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

(11) EP 4 484 585 A1

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

(43) Date of publication:
01.01.2025 Bulletin 2025/01

(21) Application number: **23803620.6**

(22) Date of filing: **11.05.2023**

(51) International Patent Classification (IPC):
C21D 8/02 *(2006.01)* ***C22C 38/00*** *(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/JP2023/017811

(87) International publication number:
WO 2023/219146 (16.11.2023 Gazette 2023/46)

(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: **12.05.2022 JP 2022079060**

(71) Applicant: **JFE Steel Corporation**
Tokyo 100-0011 (JP)

(72) Inventors:
- **OKUTANI, Masaomi**
  Tokyo 100-0011 (JP)
- **TERAZAWA, Yusuke**
  Tokyo 100-0011 (JP)
- **OHTSUBO, Hirofumi**
  Tokyo 100-0011 (JP)

(74) Representative: **Haseltine Lake Kempner LLP**
One Portwall Square
Portwall Lane
Bristol BS1 6BH (GB)

(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 in a mid-thickness part, average effective crystal grain size is 20 μm or less and maximum effective crystal grain size is 150 μm or less, and at a 1/2 thickness position, composite inclusions containing sulfides containing Ca and Mn and oxides containing Al and having a circle equivalent diameter of 0.1 μm or more are present at a number density of 25/mm^2 to 250/mm^2.

EP 4 484 585 A1

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. Specifically, the present disclosure relates to a thick, high tensile strength steel plate having a thickness exceeding 100 mm, 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] In recent years, steel structures such as ships, marine structure, pressure vessels, line pipes, and offshore wind power generators are becoming larger. With such larger sizes, there is an increasing demand for higher-strength, thicker steel material for use as base metal.

[0003] In particular, when producing a steel plate having a thickness exceeding 100 mm, a mid-thickness part tends to have a decreased cooling rate and coarser crystal grains because of the increased thickness. Therefore, crystal grain refinement of the mid-thickness part is important to produce a steel plate where the mid-thickness part has excellent strength and toughness.

[0004] For example, in Patent Literature (PTL) 1, a technique is proposed to improve toughness of base metal by controlling rolling conditions to refine average effective crystal grain size of mid-thickness microstructure.

[0005] Conventionally, the Charpy test has been the main method for evaluating steel toughness. In recent years, a crack tip opening displacement test (hereinafter also referred to as CTOD test) has been increasingly applied to evaluate steel plates used in steel structures as a method to evaluate fracture resistance with higher precision.

[0006] 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, and measuring the amount of crack opening (plastic deformation) immediately before fracture.

[0007] Further, when steel plates are applied to steel structures such as ships, marine structures, pressure vessels, line pipes, offshore wind power generators, and the like, multilayer fill welding is used.

[0008] The heat-affected zone (hereinafter also referred to as "HAZ") of a multilayer fill weld is subjected to a plurality of different thermal cycles from each of the welding passes, forming a mixture of various microstructures. In particular, the HAZ in the vicinity of the weld line (coarse grain heat-affected zone: CGHAZ), coarsened by a preceding welding pass, is reheated into a two phase region of ferrite and austenite by a subsequent welding pass, and HAZ microstructure with martensite austenite constituent (MA) mixed in a coarse matrix (hereinafter also referred to as inter-critically reheated coarse grain heat-affected zone: ICCGHAZ) has particularly low toughness. Further, when crystal grain size of base metal microstructure is coarse, toughness of sub-critically reheated HAZ (SCHAZ) may become a problem.

[0009] According to the joint CTOD test method specified in British Standard (BS) EN10225-4 (2019) and American Petroleum Institute (API) Recommended Practice RP-2Z (2005), joint CTOD properties are required for the CGHAZ in the vicinity of the weld line and the SC/inter-critically reheated HAZ (SC/ICHAZ) boundary, which is the boundary of untransformed/transformed zones of the base metal during welding.

[0010] CTOD testing of welded joints is basically performed at full thickness, and therefore when the CGHAZ is the subject of evaluation, the region where a fatigue precrack is introduced includes the ICCGHAZ microstructure. That is, 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 the CGHAZ reflect the toughness of ICCGHAZ microstructure as well as CGHAZ microstructure.

[0011] Therefore, to improve joint CTOD properties at the CGHAZ, it is also necessary to improve toughness of the ICCGHAZ microstructure.

[0012] The HAZ microstructures described above are CGHAZ, ICHAZ, and SCHAZ in order of proximity from the weld line in the microstructure formed in one welding pass during multilayer fill (multi-pass) welding. ICCGHAZ is microstructure formed in multilayer fill welding when the CGHAZ is heated to a two phase region of ferrite and austenite by the thermal hysteresis of subsequent passes, and the location and frequency at which ICCGHAZ microstructure is formed can vary depending on how welding passes are layered.

[0013] 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. However, in a bonded portion, TiN may be heated to a temperature range where TiN dissolves, and when low-temperature toughness requirements for a welded portion are stringent, satisfying the requirements mentioned above becomes difficult with only the effects mentioned above.

[0014] Further, techniques have also been used to suppress austenite grain growth by adding rare earth metal (REM) and dispersing REM acid sulfides formed, and making use of the ferrite nucleation ability of BN.

[0015] For example, PTL 2 describes a technique 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.

[0016] Further, in PTL 3, a technique is proposed using boron nitride (BN) as a ferrite nucleation site in the heat-affected zone of large-heat input welding to refine HAZ microstructure and improve HAZ toughness.

[0017] Further, in PTL 4, as a measure for countering toughness decrease at the ICCGHAZ, a technique is proposed to increase base metal strength by adding Cu in addition to suppressing the formation of MA by decreasing C and Si content.

[0018] As described above, an increase in the amount of alloying elements is necessary to achieve both thicker and stronger steel plates, but the addition of large amounts of alloying elements leads to degradation of toughness of the multilayer-fill-welded HAZ, making securing desired low temperature joint CTOD properties more difficult.

[0019] To address this problem, PTL 5 describes a technique to improve low-temperature toughness by controlling hardness of a central segregation area.

CITATION LIST

Patent Literature

[0020]

PTL 1: JP 6477993 B1
PTL 2: JP S60-184663 A
PTL 3: JP S61-253344 A
PTL 4: JP H05-186823 A
PTL 5: JP 5846311 B2

SUMMARY

(Technical Problem)

[0021] Here, the CTOD specification temperature in standards that specify joint CTOD properties (for example, API standard RP-2Z) is typically -10 °C.

[0022] 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, and capable of meeting CTOD specification temperatures that are even lower than those specified by the API standard.

[0023] According to investigation by the inventors, the conventional techniques described in PTL 1 to PTL 5 are unable to fully satisfy joint CTOD properties required for multilayer-fill-welded joints for low-temperature specifications in steel plates having a thickness exceeding 100 mm.

[0024] For example, although PTL 1 proposes rolling condition control for average effective crystal grain size refinement of mid-thickness microstructure, the technique has not been applied to steel plates having a thickness exceeding 100 mm. Further, to improve toughness in the mid-thickness part, refinement of average effective crystal grain size is insufficient; maximum effective crystal grain size also needs to be refined.

[0025] The technique proposed in PTL 2 to suppress coarsening of the austenite structure of the HAZ by adding REM in combination with Ti and dispersing fine particles in steel is targeted at steel material that has relatively low strength and low alloying element content. Therefore, the technique is not applicable to higher strength steel material with higher alloying element content, because the HAZ microstructure does not contain ferrite.

[0026] The technique proposed in PTL 3 is effective when HAZ microstructure is mainly composed of ferrite and a cooling rate of the heat-affected zone is slow, as in large-heat input welding. However, in multilayer fill welding, the heat input is relatively small, and further, the alloy component in the base metal is relatively large for steel plates exceeding 100 mm thickness. Therefore, in multilayer fill welding of steel plates, the HAZ microstructure becomes mainly bainite, and the HAZ toughness improvement effect described above cannot be obtained.

[0027] According to the technique proposed in PTL 4, satisfactory CTOD properties can be obtained at normal specification temperatures (-10 °C). However, the joint CTOD properties at lower temperature specification temperatures as mentioned above have not been investigated, and it may be considered that low-temperature CTOD specifications cannot be satisfied by only improving ICCGHAZ toughness through decreasing the base metal alloy component of C and Si.

[0028] Further, decreasing the alloying element content of base metal to improve the toughness of the ICCGHAZ is a technique that conflicts with securing strength for greater thickness, and may be considered difficult to apply to steel plates used in marine structures and the like.

[0029] PTL 5 proposes a technique for satisfactory joint CTOD properties at normal specification temperature (-10 °C) in steel plates having a thickness of 100 mm or less. However, for ultra-thick steel plates having a thickness exceeding 100 mm, mechanical properties equivalent to those of steel plates having thicknesses of 100 mm or less have not yet been obtained, and joint CTOD properties at even lower specification temperatures, as mentioned above, have not been investigated. Further, CTOD properties of the SC/ICHAZ boundary have also not been investigated.

[0030] Accordingly, in steel plates having a thickness exceeding 100 mm that combine high strength and low-temperature toughness, it is hard to say that a technology to improve the toughness of the CGHAZ, ICCGHAZ, and SCHAZ at the multilayer-fill-welded heat-affected zone has been established, and improving joint CTOD properties has been difficult.

[0031] The present disclosure is made in view of the problems described above faced by conventional technologies, and it would be helpful to provide a steel plate having a thickness exceeding 100 mm, high strength, excellent base metal toughness at low temperature, and excellent multilayer-fill-welded joint CTOD properties, as well as a method of producing same.

