.6	0.032	0.0016	0.057	0.4	0.037	0.0089	0.0010	0.0020	-	-	-	-	0.21	0.12	-	-	-	4.16	0.415	0.199	Comparative steel
AF	0.01	0.02	2.0	0.046	0.0033	0.028	-	0.036	0.0077	0.0039	-	-	-	-	-	-	-	0.0022	-	-	4.68	0.343	0.122	Comparative steel
AG	0.11	0.11	0.2	0.032	0.0040	0.020	-	0.021	0.0053	0.0063	-	-	0.54	0.54	-	-	-	-	-	-	3.96	0.359	0.187	Comparative steel
AH	0.09	0.12	2.0	0.022	0.0026	0.024	0.4	0.001	0.0006	0.0049	-	-	-	-	-	-	-	-	-	-	1.67	0.450	0.201	Comparative steel
AI	0.08	0.34	1.7	0.047	0.0049	0.020	0.6	0.032	0.0073	0.0086	0.0025	-	-	-	0.093	-	-	-	-	-	4.38	0.403	0.186	Comparative steel
AJ	0.04	0.23	1.9	0.015	0.0039	0.046	0.5	0.016	0.0046	0.0058	-	-	-	-	-	-	-	0.0061	-	-	3.48	0.387	0.181	Comparative steel
AK	0.07	0.32	0.8	0.035	0.0026	0.070	-	0.015	0.0054	0.0032	0.0027	-	-	-	-	-	-	-	-	-	2.78	0.203	0.121	Comparative steel
AL	0.10	0.28	2.0	0.030	0.0019	0.050	1.1	0.021	0.0052	0.0055	-	-	0.20	-	-	-	-	-	-	-	4.04	0.547	0.238	Comparative steel
AM	0.11	0.23	2.1	0.029	0.0031	0.046	0.8	0.012	0.0030	0.0077	-	-	-	-	-	-	0.60	-	-	-	4.00	0.513	0.236	Comparative steel
AN	0.03	0.57	0.3	0.025	0.0039	0.051	-	0.011	0.0062	0.0057	0.0165	-	-	2.10	-	-	-	-	-	-	1.77	0.500	0.204	Comparative steel
AO	0.07	0.27	1.2	0.013	0.0025	0.038	0.6	0.013	0.0042	0.0025	0.0021	-	-	-	-	-	-	-	-	-	3.10	0.310	0.149	Conforming steel
AP	0.08	0.18	1.5	0.009	0.0020	0.035	-	0.012	0.0038	0.0023	0.0022	-	-	-	-	-	-	-	-	-	3.16	0.330	0.161	Conforming steel

Note 1: balance is Fe and inevitable impurity

Note 2: underlining indicates value outside scope of present disclosure

Note 3: Ceq = [C] + [Mn] / 6 + ([Cu] + [Ni]) / 15 + ([Cr] + [Mo] + [V]) / 5

Pcm = [C] + [Si] / 30 + ([Mn] + [Cu] + [Cr]) / 20 + [Ni] / 60 + [Mo] / 15 + [V] / 10 + 5[B]

[Table 2]

[0097]

Table 2

No.	Steel sample ID	Thickness (mm)	Production conditions								Measurement results						Classification
			Heating	Hot rolling				Cooling		Tempering	Base metal properties				Welded portion properties		
			Heating temp. (°C)	Cumulative rolling reduction ratio at 950 °C or more and rolling reduction of 3 % or more per pass (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling at 950 °C or more	Cumulative rolling reduction ratio below 950 °C (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Average effective crystal grain size of mid-thickness part (μm)	Pore number density (per mm^2)	YS at 1/4 position of base metal (MPa)	YS at 1/2 position of base metal (MPa)	δ of CGHAZ at -40°C (mm)	δ of SC/ICHAZ boundary at -40 °C (mm)	
1	A	118	1008	49	0.70	56	0.58	5.8	218	-	14	0.04	518	513	0.84	1.18	Example
2	A	144	1108	39	0.68	51	0.58	9.4	512	750	39	0.02	522	519	0.39	0.31	Example
3	B	151	1005	41	0.67	45	0.59	8.9	379	500	10	0.08	337	326	0.58	0.66	Example
4	B	109	1126	49	<u>0.79</u>	60	0.54	6.4	203	-	19	<u>0.23</u>	407	370	0.25	0.21	Comparative Example
5	C	142	<u>976</u>	<u>19</u>	0.61	48	0.63	1.4	541	-	<u>53</u>	<u>0.28</u>	602	546	0.13	0.21	Comparative Example
6	C	109	1140	47	0.66	70	0.63	4.2	344	-	14	0.09	548	536	0.55	0.41	Example
7	D	126	1095	<u>26</u>	0.69	57	0.67	3.8	463	-	<u>47</u>	0.25	466	428	0.17	0.15	Comparative Example
8	D	133	1026	39	0.65	69	0.68	2.4	526	-	20	0.05	440	435	0.43	0.36	Example

