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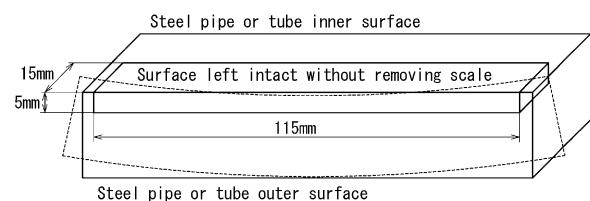
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(54) **HIGH-STRENGTH STEEL SHEET FOR SOUR-RESISTANT LINE PIPE AND METHOD FOR MANUFACTURING SAME, AND HIGH-STRENGTH STEEL PIPE USING HIGH-STRENGTH STEEL SHEET FOR SOUR-RESISTANT LINE PIPE**

(57) Provided is a high strength steel plate for a sour-resistant line pipe with excellent low-temperature toughness as well as HIC and SSCC resistance. The high strength steel plate for a sour-resistant line pipe has a chemical composition containing, by mass%, C: 0.030-0.060%, Si: 0.01-0.50%, Mn: 0.80-1.80%, P: 0.015% or less, S: 0.0015% or less, Al: 0.010-0.080%, Cr: 0.05-0.50%, Nb: 0.005-0.080%, N: 0.0010-0.0080%, and Ca: 0.0005-0.0050%, with the balance being Fe and inevitable impurities, in which a microstructure at 0.25 mm below a surface of the steel plate consists of granular bainite and tempered martensite austenite constituent, a maximum grain size is 80 μm or less and an average grain size is 20 μm or less at a mid-thickness position of the steel plate, a brittle-ductility transition temperature in a Charpy impact test is -100 °C or lower, and a tensile strength is 535 MPa or more.

FIG. 1



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Description

TECHNICAL FIELD

5 **[0001]** This disclosure relates to a high strength steel plate for a sour-resistant line pipe with excellent material homogeneity within the steel plate that is suitable for use in line pipes used for transporting crude oil and natural gas, and a method for producing the same. This disclosure also relates to a high strength steel pipe or tube using the high strength steel plate for a sour-resistant line pipe.

10 BACKGROUND

[0002] Generally, a line pipe is manufactured by forming a steel plate produced by a plate mill or hot rolling mill into a steel pipe or tube by, for example, UOE forming, press bend forming, and roll forming.

15 **[0003]** The line pipe used for transporting crude oil and natural gas containing hydrogen sulfide is required to have so-called sour resistance such as hydrogen-induced cracking resistance (HIC resistance) and sulfide stress corrosion cracking resistance (SSCC resistance), in addition to strength, toughness, weldability, and so on. Above all, in HIC, hydrogen ions from the corrosion reaction adsorb on the steel surface, enter the steel as atomic hydrogen, diffuse and accumulate around nonmetallic inclusions such as MnS and a hard second phase structure in the steel to become molecular hydrogen, which causes cracking due to its internal pressure. This HIC is considered as a problem in line pipes
20 with relatively low strength levels relative to oil well pipes or tubes, and many countermeasure techniques have been disclosed. On the other hand, with regard to SSCC, the importance of controlling the hardness of the inner surface layer of steel pipe or tube to improve SSCC resistance in more severe corrosion environment has been pointed out. In addition to these sour resistance properties, recent years have seen an increasingly severe environment for crude oil and natural gas extraction, which has increased the demand for excellent low-temperature toughness.

25 **[0004]** Normally, the thermo-mechanical control process (so-called TMCP) technique, which combines controlled rolling and controlled cooling, is applied in the production of high strength steel plates for line pipes. To ensure the sour resistance of steel plate using this TMCP technique, it is effective to increase the cooling start temperature and slow down the cooling rate during controlled cooling. However, when the cooling start temperature was increased, rolling in the non-recrystallization temperature range became insufficient, which limited the crystal grain refinement that was effective in
30 improving low-temperature toughness, and excellent low-temperature toughness could not be ensured.

[0005] To solve the above problem, for example, JP2020-012168A (PTL 1) proposes a technique to set the rolling finish temperature at 700 °C or higher and the average grain size at 15.0 μm or less. In addition, JP2020-509181A (PTL 2) proposes a technique to suppress crystal grain growth by setting the holding time between rough rolling and the start of finish rolling to 300 seconds or less.

35 CITATION LIST

Patent Literature

40 **[0006]**

PTL 1: JP2020-012168A

PTL 2: JP2020-509181A

45 SUMMARY

(Technical Problem)

50 **[0007]** Although the techniques described in PTLs 1 and 2 can improve low-temperature toughness, since the metallic structure contains ferrite, it is difficult to ensure sour resistance in a more severe corrosion environment with high hydrogen sulfide partial pressure.