[0032] Hereinafter, high strength is defined as a yield stress of 325 MPa or more in the mid-thickness part in a tensile test. Excellent base metal toughness at low temperature is defined as having an absorbed energy of 100 J or more in the Charpy test at -40 °C in the mid-thickness part. Excellent multilayer-fill-welded joint CTOD properties is defined as a crack opening displacement of 0.4 mm or more at notch location CGHAZ and at the SC/ICHAZ boundary, respectively, at a test temperature of -20 °C.

(Solution to Problem)

[0033] In order to solve the above problems, the inventors have extensively studied methods to improve CTOD properties in steel plates having a thickness exceeding 100 mm, while also achieving both high strength and improved low-temperature toughness of base metal. As a result, the inventors made the following discoveries.

[0034] Strength and toughness are strongly correlated with crystal grain size, and therefore in order to achieve both high strength at the mid-thickness part and low-temperature toughness in steel plates having a thickness exceeding 100 mm, crystal grain refinement in such regions is essential. When refining crystal grains, refining average effective crystal grain size is also important, but when coarse crystal grains are mixed even partially among such fine crystal grains, the coarse crystal grains become the weakest part of the crystal grains and become fracture origins. That is, material properties are governed not only by the average grain size, but also by the maximum grain size. Therefore, not only crystal grain refinement but also homogenization is essential.

[0035] With regard to the above, the inventors have found that the desired strength and toughness can be secured by making the maximum effective crystal grain size to 150 μm or less while keeping the average effective crystal grain size to 20 μm or less, in the base metal microstructure in the mid-thickness part, as described below.

[0036] However, with conventional technology, in a steel plate having a thickness exceeding 100 mm, it is difficult for strain to enter the mid-thickness part during rolling, and difficult to refine the average effective crystal grain size of base metal microstructure of the mid-thickness part to 20 μm or less.

[0037] Further, even when strain is appropriately introduced into the mid-thickness part and the average effective crystal grain size can be refined, then when coarse grains are mixed in, the coarse grains still become fracture origins.

[0038] The inventors discovered that such problems can be solved by eliminating coarse crystal grains that have a maximum effective crystal grain size exceeding 150 μm.

[0039] However, with conventional technology, eliminating coarse crystal grain that have a maximum effective crystal grain size exceeding 150 μm is difficult, particularly in steel plates having a thickness of 100 mm or more.

[0040] As a result of the extensive studies, the inventors discovered that these problems can be solved by the following methods.

(1) When mid-thickness temperature is in a temperature range of T_1 °C or more, which is a recrystallization temperature range, rolling with an average rolling reduction per pass (average of the rolling reduction in each pass) of 3 % or more and a cumulative rolling reduction ratio (cumulative rolling reduction/rolling start thickness) of 25 % or more can introduce sufficient strain to the mid-thickness part, which results in recrystallization to refine and homogenize crystal grains. Next, after avoiding rolling in a partial recrystallization temperature range (T_1 °C to T_2 °C) where recrystallized grains and coarse recovered grains are generated, rolling is performed at T_2 °C or less, which is a non-recrystallization temperature range, with a cumulative rolling reduction ratio of 30 % or more. According to these rolling operations, even in steel plates having a thickness exceeding 100 mm, average effective crystal grain size can be made 20 μm or less while also making the maximum effective crystal grain size 150 μm or less in the mid-thickness part.

[0041] Accordingly, in steel plates having a thickness exceeding 100 mm, in addition to clearly defining the recrystallization temperature range of T_1 °C or more and the non-recrystallization temperature range of T_2 °C or less and avoiding rolling at the partial recrystallization temperature (T_1 °C to T_2 °C), where recrystallization grains and coarse recovered grains are generated, desired fine and uniformly-sized grain microstructure can be obtained in the mid-thickness part by rolling under the conditions described above at temperatures of T_1 °C or more and T_2 °C or less.

[0042] Hereinafter, the mid-thickness part is a region from the center in the thickness direction (1/2 position) to a thickness of 10 % of the steel plate toward both main surfaces of the steel plate.

[0043] (2) When Ca, O, and S content in steel is controlled within the range of 0 to 1.5 in atomic concentration ratio (ACR) indicated in the following expression, inclusions become composite inclusions containing Ca sulfides partially containing Mn in solid solution and Al oxides.

$$ACR = \{[Ca] - (0.18 + 130\,[Ca]) \times [O]\} / 1.25 / [S]$$

[0044] Adding large amounts of alloying elements is essential when producing high strength, thick steel plates, and therefore it has conventionally been difficult to secure sufficient joint CTOD properties at low temperatures for a multilayer-fill-welded HAZ.

[0045] As a result of the extensive studies, the inventors discovered that by using composite inclusions containing two types of inclusion, that is, sulfides containing Ca and Mn and oxides containing Al, the composite inclusions can exist stably even in a region in the vicinity of the weld line where the temperature is increased to a high temperature, and the effect of suppressing austenite grain coarsening can be fully exhibited. Further, the inventors discovered that a Mn-poor layer is formed around the composite inclusions, which has a nucleation effect (nucleation site effect) on bainite and the like.

[0046] That is, when the complex inclusion having a nucleation effect is present in austenite grains, nucleation occurs not only from austenite grain boundaries but also from within the austenite grains, resulting in a finer finally obtained HAZ microstructure. As a result, HAZ toughness and joint CTOD properties are improved.

[0047] Further, the inventors discovered that the size of such composite inclusions needs to be 0.1 μm or larger in circle equivalent diameter in order to fully exhibit the nucleation site effect due to the composite inclusions described above.

[0048] Further, at least one composite inclusion needs to be present in the austenite grains of the HAZ when weld temperature is increasing in order to fully utilize refinement of the HAZ microstructure due to the nucleation site effect. In particular, austenite grain size in the vicinity of the weld line reaches about 200 μm or more, and therefore the inventors discovered that the number density of composite inclusions need to be 25/mm^2 or more in order for the finally obtained HAZ microstructure to be sufficiently fine. On the other hand, toughness of the composite inclusions themselves is low, and therefore the presence of an excessive amount of composite inclusions can instead reduce the HAZ toughness. In particular, the number of composite inclusions needs to be appropriately controlled in the mid-thickness part, where element segregation exists and multilayer-fill-welded HAZ toughness is poor. The inventors discovered that good multilayer-fill-welded joint CTOD properties are obtainable by making the number density of the composite inclusions 250/mm^2 or less.

[0049] (3) Generally, in an element segregation region of the mid-thickness part of a slab, alloying elements are concentrated and thus coarse inclusions are dispersed at low density.

[0050] As a result of the extensive studies, the inventors discovered that rolling at a high mid-thickness temperature of T_1 °C or more, with an average rolling reduction per pass of 3 % or more and a cumulative rolling reduction ratio of 25 % or more, can increase the strain applied to the mid-thickness part, elongate and break up coarse inclusions, and distribute fine inclusions to a high density. Further, the inventors discovered that such inclusions can help secure the HAZ toughness improvement effect.

[0051] (4) It is known that the toughness of base metal governs joint CTOD properties at the SC/ICHAZ boundary. As a result of the extensive studies, the inventors discovered that in order to satisfy joint CTOD properties at the SC/ICHAZ boundary at a test temperature of -20 °C, improving base metal toughness by crystal grain refinement and homogenization is required, such that the maximum effective crystal grain size is 150 μm or less and the average effective crystal grain size is 20 μm or less in the base metal microstructure.

[0052] Normally, in steel plates having a thickness exceeding 100 mm, the cooling rate of the mid-thickness part is smaller and crystal grains become coarser. Therefore, rolling conditions are set so that when mid-thickness temperature is T_1 °C or more, which is a recrystallization temperature range, average rolling reduction per pass is 3 % or more and cumulative rolling reduction ratio is 25 % or more, rolling is avoided at the partial recrystallization range temperature (T_1 °C to T_2 °C) at which recrystallization grains and coarse recovery grains would be generated, and further, at T_2 °C or less, which is a non-recrystallization temperature range, cumulative rolling reduction ratio is 30 % or more. The inventors discovered that these rolling conditions can sufficiently refine and homogenize the microstructure in the mid-thickness part, and crystal grain refinement and homogenization can occur to achieve the desired crystal grain size.

[0053] The present disclosure is based on these discoveries and further studies. Specifically, primary features of the present disclosure are described below.

[1] A steel plate having a thickness exceeding 100 mm and comprising a chemical composition containing (consisting of), in mass%, C: 0.03 % to 0.13 %, Si: 0.60 % or less, Mn: 0.9 % to 2.7 %, P: 0.050 % or less, S: 0.0050 % or less, Al: 0.002 % to 0.100 %, Ti: 0.002 % to 0.055 %, Nb: 0.005 % to 0.070 %, Ca: 0.0005 % to 0.0200 %, N: 0.0120 % or less, and O: 0.0070 % or less, with the balance being Fe and inevitable impurity, wherein the chemical composition satisfies Expressions (1) to (4) below,

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

$$0 \leq \{[Ca] - (0.18 + 130[Ca]) \times [O]\} / 1.25 / [S] \leq 1.50 \quad \ldots (2)$$

$$0.280\ \% \leq Ceq\ (= [C] + [Mn]/6 + ([Cu] + [Ni])/15 + ([Cr] + [Mo] + [V])/5) \leq 0.500\ \% \quad (3)$$

$$Pcm\ (= [C] + [Si]/30 + ([Mn] + [Cu] + [Cr])/20 + [Ni]/60 + [Mo]/15 + [V]/10 + 5[B]) \leq 0.240\ \% \quad (4)$$

where the square brackets in Expressions (1) to (4) indicate content in mass% of an element enclosed in the brackets and have a value of 0 when the element is not contained,

in a mid-thickness part, average effective crystal grain size is 20 μm or less and maximum effective crystal grain size is 150 μm or less, and

at a 1/2 thickness position, composite inclusions containing sulfides containing Ca and Mn and oxides containing Al and having a circle equivalent diameter of 0.1 μm or more are present at a number density of 25/mm^2 to 250/mm^2.