(continued)

No.	Steel sample ID	Thickness (mm)	Production conditions								Measurement results						Classification
			Heating	Hot rolling				Cooling		Tempering	Base metal properties				Welded portion properties		
			Heating temp. (°C)	Cumulative rolling reduction ratio at 950 °C or more and rolling reduction of 3 % or more per pass (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling at 950 °C or more	Cumulative rolling reduction ratio below 950 °C (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Average effective crystal grain size of mid-thickness part (μm)	Pore number density (per mm^2)	YS at 1/4 position of base metal (MPa)	YS at 1/2 position of base metal (MPa)	δ of CGHAZ at -40°C (mm)	δ of SC/ICHAZ boundary at -40 °C (mm)	
9	E	145	1190	30	0.58	59	0.66	9.6	315	600	15	0.01	543	541	1.16	0.74	Example
10	E	148	1070	43	0.69	33	0.70	4.8	504	-	43	0.06	520	514	0.33	0.26	Comparative Example
11	F	140	1189	39	0.58	61	0.73	41.4	356	-	36	0.10	545	528	0.49	0.29	Comparative Example
12	F	110	1179	31	0.56	47	0.65	28.2	379	-	19	0.09	547	533	1.02	0.85	Example
13	G	147	1089	34	0.59	69	0.65	44.7	447	550	18	0.03	484	481	0.64	0.99	Example
14	G	124	1171	41	0.56	62	0.50	63.2	587	-	14	0.08	620	611	0.52	0.28	Example
15	H	200	1050	37	0.53	57	0.60	49.0	560	600	19	0.02	526	523	0.72	0.61	Example
16	H	101	1270	35	0.57	46	0.51	9.3	306	-	37	0.03	518	515	0.44	0.16	Comparative Example
17	I	175	1011	47	0.64	48	0.61	2.4	364	-	14	0.02	491	487	0.52	0.93	Example

(continued)

No.	Steel sample ID	Thickness (mm)	Production conditions								Measurement results						Classification
			Heating	Hot rolling				Cooling		Tempering	Base metal properties				Welded portion properties		
			Heating temp. (°C)	Cumulative rolling reduction ratio at 950 °C or more and rolling reduction of 3 % or more per pass (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling at 950 °C or more	Cumulative rolling reduction ratio below 950 °C (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Average effective crystal grain size of mid-thickness part (μm)	Pore number density (per mm^2)	YS at 1/4 position of base metal (MPa)	YS at 1/2 position of base metal (MPa)	δ of CGHAZ at -40°C (mm)	δ of SC/ICHAZ boundary at -40 °C (mm)	
18	I	126	1046	40	0.51	48	0.53	0.8	244	-	40	0.09	515	502	0.73	0.26	Comparative Example
19	J	115	1142	31	0.70	61	0.56	3.7	404	-	19	0.04	364	359	0.63	1.07	Example
20	J	158	1013	45	0.50	43	0.63	11.9	625	-	41	0.10	317	301	0.31	0.19	Comparative Example
21	K	144	1069	42	0.66	61	0.57	3.2	540	-	15	0.08	514	504	0.63	0.94	Example
22	L	123	999	47	0.64	42	0.51	5.3	477	-	13	0.09	562	544	0.60	0.59	Example
23	M	115	1155	44	0.60	60	0.55	6.6	600	-	18	0.07	374	367	0.42	1.18	Example
24	N	101	1007	42	0.58	58	0.67	35.9	582	650	11	0.05	551	545	0.46	0.44	Example
25	O	123	1181	35	0.57	60	0.56	14.2	399	-	19	0.06	527	521	0.26	0.20	Comparative Example