[2] The steel plate according to [1], wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of Ni: 2.5 % or less, Cu: 2.0 % or less, Cr: 1.5 % or less, Mo: 1.5 % or less, V: 0.25 % or less, W: 0.45 % or less, B: 0.0045 % or less, REM: 0.025 % or less, and Mg: 0.005 % or less.

[3] A method of producing a steel plate, the method comprising:

heating a material having the chemical composition defined in [1] or [2] to a temperature of 990 °C or more and 1210 °C or less; then rolling under rolling conditions including an average rolling reduction per pass of 3 % or more and a cumulative rolling reduction ratio of 25 % or more in a temperature range where mid-thickness temperature is T_1 °C or more as defined in Expression (5) below; rolling under rolling conditions including a cumulative rolling reduction ratio of 30 % or more in a temperature range where the mid-thickness temperature is T_2 °C or less as defined in Expression (6) below; and then cooling at an average cooling rate of 1.0 °C/s to 50.0 °C/s in the mid-thickness temperature to a cooling stop temperature of 600 °C or less,

[Math. 1]

$$T_1 = 174 \log\left[sol.[Nb] \times \left([C] + \frac{12}{14}[N]\right)\right] + 1444 \quad \ldots (5)$$

(Here, sol.[Nb] is derived from Expression (7))

[Math. 2]

$$T_2 = T_1 - 75 \quad \ldots (6)$$

[Math. 3]

$$\mathrm{sol.[Nb]} = \exp\left[2.3\left\{2.26 - \frac{6770}{T_0 + 273} - \log\left([C] + \frac{12}{14}[N]\right)\right\}\right] \quad \ldots (7)$$

and in Expressions (5) and (7), [C] and [N] represent mass% of C and N, respectively, T_0 represents heating temperature of the material in °C, and sol.[Nb] represents Nb solute in mass%, and sol.[Nb] ≤ [Nb] where [Nb] is the total Nb content in mass% in the steel plate.

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

(Advantageous Effect)

[0054] According to the present disclosure, a steel plate having high strength and excellent toughness of base metal and multilayer-fill-welded joint CTOD properties at low temperatures is provided, as well as a method of producing same.

DETAILED DESCRIPTION

[0055] The reasons for limitations placed on the features of the present disclosure are explained below.

[Chemical composition]

[0056] First, the reasons for limiting the chemical composition of the steel plate and the material to the ranges of the present disclosure are described. Hereinafter, "%" of each component means "mass%" unless otherwise specified.

C: 0.03 % to 0.13 %

[0057] C is an element that increases hardenability and improves strength of steel. C content needs to be 0.03 % or more. However, the C content exceeding 0.13 % increases the hardness of C-enriched portions and degrades joint CTOD properties. The C content is therefore in the range from 0.03 % to 0.13 %. The C content is preferably 0.04 % or more. The C content is preferably 0.12 % or less. The C content is more preferably 0.06 % or more. The C content is more preferably 0.10 % or less.

Si: 0.60 % or less

[0058] Si is also used as a deoxidizer, but is an element inevitably included as an impurity, and excessive Si content exceeding 0.60 % decreases joint CTOD properties. The Si content is therefore limited to an upper limit of 0.60 %. The upper limit is preferably 0.50 % or less. A lower limit is not particularly limited, but lowering Si excessively leads to increased refining time and higher costs, and therefore the lower limit of the Si content is preferably around 0.02 %. The Si content is more preferably 0.04 % or more.

Mn: 0.9 % to 2.7 %

[0059] 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 these effects, addition of 0.9 % or more is required. However, addition exceeding 2.7 % 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 0.9 % to 2.7 %. The Mn content is preferably 1.1 % or more. The Mn content is preferably 2.5 % or less. The Mn content is more preferably 1.2 % or more. The Mn content is more preferably 2.3 % or less.

P: 0.050 % or less

[0060] 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. The P content is more preferably 0.005 % or more.

S: 0.0050 % or less

[0061] 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. The S content is more preferably 0.0005 % or more.

Al: 0.002 % to 0.100 %

[0062] Al is an element required for formation of composite inclusions to improve toughness of multilayer-fill-welded HAZ and to improve joint CTOD properties, and needs to be added at 0.002 % or more. However excessive addition of more than 0.100 % causes the amount of composite inclusions to become excessive and joint CTOD properties in a low temperature range to degrade. The Al content is therefore in the range from 0.002 % to 0.100 %. The Al content is preferably 0.005 % or more. The Al content is preferably 0.090 % or less. The Al content is more preferably 0.020 % or more. The Al content is more preferably 0.075 % or less.

Ti: 0.002 % to 0.055 %

[0063] 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. However, when the Ti content exceeds 0.055 %, Ti nitrides coarsen and toughness of the heat-affected zone instead degrades, resulting in degradation of joint CTOD properties. The Ti content is therefore in the range from 0.002 % to 0.055 %. The Ti content is preferably 0.005 % or more. The Ti content is preferably 0.050 % or less. The Ti content is more preferably 0.010 % or more. The Ti content is more preferably 0.045 % or less.

Nb: 0.005 % to 0.070 %

[0064] Nb is an element that broadens the non-recrystallization temperature range of austenite phase and has an effect of improving strength and toughness of base metal via efficient non-recrystallization range rolling to obtain a fine grain microstructure. When Nb is not added, the non-recrystallization temperature T_2 becomes too low, and the rolling temperature for non-recrystallization range rolling for fine grain formation becomes too low. Rolling at low temperatures increases the deformation resistance of the rolled material and increases load on the rolling mill, resulting in an increase in the number of rolling passes, which reduces production efficiency and makes it difficult to increase pass rolling reduction. As a result, appropriate introduction of strain to 1/2 t in steel plates having a thickness exceeding 100 mm becomes impossible, making obtaining desired properties difficult. To achieve such effects, the Nb content needs to be 0.005 % or more. However, when the Nb content exceeds 0.070 %, joint CTOD properties degrade. The Nb content is therefore in the range from 0.005 % to 0.070 %. The Nb content is preferably 0.010 % or more. The Nb content is preferably 0.060 % or less. The Nb content is more preferably 0.015 % or more. The Nb content is more preferably 0.050 % or less.

Ca: 0.0005 % to 0.0200 %

[0065] Ca is an element that improves toughness of multilayer-fill-welded HAZ and improves joint CTOD properties by forming acid sulfides that are highly stable at high temperatures. To achieve such effects, the Ca content needs to be 0.0005 % or more. However, the content exceeding 0.0200 % causes excessive precipitation of acid sulfides, which instead degrades joint CTOD properties. The Ca content is therefore in the range from 0.0005 % to 0.0200 %. The Ca content is preferably 0.0010 % or more. The Ca content is preferably 0.0170 % or less. The Ca content is more preferably 0.0015 % or more. The Ca content is more preferably 0.0150 % or less.

N: 0.0120 % or less

[0066] N is an element that reduces HAZ toughness and degrades joint CTOD properties, and therefore an upper limit of N content is limited to 0.0120 %. 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. The N content is more preferably 0.0020 % or more. The N content is more preferably 0.0110 % or less. The N content is more preferably 0.0030 % or more. The N content is more preferably 0.0090 % or less.

O: 0.0070 % or less

[0067] O is an element that decreases HAZ toughness and degrades joint CTOD properties, and therefore an upper limit of O content is limited to 0.0070 %. 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. The O content is more preferably 0.0010 % or more. The O content is more preferably 0.0060 % or less. The O content is even more preferably 0.0015 % or more. The O content is even more preferably 0.0055 % or less.

[0068] The chemical composition of the steel plate according to an embodiment consists of the required elements described above, with the balance being Fe and inevitable impurity.

[0069] 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 contain at least one optional element selected from the group consisting of Ni, Cu, Cr, Mo, V, W, B, REM, and Mg, in a quantity indicated below.

Ni: 2.5 % or less

[0070] Ni is an element which can increase strength of a steel plate without greatly degrading toughness of both base metal and joints. However, when Ni content exceeds 2.5 %, production costs and environmental impact increase. The Ni content is therefore limited to 2.5 % or less. The Ni content is more preferably 2.0 % or less. However, when added, the Ni content is preferably 0.1 % or more.

Cu: 2.0 % or less

[0071] 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 2.0 %, surface cracks caused by a Cu-enriched layer that forms just below scale become a problem. The Cu content is therefore limited to 2.0 % or less. The Cu content is more preferably 1.8 % or less. However, when added, the Cu content is preferably 0.05 % or more. The Cu content is more preferably 0.1 % or more.

Cr: 1.5 % or less

[0072] Cr is an element that has an effect of increasing strength of steel through improving hardenability. However, Cr content exceeding 1.5 % degrades joint CTOD properties, and therefore the Cr content is limited to 1.5 % or less. The Cr content is more preferably 1.3 % or less. However, when added, the Cr content is preferably 0.05 % or more. The Cr content is more preferably 0.1 % or more.

Mo: 1.5 % or less

[0073] Mo is an element that has an effect of increasing strength of steel through improving hardenability. However, Mo content exceeding 1.5 % degrades joint CTOD properties, and therefore the Mo content is limited to 1.5 % or less. The Mo content is more preferably 1.3 % or less. However, when added, the Mo content is preferably 0.05 % or more. The Mo content is more preferably 0.1 % or more.

V: 0.25 % or less

[0074] V is an element that improves strength of the base metal, but when V content exceeds 0.25 %, HAZ toughness decreases and joint CTOD properties degrade, and therefore the V content is limited to 0.25 % or less. The V content is more preferably 0.20 % or less. However, when added, the V content is preferably 0.01 % or more. The V content is more preferably 0.03 % or more.

W: 0.45 % or less

[0075] W is an element that improves strength of the base metal, but when W content exceeds 0.45 %, HAZ toughness decreases and joint CTOD properties degrade, and therefore the W content is limited to 0.45 % or less. The W content is more preferably 0.40 % or less. However, when added, the W content is preferably 0.05 % or more. The W content is more preferably 0.15 % or more.

B: 0.0045 % or less

[0076] B is an element that can improve hardenability and thereby strength of a steel plate when contained in trace amounts. However, when B content exceeds 0.0045 %, HAZ toughness decreases and joint CTOD properties degrade, and therefore the B content is limited to 0.0045 % or less. The B content is more preferably 0.0040 % or less. However, when added, the B content is preferably 0.0005 % or more. The B content is more preferably 0.0010 % or more.

REM: 0.025 % or less

[0077] Rare earth metals (REM) suppress austenite grain growth in the HAZ and improve HAZ toughness by forming acid sulfide inclusions, but when REM content exceeds 0.025 %, toughness of base metal and HAZ toughness are instead decreased and joint CTOD properties degrade. The REM content is therefore limited to 0.025 % or less. The REM content is more preferably 0.020 % or less. However, when added, the REM content is preferably 0.001 % or more. The REM content is more preferably 0.010 % or more.

Mg: 0.005 % or less

[0078] Mg is an element that suppresses growth of austenite grains in the heat-affected zone by forming oxide inclusions and improves toughness of the heat-affected zone. However, when Mg content exceeds 0.005 %, the effect of addition saturates, and an effect commensurate with content cannot be expected, which is economically disadvantageous. The Mg content is therefore limited to 0.005 % or less. The Mg content is more preferably 0.004 % or less. However, when added, the Mg content is preferably 0.0005 % or more. The Mg content is more preferably 0.001 % or more.

[0079] According to the present disclosure, chemical composition of the steel plate and the material is required to further satisfy each of the four conditions described below.

$$1.50 \leq [Ti] / [N] \leq 5.00 \qquad \ldots (1)$$

[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 [Ti] / [N] range is preferably 1.80 or more. The [Ti] / [N] range is preferably 4.50 or less. The [Ti] / [N] range is more preferably 2.00 or more. The [Ti] / [N] range is more preferably 4.00 or less.

$$0 \leq \{[Ca] - (0.18 + 130[Ca]) \times [O]\} / 1.25 / [S] \leq 1.50 \qquad \ldots (2)$$

[0080] {[Ca] - (0.18 + 130 [Ca]) x [O]} / 1.25 / [S] is the atomic concentration ratio (ACR) of Ca, O, and S in steel. When the ACR is less than 0, the main form of sulfide inclusions is MnS. MnS has a low melting point and melts in the vicinity of the weld line during welding, and therefore the effect of suppressing austenite grain coarsening in the vicinity of the weld line and the effect of transformation during cooling after welding cannot be obtained, resulting in joint CTOD properties degrading. On the other hand, when the ACR exceeds 1.50, the main form of sulfide inclusions is CaS. CaS does not form a Mn-poor layer around CaS, which is necessary to form nucleation sites, and therefore the nucleation site effect is not obtained and joint CTOD properties are degraded. Accordingly, the ACR range is 0 or more and 1.50 or less. The ACR range is preferably 0.20 or more. The ACR range is preferably 1.40 or less. The ACR range is more preferably 0.40 or more. The ACR range is more preferably 1.20 or less.

Ceq: 0.280 % or more and 0.500 % or less

[0081] When the equivalent carbon content Ceq, 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. That is, when Ceq is more than 0.500 %, the HAZ matrix itself suffers toughness degradation, and therefore even with HAZ toughness improvement techniques through composite 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 0.500 %. The Ceq range is preferably 0.300 % or more. The Ceq range is preferably 0.490 % or less. The Ceq range is more preferably 0.320 % or more. The Ceq range is more preferably 0.480 % or less.

Ceq (%) = [C] + [Mn]/6 + ([Cu] + [Ni])/15 + ([Cr] + [Mo] + [V])/ --> 5 (3)

Pcm: 0.240 % or less

[0082] When the weld cracking parameter Pcm defined by the following Expression (4) 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 Pcm exceeds 0.240 %, the HAZ matrix itself suffers toughness degradation, and therefore the required joint CTOD properties cannot be obtained. Pcm is therefore 0.240 % or less. Pcm is preferably 0.230 % or less. Pcm is more preferably 0.210 % or less. A lower limit is not particularly limited. Excessive attempts to decrease Pcm result in too low a Ceq value, and therefore the lower limit is preferably about 0.140 %. Pcm is more preferably 0.155 % or more.

$$\text{Pcm (\%)} = [C] + [Si]/30 + ([Mn] + [Cu] + [Cr])/20 + [Ni]/60 + [Mo]/15 + [V]/10 + 5[B] \quad (4)$$

[0083] The square brackets [] in Expressions (1) to (4) 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]

[0084] Average effective crystal grain size at mid-thickness part (meaning a range of 10 % of the thickness of the steel plate towards each surface, centered at the 1/2 thickness position of the steel plate): 20 μm or less

[0085] 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 base metal toughness, thereby increasing joint CTOD properties at SC/ICHAZ boundaries. The smaller the average effective crystal grain size, the more advantageous, and therefore a lower limit of the average effective crystal grain size is not particularly limited. Typically, the lower limit is about 1 μm.

[0086] 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.

[Maximum effective crystal grain size]

[0087] According to the present disclosure, the maximum effective crystal grain size of the microstructure in the mid-thickness part is 150 μm or less. For example, even when the average effective crystal grain size is 20 μm or less, when coarse crystal grains having an effective crystal grain size exceeding 150 μm are mixed into the mid-thickness part, the coarse crystal grains become fracture origins and lead to a decrease in base metal strength, base metal toughness, and SCHAZ toughness in the mid-thickness part. The maximum effective crystal grain size is therefore 150 μm or less. The maximum effective crystal grain size can be measured by the method described in the EXAMPLES section below.

[Composite inclusions]

[0088] The present disclosure limits the number density at the 1/2 thickness position of composite inclusions containing sulfides containing Ca and Mn and oxides containing Al and having a circle equivalent diameter of 0.1 μm or more to a range from 25/mm^2 to 250/mm^2.

[0089] When Mn-containing sulfides are formed, Mn-poor regions forming around the composite inclusions are effective as nucleation sites. Further, the inclusion of Ca in such sulfides results in a high melting point and allows the inclusions to remain at the temperatures reached by the HAZ in the vicinity of the weld line. As a result, the austenite grain growth suppression and nucleation site effects are exhibited, and joint CTOD properties are improved. In order to fully exhibit the above effect, the number density of composite inclusions at the 1/2 thickness position needs to be 25/mm^2 or more. On the other hand, the presence of excessive amounts of composite inclusions can degrade joint CTOD properties. Therefore, the number density of composite inclusions having a circle equivalent diameter of 0.1 μm or more at the 1/2 thickness position is 250/mm^2 or less. The number density is preferably 30/mm^2 or more. The number density is preferably 215/mm^2 or less. The number density is more preferably 50/mm^2 or more. The number density is more preferably 200/mm^2 or less. The number density can be measured by the method described in the EXAMPLES section below.

[0090] Here, the frequency of measurement of average effective crystal grain size, maximum effective crystal grain size, and composite inclusions may be such that one or two cross-sections at the mid-thickness part of any one steel plate are measured among steel plates produced under the same material smelting conditions and rolling conditions. As long as the material steelmaking method and rolling conditions are not changed, the crystal grain size and inclusion number density are highly reproducible, and therefore measurement results at the above measurement frequency are representative of the whole.

[Production method]

[0091] 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. Further, 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.

• Material heating conditions

[0092] According to the present disclosure, a method of preparing the material 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 material may be produced, for example, by a continuous casting method. Further, molten steel from which the material is produced may be further subjected to secondary refining such as ladle refining.

[0093] The material having the chemical composition and produced as described above is heated to a temperature of 990 °C or more and 1210 °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 1210 °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 1210 °C or less. The temperature is preferably 1010 °C or more. The temperature is preferably 1190 °C or less. The temperature is more preferably 1030 °C or more. The temperature is more preferably 1170 °C or less.