(continued)

No.	Steel sample ID	Thickness (mm)	Production conditions								Measurement results						Classification
			Heating	Hot rolling				Cooling		Tempering	Base metal properties				Welded portion properties		
			Heating temp. (°C)	Cumulative rolling reduction ratio at 950 °C or more and rolling reduction of 3 % or more per pass (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling at 950 °C or more	Cumulative rolling reduction ratio below 950 °C (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Average effective crystal grain size of mid-thickness part (μm)	Pore number density (per mm^2)	YS at 1/4 position of base metal (MPa)	YS at 1/2 position of base metal (MPa)	δ of CGHAZ at -40°C (mm)	δ of SC/ICHAZ boundary at -40 °C (mm)	
26	P	118	1053	31	0.54	58	0.60	2.9	588	-	15	0.05	507	501	0.22	0.24	Comparative Example
27	Q	106	1018	43	0.57	52	0.53	8.5	425	-	12	0.04	510	505	0.23	0.28	Comparative Example

(continued)

Heat-ing				Hot rolling				Cooling		Tem-pering	Base metal		properties		Welded portion properties		
Heat-ing temp. (°C)	Cumula-tive rolling reduc-tion ratio at 950 °C or more and rolling reduc-tion of 3 % or more per pass (%)	Average deforma-tion resis-tance ratio between mid-thick-ness part and surface for rolling at 950 °C or more	Cumula-tive rolling reduc-tion ratio below 950 °C (%)	Average deforma-tion resis-tance ratio between mid-thick-ness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Temper-ing temp. (°C)	Aver-age effec-tive crystal grain size of mid-thick-ness part (μm)	Pore num-ber den-sity (per mm^2)	YS at 1/4 position of base metal (MPa)	YS at 1/2 posi-tion of base metal (MPa)	δ of CGH-AZ at -40 °C (mm)	δ of SC/I-CHAZ bound-ary at -40 °C (mm)				
28	R	102	1196	31	0.64	68	0.67	24.6	557	-	20	0.02	511	508	0.29	0.29	Compara-tive Ex-ample
29	S	107	1035	42	0.50	61	0.70	14.1	403	500	14	0.07	500	490	0.26	0.17	Compara-tive Ex-ample
30	T	103	992	32	0.51	62	0.60	6.5	481	-	18	0.07	400	387	0.11	0.29	Compara-tive Ex-ample
31	U	143	1125	38	0.68	51	0.63	4.4	211	-	19	0.07	501	488	0.25	0.21	Compara-tive Ex-ample
32	V	132	1036	33	0.51	44	0.66	4.1	473	-	14	0.10	484	468	0.17	0.25	Compara-tive Ex-ample

(continued)

Heating				Hot rolling				Cooling		Tempering	Base metal		properties		Welded portion properties		
Heating temp. (°C)	Cumulative rolling reduction ratio at 950 °C or more and rolling reduction of 3 % or more per pass (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling at 950 °C or more	Cumulative rolling reduction ratio below 950 °C (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Average effective crystal grain size of mid-thickness part (μm)	Pore number density (per mm^2)	YS at 1/4 position of base metal (MPa)	YS at 1/2 position of base metal (MPa)	δ of CGHAZ at -40 °C (mm)	δ of SC/ICHAZ boundary at -40 °C (mm)				
33	W	105	1163	41	0.66	46	0.56	4.9	535	-	20	0.02	461	458	0.18	0.23	Comparative Example
34	X	132	1156	43	0.65	64	0.52	21.7	467	500	20	0.06	529	517	0.19	0.26	Comparative Example
35	Y	147	1157	50	0.55	67	0.54	1.9	491	-	13	0.02	550	547	0.22	0.29	Comparative Example
36	Z	111	1144	44	0.68	49	0.67	79	546	-	12	0.05	497	490	0.14	0.29	Comparative Example
37	AA	136	1124	43	0.55	62	0.52	43.0	215	600	15	0.08	505	492	0.23	0.15	Comparative Example