• Hot rolling conditions

[0094] According to the present disclosure, in hot rolling, it is important to control the rolling conditions for both the recrystallization temperature range defined as the T_1 temperature or more, according to Expression (5) below, and the non-recrystallization temperature range defined as the T_2 temperature or less, according to Expression (6) below. It is also important to avoid rolling at the partial recrystallization temperature range (T_1 °C to T_2 °C) where recrystallization grains and coarse recovered grains are generated. The recrystallization temperature range and the non-recrystallization temperature range vary depending on the composition, and therefore clarifying the recrystallization temperature range and the non-recrystallization temperature range for each chemical composition of steel by Expressions (5) and (6) is important.
[Math. 4]

$$T_1 = 174 \log\left[sol.[Nb] \times \left([C] + \frac{12}{14}[N]\right)\right] + 1444 \quad \ldots (5)$$

(Here, sol.[Nb] is derived from Expression (7))
[Math. 5]

$$T_2 = T_1 - 75 \quad \ldots (6)$$

[Math. 6]

$$\text{sol.}\,[\text{Nb}] = \exp\left[2.3\left\{2.26 - \frac{6770}{T_0+273} - \log\left([C] + \frac{12}{14}[N]\right)\right\}\right] \quad \ldots (7)$$

(In Expressions (5) and (7), [C] and [N] represent mass% of C and N, respectively, T_0 represents heating temperature of the material in °C, and sol.[Nb] represents Nb solute in mass%. However, when [Nb] is the total Nb content in mass% in the steel plate, sol.[Nb] is always sol.[Nb] ≤ [Nb]. Accordingly, when the result of the calculation in Expression (7) is that sol.[Nb] > [Nb], then sol.[Nb] in Expression (7) is the value of [Nb].)

[0095] Rolling in the recrystallization temperature range defined as the mid-thickness temperature being the T_1 temperature or more is carried out with an average rolling reduction per pass of 3 % or more and cumulative rolling reduction ratio of 25 % or more.

[0096] The purpose of rolling in the recrystallization temperature range is to refine the microstructure by recrystallization, homogenize microstructure, and to refine and disperse coarse inclusions, even in steel plates having a thickness exceeding 100 mm. When hot rolling is performed in the partial recrystallization temperature range where the mid-thickness temperature is T_1 °C to T_2 °C, a mixed-grain-size microstructure of recrystallized grains and coarse recovered grains is formed and the desired uniformly-sized grain microstructure cannot be obtained. Therefore, it is necessary to roll at the mid-thickness temperature of T_1 °C or more while avoiding rolling at the mid-thickness temperature of T_1 °C to T_2 °C. When the average rolling reduction per pass is less than 3 %, it is not possible to introduce sufficient strain into the mid-thickness part in a steel plate having a thickness exceeding 100 mm thick, and the mid-thickness part microstructure cannot be sufficiently refined. Further, even when the average rolling reduction per pass is 3 % or more, when cumulative rolling reduction ratio is less than 25 %, recrystallization does not progress sufficiently and uniform microstructure cannot be obtained. For this reason, rolling in the recrystallization temperature range is performed with an average rolling reduction per pass of 3 % or more and a cumulative rolling reduction ratio of 25 % or more. The cumulative rolling reduction ratio is preferably 30 % or more. The cumulative rolling reduction ratio is more preferably 35 % or more.

[0097] Subsequent rolling in the non-recrystallization temperature range, where the mid-thickness temperature is defined as the T_2 temperature or less, is performed so that the cumulative rolling reduction ratio is 30 % or more.

[0098] Rolling when the mid-thickness temperature is in the non-recrystallization temperature range prevents recrystallization in the steel microstructure, and therefore the strain introduced by rolling is not consumed by recrystallization but accumulates and becomes the driving force for nucleation in the subsequent cooling process. As a result, the finally obtained steel plate can have a refined microstructure. On the other hand, when the cumulative rolling reduction ratio in the non-recrystallization temperature range of the mid-thickness part is less than 30 %, the crystal grain refinement effect is insufficient and the average effective crystal grain size in the mid-thickness part cannot be made to be 20 μm or less. For this reason, rolling in the non-recrystallization temperature range is performed with a cumulative rolling reduction ratio of 30 % or more. The cumulative rolling reduction ratio is preferably 35 % or more. The cumulative rolling reduction ratio is more preferably 40 % or more.

[0099] The conditions for rolling in the non-recrystallization temperature range are not particularly limited. A larger average rolling reduction per pass (average of rolling reduction in each pass) is preferable, and specifically, the average rolling reduction per pass is preferably 3 % or more.

[Cooling]

[0100] After completion of the hot rolling, the obtained hot-rolled steel plate is cooled. The cooling can be done by any method as long as the conditions described below are met. For example, the cooling can be done by water cooling.

Average cooling rate: 1.0 °C/s to 50.0 °C/s

[0101] When the average cooling rate at mid-thickness is less than 1.0 °C/s, a coarse ferrite phase is generated in the matrix microstructure, resulting in a decrease in matrix strength and toughness of base metal and degradation of SC/ICHAZ CTOD properties. On the other hand, when the average cooling rate is greater than 50.0 °C/s, an increase in hard bainite phase increases base metal strength and degrades SC/ICHAZ CTOD properties. The average cooling rate at the mid-thickness position is therefore 1.0 °C/s to 50.0 °C/s. The average cooling rate at the mid-thickness position is preferably 1.2 °C/s or more. The average cooling rate is preferably 45 °C/s or less. The average cooling rate is more preferably 1.5°C/s or more. The average cooling rate is more preferably 40°C/s or less.

[0102] Regarding the temperature measurement range of the cooling rate, when the cooling stop temperature is 500 °C or less, the range is 700 °C to 500 °C. When the cooling stop temperature is greater than 500 °C, the range is 700 °C to the cooling stop temperature.

Cooling stop temperature: 600 °C or less

[0103] In the cooling, the hot-rolled steel plate is cooled to a cooling stop temperature where the mid-thickness temperature is 600 °C or less. When the cooling stop temperature is greater than 600 °C, microstructure after transformation becomes coarse, resulting in insufficient base metal strength, a decrease in base metal toughness, and degradation of SC/ICHAZ CTOD properties. The cooling stop temperature at the mid-thickness temperature is therefore 600 °C or less. The cooling stop temperature is preferably 580 °C or less. The cooling stop temperature is more preferably 560 °C or less. A lower limit of the cooling stop temperature is not particularly limited. The lower limit is preferably about 200 °C.

[Tempering treatment]

Tempering Temperature: 700 °C or less

[0104] After the cooling stop, the steel plate may be subjected to tempering treatment. Tempering treatment can further improve base metal toughness. At this time, a tempering temperature higher than 700 °C generates a coarse ferrite phase, thus degrading base metal toughness and SCHAZ toughness. Accordingly, the tempering temperature at the mid-thickness temperature is 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 as long as the effect of improving base metal toughness can be obtained. The lower limit may be around 300 °C.

[0105] In the production method according to the present disclosure, anything not described herein may follow a conventional method.

EXAMPLES

[0106] 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.

[0107] Material having a chemical composition listed in Table 1 was used to produce steel plates under the production conditions listed in Table 2. Rolling at T_1 °C or more was performed with an average rolling reduction per pass ≥ 3 %. 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.

[0108] Average effective crystal grain size, maximum effective crystal grain size, number density of composite inclusions containing sulfides containing Ca and Mn and oxides containing Al, yield stress, toughness, and CTOD properties were measured for each of the steel plates obtained by the following methods.

[Average effective crystal grain size and maximum effective crystal grain size]

[0109] 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, so as to include the mid-thickness part. 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. The maximum value of circle equivalent diameter obtained was defined as the maximum effective grain size.

[0110] EBSP analysis conditions

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

[Number density of composite inclusions containing sulfides containing Ca and Mn and oxides containing Al]

[0111] Samples were taken from the center of the steel plate in the longitudinal, width, and thickness directions, and mirror polished, finishing with diamond buffing + alcohol. Then, using a field emission scanning electron microscope (FE-SEM), composite inclusions having a circle equivalent diameter of 0.1 μm or more in the 1 mm × 1 mm evaluation area, the center of which is the center of the area, were identified by EDX (energy dispersive X-ray spectroscopy) analysis, and the number density of the composite inclusions was also evaluated. Evaluation of inclusion type was performed such that an inclusion was judged to contain an element when the chemical composition of the inclusion, quantified by the ZAF method, contained 3 % or more of the element in terms of atomic fraction.

[Yield stress]

[0112] Tensile tests were conducted according to EN 10002-1 to determine yield stress (YS) at 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 1/2 positions of plate thickness. When the upper yield point appeared in the tensile test, the upper yield point was used as the yield stress, and when the upper yield point did not appear, the 0.2 % proof stress was used as the yield stress.

[Base metal toughness]

[0113] Three V-notch test pieces as specified in Japanese Industrial Standard JIS Z2242 were taken from the 1/2 thickness position of the steel plate so that the longitudinal direction of each test piece was perpendicular to the rolling direction of the plate. The absorbed energy $vE_{-40\ °C}$ at -40 °C was measured by the Charpy impact test. The base metal toughness was considered to be good when the average $vE_{-40\ °C}$ of three such test pieces was 100 J or more.

[0114] 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]

[0115] 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 EN10225-4 (2019), and the crack opening displacement (CTOD value (δ)) was evaluated at the test temperature of -20 °C using test pieces each having a square cross-section of t x t (where t is plate thickness).

[0116] 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.

[0117] A higher CTOD value (δ) indicates that a brittle crack is less likely to occur.

[0118] 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 EN10225-4 (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.

[0119] The measurement results are listed in Table 2.