(continued)

Heating				Hot rolling				Cooling		Tempering	Base metal		properties		Welded portion properties		
Heating temp. (°C)	Cumulative rolling reduction ratio at 950 °C or more and rolling reduction of 3 % or more per pass (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling at 950 °C or more	Cumulative rolling reduction ratio below 950 °C (%)	Average deformation resistance ratio between mid-thickness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Average effective crystal grain size of mid-thickness part (μm)	Pore number density (per mm^2)	YS at 1/4 position of base metal (MPa)	YS at 1/2 position of base metal (MPa)	δ of CGHAZ at -40 °C (mm)	δ of SC/ICHAZ boundary at -40 °C (mm)				
38	AB	115	1084	34	0.59	60	0.53	6.6	491	-	13	0.03	521	518	0.16	0.28	Comparative Example
39	AC	130	1097	35	0.57	70	0.69	36.4	328	-	10	0.03	589	584	0.25	0.12	Comparative Example
40	AD	103	1027	39	0.62	40	0.55	7.3	530	-	18	0.02	515	512	0.25	0.15	Comparative Example
41	AE	119	1019	42	0.63	54	0.50	6.5	524	-	17	0.09	489	478	0.22	0.13	Comparative Example
42	AF	149	1054	34	0.64	63	0.59	30.9	540	650	19	0.02	295	292	0.32	0.41	Comparative Example

(continued)

Heat-ing				Hot rolling				Cooling		Tem-pering	Base metal		properties		Welded portion properties		
Heat-ing temp. (°C)	Cumula-tive rolling reduc-tion ratio at 950 °C or more and rolling reduc-tion of 3 % or more per pass (%)	Average deforma-tion resis-tance ratio between mid-thick-ness part and surface for rolling at 950 °C or more	Cumula-tive rolling reduc-tion ratio below 950 °C (%)	Average deforma-tion resis-tance ratio between mid-thick-ness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Temper-ing temp. (°C)	Aver-age effec-tive crystal grain size of mid-thick-ness part (μm)	Pore num-ber den-sity (per mm²)	YS at 1/4 position of base metal (MPa)	YS at 1/2 posi-tion of base metal (MPa)	δ of CGH-AZ at -40 °C (mm)	δ of SC/I-CHAZ bound-ary at -40 °C (mm)				
43	AG	120	1060	46	0.68	57	0.67	3.1	496	-	16	0.02	291	287	0.40	0.39	Compara-tive Ex-ample
44	AH	127	1062	37	0.70	47	0.53	4.0	566	-	24	0.08	493	479	0.23	0.27	Compara-tive Ex-ample
45	AI	133	1071	41	0.69	52	0.55	2.9	524	-	19	0.02	447	444	0.18	0.24	Compara-tive Ex-ample
46	AJ	135	1056	44	0.55	53	0.54	2.8	488	500	15	0.02	435	432	0.19	0.28	Compara-tive Ex-ample
47	AK	108	1079	37	0.62	44	0.53	4.3	589	-	15	0.05	265	258	0.37	0.42	Compara-tive Ex-ample

(continued)

Heat-ing				Hot rolling				Cooling		Tem-pering	Base metal		properties		Welded portion properties		
Heat-ing temp. (°C)	Cumula-tive rolling reduc-tion ratio at 950 °C or more and rolling reduc-tion of 3 % or more per pass (%)	Average deforma-tion resis-tance ratio between mid-thick-ness part and surface for rolling at 950 °C or more	Cumula-tive rolling reduc-tion ratio below 950 °C (%)	Average deforma-tion resis-tance ratio between mid-thick-ness part and surface for rolling below 950 °C	Average cooling rate* (°C/s)	Cooling stop temp. (°C)	Temper-ing temp. (°C)	Aver-age effec-tive crystal grain size of mid-thick-ness part (μm)	Pore num-ber den-sity (per mm²)	YS at 1/4 position of base metal (MPa)	YS at 1/2 posi-tion of base metal (MPa)	δ of CGH-AZ at -40 °C (mm)	δ of SC/I-CHAZ bound-ary at -40 °C (mm)				
48	AL	137	1017	35	0.66	41	0.66	5.0	457	-	18	0.05	616	609	0.23	0.20	Compara-tive Ex-ample
49	AM	105	1115	45	0.56	56	0.52	8.6	336	-	13	0.09	544	527	0.17	0.20	Compara-tive Ex-ample
50	AN	145	999	33	0.52	67	0.53	7.2	553	-	20	0.04	526	519	0.19	0.23	Compara-tive Ex-ample
51	AO	103	1100	44	0.63	50	0.63	3.0	503	-	13	0.08	367	359	0.78	0.83	Example
52	AO	102	1100	46	0.84	50	0.64	3.2	498	-	14	0.34	353	308	0.77	0.81	Compara-tive Ex-ample
53	AP	120	1050	48	0.60	50	0.59	2.8	451	-	18	0.07	389	375	0.53	0.71	Example