[Table 1]

[0120]

Table 1

Ref. ID	Chemical composition (mass%)												[Ti]/[-N]	ACR (Expression (2))	Ceq (%)	Pcm (%)	Classification
	C	Si	Mn	P	S	Al	Ti	Nb	Ca	N	O	Other					
A	0.03	0.29	2.7	0.008	0.0005	0.055	0.021	0.025	0.0067	0.0048	0.0059	-	4.38	0.80	0.480	0.175	Example
B	0.06	0.07	1.6	0.011	0.0010	0.022	0.053	0.012	0.0080	0.0106	0.0054	-	5.00	1.13	0.327	0.142	Example
C	0.12	0.10	1.7	0.027	0.0019	0.062	0.012	0.015	0.0008	0.0042	0.0020	-	2.86	0.10	0.403	0.208	Example
D	0.04	0.32	1.8	0.009	0.0038	0.093	0.013	0.027	0.0025	0.0040	0.0045	-	3.25	0.05	0.340	0.141	Example
E	0.06	0.12	1.9	0.019	0.0049	0.047	0.004	0.066	0.0058	0.0025	0.0027	-	1.60	0.54	0.377	0.159	Example
F	0.13	0.58	0.9	0.047	0.0021	0.036	0.014	0.006	0.0190	0.0037	0.0070	-	3.78	0.17	0.280	0.194	Example
G	0.07	0.29	1.5	0.023	0.0022	0.040	0.018	0.040	0.0023	0.0113	0.0038	-	1.59	0.17	0.320	0.155	Example
H	0.09	0.05	1.6	0.024	0.0045	0.075	0.028	0.059	0.0135	0.0074	0.0052	-	3.78	0.61	0.357	0.172	Example
I	0.04	0.20	2.1	0.039	0.0029	0.035	0.019	0.031	0.0048	0.0084	0.0029	Ni:1.0, Cu:0.3, V:0.10, Mg:0.004	2.26	0.68	0.497	0.193	Example
J	0.08	0.42	1.4	0.038	0.0008	0.031	0.008	0.018	0.0025	0.0027	0.0044	Ni:0.4, Cr:0.3, Mo:0.3, B:0.0040	2.96	0.28	0.460	0.226	Example
K	0.06	0.03	1.9	0.016	0.0011	0.034	0.025	0.024	0.0058	0.0054	0.0055	Cu:1.5, W:0.15, REM:0.022	4.63	0.48	0.477	0.231	Example
L	0.04	0.10	1.1	0.010	0.0042	0.031	0.026	0.016	0.0092	0.0072	0.0013	Cr:1.3, Mg:0.001	3.61	1.41	0.483	0.163	Example
M	0.06	0.08	1.5	0.012	0.0040	0.089	0.012	0.027	0.0146	0.0049	0.0036	Ni:2.2, V:0.20, W:0.40, B:0.0020	2.45	1.42	0.497	0.204	Example

(continued)

Ref. ID	Chemical composition (mass%)												[Ti]/[-N]	ACR (Expression (2))	Ceq (%)	Pcm (%)	Classification
	C	Si	Mn	P	S	Al	Ti	Nb	Ca	N	O	Other					
N	0.05	0.09	1.0	0.007	0.0010	0.003	0.014	0.025	0.0025	0.0076	0.0020	Cu:0.2, Mo:1.3, REM:0.010	1.84	1.19	0.490	0.200	Example
O	0.08	0.12	2.0	0.041	0.0026	0.037	0.018	0.010	0.0004	0.0072	0.0011	-	2.50	0.04	0.413	0.184	Comparative Example
P	0.04	0.16	1.9	0.044	0.0046	0.039	0.012	0.017	0.0210	0.0031	0.0049	-	3.87	1.17	0.357	0.140	Comparative Example
Q	0.03	0.42	0.9	0.046	0.0034	0.083	0.021	0.044	0.0081	0.0051	0.0063	Cr:1.6, W:0.22, B:0.0020	4.12	0.08	0.500	0.179	Comparative Example
R	0.09	0.22	0.8	0.045	0.0014	0.065	0.009	0.054	0.0030	0.0058	0.0023	Ni:1.5	1.55	0.97	0.323	0.162	Comparative Example
S	0.03	0.26	0.9	0.021	0.0044	0.048	0.033	0.067	0.0042	0.0070	0.0030	Mo:1.6, REM:0.011, Mg:0.003	4.71	0.37	0.500	0.190	Comparative Example
T	0.05	0.57	2.5	0.031	0.0027	0.034	0.048	0.027	0.0124	0.0101	0.0050	Cr:0.1, V:0.05, W:0.48, B:0.0040	4.75	1.02	0.497	0.224	Comparative Example
U	0.11	0.24	1.7	0.020	0.0030	0.010	0.015	0.004	0.0069	0.0079	0.0057	-	1.90	0.20	0.393	0.203	Comparative Example
V	0.14	0.26	1.2	0.023	0.0047	0.062	0.013	0.045	0.0012	0.0061	0.0016	-	2.13	0.11	0.340	0.209	Comparative Example
W	0.08	0.49	1.5	0.020	0.0053	0.082	0.008	0.036	0.0018	0.0019	0.0031	-	4.21	0.08	0.330	0.171	Comparative Example
X	0.07	0.23	2.0	0.055	0.0017	0.019	0.041	0.043	0.0116	0.0092	0.0061	-	4.46	0.61	0.403	0.178	Comparative Example
Y	0.08	0.51	2.3	0.032	0.0032	0.047	0.057	0.023	0.0069	0.0120	0.0022	-	4.75	1.13	0.463	0.212	Comparative Example

(continued)

Ref. ID	Chemical composition (mass%)												[Ti]/[-N]	ACR (Expression (2))	Ceq (%)	Pcm (%)	Classification
	C	Si	Mn	P	S	Al	Ti	Nb	Ca	N	O	Other					
Z	0.10	0.16	1.4	0.046	0.0018	0.046	0.010	0.080	0.0051	0.0025	0.0028	-	4.00	1.22	0.333	0.175	Comparative Example
AA	0.02	0.44	2.6	0.046	0.0012	0.043	0.016	0.042	0.0037	0.0049	0.0026	-	3.27	1.32	0.453	0.165	Comparative Example
AB	0.05	0.63	2.5	0.048	0.0010	0.096	0.007	0.059	0.0040	0.0035	0.0040	-	2.00	0.96	0.467	0.196	Comparative Example
AC	0.12	0.08	1.3	0.025	0.0010	0.085	0.037	0.047	0.0034	0.0083	0.0043	Ni:0.9, Cr:0.2, Mo:0.2, W:0.15, REM:0.027, Mg:0.002	4.46	0.58	0.477	0.226	Comparative Example
AD	0.04	0.21	2.0	0.012	0.0028	0.019	0.046	0.030	0.0071	0.0098	0.0059	Cu:0.1, Mo:0.2, V:0.26	4.69	0.17	0.472	0.191	Comparative Example
AE	0.10	0.09	1.5	0.035	0.0028	0.110	0.015	0.061	0.0033	0.0036	0.0018	-	4.17	0.63	0.350	0.178	Comparative Example
AF	0.13	0.58	1.5	0.018	0.0043	0.001	0.038	0.041	0.0022	0.0089	0.0031	-	4.27	0.14	0.380	0.224	Comparative Example
AG	0.05	0.08	1.8	0.044	0.0029	0.028	0.001	0.038	0.0140	0.0006	0.0055	-	1.67	0.83	0.350	0.143	Comparative Example
AH	0.03	0.34	2.8	0.037	0.0037	0.061	0.053	0.021	0.0064	0.0112	0.0062	-	4.73	0.03	0.497	0.181	Comparative Example
AI	0.05	0.11	1.0	0.024	0.0023	0.035	0.021	0.060	0.0073	0.0051	0.0064	Ni:0.6, Cu:1.5, V:0.08, B:0.0061, REM:0.017, Mg:0.004	4.12	0.03	0.373	0.227	Comparative Example
AJ	0.07	0.53	1.9	0.014	0.0017	0.055	0.044	0.025	0.0081	0.0130	0.0065	-	3.38	0.04	0.387	0.183	Comparative Example

(continued)

Ref. ID	Chemical composition (mass%)												[Ti]/[-N]	ACR (Expression (2))	Ceq (%)	Pcm (%)	Classification
	C	Si	Mn	P	S	Al	Ti	Nb	Ca	N	O	Other					
AK	0.12	0.30	1.6	0.023	0.0046	0.059	0.035	0.022	0.0190	0.0086	0.0071	-	4.07	0.03	0.387	0.210	Comparative Example
AL	0.10	0.43	2.0	0.049	0.0045	0.094	0.026	0.025	0.013 5	0.0104	0.0021	-	2.50	1.68	0.433	0.214	Comparative Example
AM	0.12	0.59	2.1	0.049	0.0011	0.022	0.020	0.060	0.0097	0.0056	0.0064	-	3.57	0.35	0.470	0.245	Comparative Example
AN	0.07	0.37	1.2	0.033	0.0028	0.097	0.011	0.033	0.0118	0.0030	0.0043	-	3.67	1.27	0.270	0.142	Comparative Example
AO	0.09	0.37	1.6	0.038	0.0031	0.035	0.009	0.059	0.0102	0.0077	0.0061	-	1.17	0.26	0.357	0.182	Comparative Example
AP	0.10	0.15	2.5	0.044	0.0025	0.032	0.013	0.015	0.0133	0.0029	0.0047	-	4.48	1.38	0.517	0.230	Comparative Example
AQ	0.07	0.55	1.9	0.045	0.0016	0.095	0.018	0.019	0.0025	0.0038	0.0065	-	4.74	-0.39	0.387	0.183	Comparative Example
AR	0.07	0.13	2.3	0.019	0.0049	0.068	0.044	0.062	0.0045	0.0087	0.0037	-	5.06	0.27	0.453	0.189	Comparative Example

Note 1: the balance is Fe and inevitable impurity
Note 2: underlining indicates value outside scope of present disclosure
Note 3: AcR = {[Ca] - (0.18 + 130 [Ca]) x [O]} / 1.25 / [S]
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]

[0121]

Table 2

			Production conditions								Measurement results							
			Heating	Hot rolling			Cooling		Tempering	Base metal properties					Welded portion properties		
No.	Steel sample ID	Thickness (mm)	Heating temp. (°C)	Cumulative rolling reduction ratio at T_1°C or more (%)	T_1°C to T_2°C rolling	Cumulative rolling reduction ratio at T_2°C or less (%)	Average cooling rate (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Mid-thickness part average effective crystal grain size (μm)	Mid-thickness part maximum effective crystal grain size (μm)	1/2 position composite inclusions [2]) (per mm^2)	1/2 position YS (MPa)	1/2 position $vE_{-40°C}$ (J)	-20°C CGHAZ δ (mm)	-20°C SC/ICHAZ boundary δ (mm)	Classification
1	A	101	1077	27	No	56	4.8	218	-	14	91	179	510	200	0.94	1.08	Example
2	A	146	1093	42	No	43	10.4	512	750	19	145	205	337	103	0.85	0.41	Example
3	B	150	1158	41	No	44	77	379	500	10	102	154	373	121	0.68	0.76	Example
4	B	135	1107	48	No	47	10.6	625	-	41	85	122	298	64	0.51	0.31	Comparative Example
5	C	137	975	14	No	59	1.3	541	-	27	170	17	426	89	0.33	0.38	Comparative Example
6	C	113	1068	38	No	48	4.2	344	-	14	98	215	447	123	1.16	0.74	Example
7	D	129	1195	31	No	33	0.8	244	-	40	200	189	312	26	0.71	0.27	Comparative Example
8	D	120	1051	28	No	54	2.4	526	-	20	76	169	369	175	0.43	0.56	Example
9	E	137	1180	39	No	51	9.6	315	600	15	81	152	427	167	0.86	0.92	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 T_1°C or more (%)	T_1°C to T_2°C rolling	Cumulative rolling reduction ratio at T_2°C or less (%)	Average cooling rate (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Mid-thickness part average effective crystal grain size (μm)	Mid-thickness part maximum effective crystal grain size (μm)	1/2 position composite inclusions 2) (per mm^2)	1/2 position YS (MPa)	1/2 position $vE_{-40°C}$ (J)	-20°C CGHAZ δ (mm)	-20°C SC/ICHAZ boundary δ (mm)	
10	E	130	1158	37	No	56	63.2	587	-	14	97	127	680	182	0.52	0.28	Comparative Example
11	F	150	1230	32	No	53	9.3	306	-	37	173	177	301	39	0.44	0.15	Comparative Example
12	F	200	1077	26	No	37	28.2	379	-	19	110	176	328	208	0.92	1.04	Example
13	G	103	1169	30	No	44	44.7	447	550	18	72	81	350	177	0.74	0.98	Example
14	G	119	1086	21	No	64	3.1	462	-	16	189	15	370	36	0.27	0.33	Comparative Example
15	H	144	1185	36	No	44	49.0	560	600	19	93	72	452	182	0.61	0.72	Example
16	H	124	1110	39	No	27	2.8	453	-	39	71	132	307	22	0.59	0.22	Comparative Example
17	I	142	1153	34	No	38	2.4	364	-	14	84	132	527	149	0.62	0.83	Example
19	J	170	1105	27	No	34	3.7	404	-	19	89	193	424	172	0.53	0.97	Example
20	K	149	1017	40	No	39	3.2	540	-	15	104	170	415	182	0.73	1.04	Example
21	L	127	1178	35	No	41	5.3	477	-	13	96	77	483	144	0.50	0.69	Example

(continued)

N-o.	Steel sample ID	Thickness (mm)	Production conditions							Measurement results							
			Heating	Hot rolling			Cooling		Tempering	Base metal properties					Welded portion properties		Classification
			Heating temp. (°C)	Cumulative rolling reduction ratio at T_1°C or more (%)	T_1°C to T_2°C rolling	Cumulative rolling reduction ratio at T_2°C or less (%)	Average cooling rate (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Mid-thickness part average effective crystal grain size (μm)	Mid-thickness part maximum effective crystal grain size (μm)	1/2 position composite inclusions 2) (per mm^2)	1/2 position YS (MPa)	1/2 position $vE_{-40°C}$ (J)	-20°C CGHAZ δ (mm)	-20°C SC/ICHAZ boundary δ (mm)	
22	M	130	1066	36	No	56	6.6	600	-	18	78	141	461	183	0.52	1.28	Example
23	N	140	1111	33	No	52	35.9	582	650	11	92	107	516	184	0.56	0.54	Example
24	O	126	1006	33	No	40	14.2	399	-	19	89	21	425	170	0.14	0.29	Comparative Example
25	P	141	1142	45	No	43	2.9	588	-	15	110	275	380	159	0.26	0.21	Comparative Example
26	Q	132	1110	49	No	51	8.5	425	-	12	94	164	492	142	0.18	0.17	Comparative Example
27	R	148	1146	40	No	37	24.6	557	-	20	88	62	310	216	0.68	0.87	Comparative Example
28	S	126	1069	38	No	37	14.1	403	500	14	86	83	494	135	0.26	0.29	Comparative Example
29	T	136	1176	34	No	56	6.5	481	-	18	83	114	520	184	0.19	0.27	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 T_1°C or more (%)	T_1°C to T_2°C rolling	Cumulative rolling reduction ratio at T_2°C or less (%)	Average cooling rate (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Mid-thickness part average effective crystal grain size (μm)	Mid-thickness part maximum effective crystal grain size (μm)	1/2 position composite inclusions 2) (per mm^2)	1/2 position YS (MPa)	1/2 position $vE_{-40°C}$ (J)	-20°C CGHAZ δ (mm)	-20°C SC/ICHAZ boundary δ (mm)	
30	U	131	1112	44	No	35	4.4	211	-	31	97	96	311	73	0.47	0.20	Comparative Example
31	V	146	1153	42	No	44	4.1	473	-	14	79	108	372	219	0.22	0.13	Comparative Example
32	W	129	1130	37	No	35	4.9	535	-	20	106	216	350	196	0.23	0.33	Comparative Example
33	X	120	1183	33	No	44	21.7	467	500	20	90	169	427	196	0.11	0.25	Comparative Example
34	Y	107	1137	34	No	58	1.9	491	-	13	80	195	474	193	0.23	0.20	Comparative Example
35	Z	109	1197	41	No	63	7.9	546	-	12	88	190	386	175	0.25	0.28	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 T_1°C or more (%)	T_1°C to T_2°C rolling	Cumulative rolling reduction ratio at T_2°C or less (%)	Average cooling rate (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Mid-thickness part average effective crystal grain size (μm)	Mid-thickness part maximum effective crystal grain size (μm)	1/2 position composite inclusions [2] (per mm^2)	1/2 position YS (MPa)	1/2 position $vE_{-40°C}$ (J)	-20°C CGHAZ δ (mm)	-20°C SC/ICHAZ boundary δ (mm)	
36	AA	101	1108	49	No	53	43.0	215	600	15	85	119	293	212	0.91	1.23	Comparative Example
37	AB	111	1192	43	No	54	6.6	491	-	13	100	91	495	197	0.32	0.12	Comparative Example
38	AC	141	1167	35	No	38	36.4	328	-	10	81	186	499	81	0.23	0.23	Comparative Example
39	AD	114	1116	37	No	58	7.3	530	-	18	77	121	445	182	0.29	0.29	Comparative Example
40	AE	141	1131	43	No	36	6.5	524	-	17	71	270	371	216	0.23	0.28	Comparative Example
41	AF	103	1156	38	No	64	30.9	540	650	19	108	19	409	190	0.16	0.15	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 T_1°C or more (%)	T_1°C to T_2°C rolling	Cumulative rolling reduction ratio at T_2°C or less (%)	Average cooling rate (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)		Mid-thickness part average effective crystal grain size (μm)	Mid-thickness part maximum effective crystal grain size (μm)	1/2 position composite inclusions [2] (per mm^2)	1/2 position YS (MPa)	1/2 position $vE_{-40°C}$ (J)	-20°C CGHAZ δ (mm)	-20°C SC/ICHAZ boundary δ (mm)	
42	AG	126	1025	40	No	57	3.1	496	-		16	102	49	395	191	0.24	0.26		Comparative Example
43	AH	112	1200	47	No	35	4.0	566	-		14	94	97	511	37	0.37	0.19		Comparative Example
44	AI	143	1045	28	No	39	2.9	524	-		19	103	59	404	173	0.25	0.39		Comparative Example
45	AJ	128	1027	39	No	51	2.2	470	-		17	103	41	427	154	0.17	0.20		Comparative Example
46	AK	130	1176	27	No	45	1.9	461	-		11	95	101	414	154	0.25	0.24		Comparative Example
47	AL	111	1048	35	No	60	3.4	443	-		13	89	29	480	123	0.17	0.56		Comparative Example

(continued)