Note: underlining indicates value outside scope of present disclosure
* When cooling stop temperature is 500 °C or less, average value from 700 °C to 500 °C, and when cooling stop temperature is higher than 500 °C, average value from 700 °C to the cooling stop temperature higher than 500 °C.

[0098] As can be seen in Table 2, the steel plates satisfying the conditions of the present disclosure (Examples) had manufacturing conditions, effective crystal grain size of the base metal, and pore number densities all within acceptable ranges, yield stress at the 1/4 thickness position and at the mid-thickness position of 320 MPa or more, CTOD values at the CGHAZ and CTOD values at the SC/ICHAZ boundary both 0.30 mm or more at -40 °C, and combined high strength with excellent joint CTOD properties.

[0099] In contrast, among the steel plates that did not satisfy the conditions of the present disclosure (Comparative Examples), No. 42, No. 43, and No. 47 each had a yield stress of less than 320 MPa at the 1/4 thickness position and at the mid-thickness position. No. 20 had a yield stress of less than 320 MPa at the 1/4 thickness position and at the mid-thickness position and a CTOD value of less than 0.30 mm at the SC/ICHAZ boundary. No. 52 had a yield strength of 320 MPa or more at the 1/4 thickness position, but the yield stress at the mid-thickness position was less than 320 MPa. Other Comparative Examples had one or both of the CTOD values of the CGHAZ and the SC/ICHAZ boundary less than 0.30 mm. All of the Comparative Examples had inferior base metal strength and joint CTOD properties compared to the Examples.

Claims

1. A steel plate comprising a chemical composition containing, in mass%,

C: 0.02 % to 0.12 %,
Si: 0.70 % or less,
Mn: 0.3 % to 3.0 %,
P: 0.050 % or less,
S: 0.0050 % or less,
Al: 0.002 % to 0.100 %,
Ti: 0.002 % to 0.060 %,
N: 0.0130 % or less, and
O: 0.0100 % or less,
with the balance being Fe and inevitable impurity, wherein the chemical composition satisfies Expressions (1) to (3) below,
average effective crystal grain size in a mid-thickness part is 20 μm or less, and the number of pores in the steel plate having a circle equivalent diameter of 180 μm or more is 0.10 or less per mm^2,

$$1.50 \leq \mathrm{Ti/N} \leq 5.00 \qquad \ldots (1)$$

$$0.280\ \% \leq \mathrm{Ceq}\ (= [C] + [Mn]/6 + ([Cu] + [Ni])/15 + ([Cr] + [Mo] + [V])/5) \leq 0.540\ \% \qquad (2)$$

$$\mathrm{Pcm}\ (= [C] + [Si]/30 + ([Mn] + [Cu] + [Cr])/20 + [Ni]/60 + [Mo]/15 + [V]/10 + 5[B]) \leq 0.250\ \% \qquad (3)$$

where the square brackets in Expressions (1) to (3) indicate content in mass% of an element enclosed in the brackets and have a value of 0 when the element is not contained.

2. The steel plate according to claim 1, wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of

Ni: 2.0 % or less,
Ca: 0.0180 % or less,
Cu: 2.00 % or less,
Cr: 2.00 % or less,
Mo: 2.00 % or less,
Nb: 0.070 % or less,
V: 0.20 % or less,
W: 0.50 % or less,
B: 0.0050 % or less,
REM: 0.030% or less and,

Mg: 0.0150 % or less.

3. A method of producing the steel plate according to claim 1 or 2, the method comprising:

heating a slab having the chemical composition according to claim 1 or 2 to a temperature range from 990 °C or more to 1200 °C or less; hot rolling the under a set of conditions satisfying Expression (4) below, with a mid-thickness temperature of 950 °C or more, a rolling reduction ratio of 3 % or more per pass, and a cumulative rolling reduction ratio of 30 % or more; hot rolling at a mid-thickness temperature of less than 950 °C and a cumulative rolling reduction ratio of 40 % or more; then, when cooling to a cooling stop temperature of 600 °C or less at an average cooling rate at mid-thickness of 1.0 °C/s or more, when the cooling stop temperature is 500 °C or less, the average value from 700 °C to 500 °C is the average cooling rate, and when the cooling stop temperature is higher than 500 °C, the average value from 700 °C to the cooling stop temperature that is higher than 500 °C is the average cooling rate,

$$k_{fm}(\text{mid-thickness}) / k_{fm}(\text{surface}) \leq 0.70 \quad \ldots (4)$$

where k_{fm} is derived from Expression (5),
[Math. 1]

$$k_{fm} = e^{\left(0.126 - 1.75[C] + 0.594[C]^2 + \frac{2851 + 2968[C] - 1120[C]^2}{T_k}\right)} \times \varepsilon^{0.21} \times \dot{\varepsilon}^{0.13} \quad \cdots (5)$$

where ε is derived from Expression (6) and $\dot{\varepsilon}$ is derived from Expression (7)
[Math. 2]

$$\varepsilon = \ln \frac{h_1}{h_0} \quad \cdots (6)$$

[Math. 3]

$$\dot{\varepsilon} = \frac{2\pi n}{60\sqrt{r}} \times \sqrt{\frac{R}{h_0}} \times \ln\left(\frac{1}{1-r}\right) \quad \cdots (7)$$

where, in Expressions (5) to (7), [C] is mass% of C, T_k is absolute temperature (K) at mid-thickness or steel plate surface, h_0 is thickness on rolling entry, h_1 is thickness on rolling delivery, n is the roller rotational speed (rpm), r is rolling reduction, and R is roller radius (mm).

4. The method of producing a steel plate according to claim 3, wherein, after the cooling to the cooling stop temperature, a tempering treatment is performed at a temperature of 700 °C or less.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2023/000227

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; ***C21D 8/02***(2006.01)i; ***C22C 38/14***(2006.01)i; ***C22C 38/58***(2006.01)i
FI: C22C38/00 301B; C22C38/14; C22C38/58; C21D8/02 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)

C22C38/00-38/60; C21D8/02

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2023
Registered utility model specifications of Japan 1996-2023
Published registered utility model applications of Japan 1994-2023

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	WO 2018/216665 A1 (JFE STEEL CORPORATION) 29 November 2018 (2018-11-29) claims, paragraphs [0001], [0035]-[0094]	2 1, 3-4
A	JP 2007-302908 A (SUMITOMO METAL IND LTD) 22 November 2007 (2007-11-22)	1-4
A	WO 2021/182618 A1 (NIPPON STEEL CORPORATION) 16 September 2021 (2021-09-16)	1-4
A	JP 3-44417 A (NIPPON STEEL CORP) 26 February 1991 (1991-02-26)	1-4
A	WO 2016/035110 A1 (JFE STEEL CORPORATION) 10 March 2016 (2016-03-10)	1-4

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

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

Date of the actual completion of the international search	Date of mailing of the international search report
09 March 2023	**28 March 2023**

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

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/000227

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WO 2018/216665 A1	29 November 2018	US 2020/0115782 A1 claims, paragraphs [0001], [0079]-[0183] EP 3633057 A1 CN 110651059 A KR 10-2019-0142358 A	
JP 2007-302908 A	22 November 2007	(Family: none)	
WO 2021/182618 A1	16 September 2021	JP 7184210 B2 EP 4119688 A1 CN 115244205 A KR 10-2022-0133985 A	
JP 3-44417 A	26 February 1991	(Family: none)	
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- JP H05186823 A **[0014]**
- JP S61253344 A **[0014]**
- WO 2014038200 A1 **[0014]**