N-o.	Steel sam-ple ID	Thick-ness (mm)	Production conditions							Measurement results							Classifica-tion
			Heat-ing	Hot rolling			Cooling		Temper-ing	Base metal properties					Welded portion properties		
			Heat-ing temp. (°C)	Cumula-tive rolling reduction ratio at T_1°C or more (%)	T_1°C to T_2°C roll-ing	Cumula-tive rolling reduction ratio at T_2°C or less (%)	Aver-age cooling rate (°C/s)	Cool-ing stop temp. (°C)	Temper-ing temp. (°C)	Mid-thick-ness part average effec-tive crystal grain size (μm)	Mid-thick-ness part maxi-mum effective crystal grain size (μm)	1/2 position compo-site inclu-sions [2]) (per mm^2)	1/2 posi-tion YS (MPa)	1/2 posi-tion $vE_{-40°C}$ (J)	-20°C CGH-AZ δ (mm)	-20°C SC/I-CHAZ bound-ary δ (mm)	
48	AM	143	1118	27	No	55	1.9	498	-	18	105	147	487	205	0.19	0.29	Compara-tive Exam-ple
49	AN	126	1196	36	No	40	2.8	488	500	15	105	164	297	212	1.03	1.11	Compara-tive Exam-ple
50	AO	132	1143	29	No	43	4.3	589	-	15	77	130	389	149	0.19	0.24	Compara-tive Exam-ple
51	AP	107	1085	32	No	46	5.0	457	-	18	100	179	529	209	0.18	0.15	Compara-tive Exam-ple
52	AQ	135	1031	43	No	39	8.6	336	-	13	103	20	404	179	0.22	0.72	Compara-tive Exam-ple
53	AR	140	1196	38	No	50	7.2	553	-	20	100	62	493	124	0.22	0.28	Compara-tive Exam-ple

(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 T_1°C or more (%)	T_1°C to T_2°C rolling	Cumulative rolling reduction ratio at T_2°C or less (%)	Average cooling rate (°C/s)	Cooling stop temp. (°C)	Tempering temp. (°C)	Mid-thickness part average effective crystal grain size (μm)	Mid-thickness part maximum effective crystal grain size (μm)	1/2 position composite inclusions [2]) (per mm^2)	1/2 position YS (MPa)	1/2 position $vE_{-40°C}$ (J)	-20°C CGHAZ δ (mm)	-20°C SC/ICHAZ boundary δ (mm)	
54	A	101	1120	35	<u>Yes</u>	50	3.4	376	-	18	205	109	308	87	0.54	0.28	Comparative Example
55	B	120	1130	45	<u>Yes</u>	50	3.2	401	-	17	189	68	312	76	0.61	0.31	Comparative Example
56	C	130	1100	60	<u>Yes</u>	30	2.7	421	-	19	176	134	305	43	0.49	0.29	Comparative Example
57	D	120	1100	60	Yes	30	3.3	399	-	18	181	128	314	38	0.71	0.30	Comparative Example

Note: underlining indicates value outside scope of present disclosure

[0122] As can be seen from Table 2, steel plates that satisfied the conditions of the present disclosure (Examples) were produced under production conditions that fell within the scope of the present disclosure, and the base metal had values for average effective crystal grain size, maximum effective crystal grain size, and number density of composite inclusions containing sulfides containing Ca and Mn and oxides containing Al that all fell within the scope of the present disclosure. The results exhibited excellent base metal properties, with a yield stress of 325 MPa and a base metal $vE_{-40\ °C}$ of 100 J or more. Further, excellent joint CTOD properties were provided, as both the CTOD value of the CGHAZ and the CTOD value of the SC/ICHAZ boundary (δ) were 0.40 mm or more at -20 °C.

[0123] In contrast, steel plates that did not satisfy the conditions of the present disclosure (Comparative Examples) were inferior to the Example steel plates in either or both of the base metal properties and joint CTOD properties.

Claims

1. A steel plate having a thickness exceeding 100 mm and comprising a chemical composition containing, in mass%,

   C: 0.03 % to 0.13 %,
   Si: 0.60 % or less,
   Mn: 0.9 % to 2.7 %,
   P: 0.050 % or less,
   S: 0.0050 % or less,
   Al: 0.002 % to 0.100 %,
   Ti: 0.002 % to 0.055 %,
   Nb: 0.005 % to 0.070 %,
   Ca: 0.0005 % to 0.0200 %,
   N: 0.0120 % or less, and
   O: 0.0070 % or less,
   with the balance being Fe and inevitable impurity, wherein
   the chemical composition satisfies Expressions (1) to (4) below:

$$1.50 \le [Ti] / [N] \le 5.00 \qquad \dots (1)$$

$$0 \le \{[Ca] - (0.18 + 130[Ca]) \times [O]\} / 1.25 / [S] \le 1.50 \qquad \dots (2)$$

$$0.280\ \% \le Ceq\ (= [C] + [Mn]/6 + ([Cu] + [Ni])/15 + ([Cr] + [Mo] + [V])/5) \le 0.500\ \% \qquad (3)$$

$$Pcm\ (= [C] + [Si]/30 + ([Mn] + [Cu] + [Cr])/20 + [Ni]/60 + [Mo]/15 + [V]/10 + 5[B]) \le 0.240\ \% \qquad (4)$$

   where the square brackets in Expressions (1) to (4) indicate content in mass% of an element enclosed in the brackets and have a value of 0 when the element is not contained,
   in a mid-thickness part, average effective crystal grain size is 20 μm or less and maximum effective crystal grain size is 150 μm or less, and
   at a 1/2 thickness position, composite inclusions containing sulfides containing Ca and Mn and oxides containing Al and having a circle equivalent diameter of 0.1 μm or more are present at a number density of $25/mm^2$ to $250/mm^2$.

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: 2.5 % or less,
   Cu: 2.0 % or less,
   Cr: 1.5 % or less,
   Mo: 1.5 % or less,
   V: 0.25 % or less,
   W: 0.45 % or less,

B: 0.0045 % or less,
REM: 0.025 % or less and,
Mg: 0.005 % or less.

3. A method of producing a steel plate, the method comprising:

heating a material having the chemical composition defined in claim 1 or 2 to a temperature of 990 °C or more and 1210 °C or less; then rolling with an average rolling reduction per pass of 3 % or more and a cumulative rolling reduction ratio of 25 % or more when a mid-thickness temperature is T_1 °C or more as defined in Expression (5) below; rolling with a cumulative rolling reduction ratio of 30 % or more when the mid-thickness temperature is T_2 °C or less as defined in Expression (6) below; and then cooling at an average cooling rate of 1.0 °C/s to 50.0 °C/s in the mid-thickness temperature to a cooling stop temperature of 600 °C or less,
[Math. 1]

$$T_1 = 174 \log\left[sol.[Nb] \times \left([C] + \frac{12}{14}[N]\right)\right] + 1444 \quad \ldots (5)$$

wherein sol.[Nb] is derived from Expression (7),
[Math. 2]

$$T_2 = T_1 - 75 \quad \ldots (6)$$

[Math. 3]

$$\text{sol. [Nb]} = \exp\left[2.3\left\{2.26 - \frac{6770}{T_0+273} - \log\left([C] + \frac{12}{14}[N]\right)\right\}\right] \quad \ldots (7)$$

and in Expressions (5) and (7), [C] and [N] represent mass% of C and N content, respectively, T_0 represents heating temperature of the material in °C, and sol.[Nb] represents Nb solute in mass%, and sol.[Nb] ≤ [Nb] where [Nb] is the total Nb content in mass% in the steel plate.

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/JP2023/017811**

A. CLASSIFICATION OF SUBJECT MATTER

C21D 8/02(2006.01)i; ***C22C 38/00***(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

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

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2015/151519 A1 (JFE STEEL CORPORATION) 08 October 2015 (2015-10-08) entire text	1-4
A	WO 2014/155440 A1 (JFE STEEL CORPORATION) 02 October 2014 (2014-10-02) entire text	1-4
A	WO 2021/054345 A1 (JFE STEEL CORPORATION) 25 March 2021 (2021-03-25) entire text	1-4
A	WO 2013/118313 A1 (JFE STEEL CORPORATION) 15 August 2013 (2013-08-15) entire text	1-4
A	WO 2014/141632 A1 (JFE STEEL CORPORATION) 18 September 2014 (2014-09-18) entire text	1-4
A	WO 2020/255993 A1 (NIPPON STEEL CORPORATION) 24 December 2020 (2020-12-24) entire text	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
11 July 2023	**25 July 2023**

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

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

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/017811

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
WO 2015/151519 A1	08 October 2015	US 2017/0137905 A1 entire text EP 3128033 A1 CN 106133168 A KR 10-2016-0127808 A	
WO 2014/155440 A1	02 October 2014	CN 105102650 A entire text KR 10-2015-0126697 A BR 112015020815 A2	
WO 2021/054345 A1	25 March 2021	EP 4032993 A1 entire text KR 10-2022-0047632 A CN 114423878 A	
WO 2013/118313 A1	15 August 2013	EP 2813596 A1 entire text CN 104105810 A KR 10-2014-0117560 A KR 10-2016-0090399 A	
WO 2014/141632 A1	18 September 2014	US 2016/0040274 A1 entire text EP 2975148 A1 CN 105008574 A KR 10-2015-0119285 A	
WO 2020/255993 A1	24 December 2020	TW 202106898 A entire text	

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

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- JP 6477993 B **[0020]**
- JP S60184663 A **[0020]**
- JP S61253344 A **[0020]**
- JP H05186823 A **[0020]**
- JP 5846311 B **[0020]**