[0008] In particular, pipelines used in cold climates require excellent low-temperature toughness. However, because in order to prevent the formation of ferrite, cooling must start at a temperature equal to or higher than the Ar₃ point, and the cumulative strain during rolling is small, it is difficult to achieve fine grain size, and excellent low-temperature toughness
55 has not been obtained in the past.

[0009] It could thus be helpful to provide a high strength steel plate for a sour-resistant line pipe with excellent low-temperature toughness as well as HIC resistance and SSCC resistance, together with an advantageous method for producing the same. This disclosure also provides a high strength steel pipe or tube using the high strength steel plate for a

sour-resistant line pipe.

(Solution to Problem)

[0010] We repeated numerous experiments and studies on the chemical composition, microstructure, and producing conditions of steel plate to ensure not only sour resistance but also low-temperature toughness. As a result, we found that to further improve the low-temperature toughness of high strength steel plate, at the mid-thickness position of the steel plate, the maximum grain size should be 80 μm or less and the average grain size should be 20 μm or less. Furthermore, in order to achieve such a steel microstructure, the hot rolling conditions in the recrystallization temperature range must be strictly controlled, and we have succeeded in finding such conditions. This disclosure is based on these discoveries.

[0011] We thus provide the following.

[1] A high strength steel plate for a sour-resistant line pipe comprising a chemical composition containing (consisting of), by mass%, C: 0.030 % or more and 0.060 % or less, Si: 0.01 % or more and 0.50 % or less, Mn: 0.80 % or more and 1.80 % or less, P: 0.015 % or less, S: 0.0015 % or less, Al: 0.010 % or more and 0.080 % or less, Cr: 0.05 % or more and 0.50 % or less, Nb: 0.005 % or more and 0.080 % or less, N: 0.0010 % or more and 0.0080 % or less, and Ca: 0.0005 % or more and 0.0050 % or less, with the balance being Fe and inevitable impurities, wherein

a microstructure at 0.25 mm below a surface of the steel plate consists of granular bainite and tempered martensite austenite constituent,
a maximum grain size is 80 μm or less and an average grain size is 20 μm or less at a mid-thickness position of the steel plate,
a brittle-ductility transition temperature in a Charpy impact test is -100 °C or lower, and
a tensile strength is 535 MPa or more.

[2] The high strength steel plate for a sour-resistant line pipe according to [1], wherein the chemical composition further contains, by mass%, at least one selected from the group consisting of Cu: 0.30 % or less, Ni: 0.10 % or less, and Mo: 0.50 % or less.

[3] The high strength steel plate for a sour-resistant line pipe according to [1] or [2], wherein the chemical composition further contains, by mass%, at least one selected from the group consisting of V: 0.005 % or more and 0.1 % or less, Ti: 0.005 % or more and 0.1 % or less, Zr: 0.0005 % or more and 0.02 % or less, Mg: 0.0005 % or more and 0.02 % or less, and REM: 0.0005 % or more and 0.02 % or less.

[4] A method for producing a high strength steel plate for a sour-resistant line pipe, the method comprising:

heating a slab having a chemical composition containing (consisting of), by mass%, C: 0.030 % or more and 0.060 % or less, Si: 0.01 % or more and 0.50 % or less, Mn: 0.80 % or more and 1.80 % or less, P: 0.015 % or less, S: 0.0015 % or less, Al: 0.010 % or more and 0.080 % or less, Cr: 0.05 % or more and 0.50 % or less, Nb: 0.005 % or more and 0.080 % or less, N: 0.0010 % or more and 0.0080 % or less, and Ca: 0.0005 % or more and 0.0050 % or less, with the balance being Fe and inevitable impurities to a temperature of 1000 °C or higher and 1250 °C or lower;

then subjecting the slab to hot rolling, which satisfies a total rolling reduction in a recrystallization temperature range being 35 % or more and 55 % or less and a rolling reduction in a final rolling pass in the recrystallization temperature range being 10 % or more to obtain a steel plate; and

then subjecting the steel plate to controlled cooling under a set of conditions including:

a temperature of a surface of the steel plate at the start of cooling being equal to or higher than A_{r3} point;
an average cooling rate in a temperature range from 750 °C to 550 °C in terms of a temperature at 0.25 mm below the surface of the steel plate being 15 °C/s or higher and 35 °C/s or lower;
an average cooling rate in a temperature range from 750 °C to 550 °C in terms of a temperature at a mid-thickness position of the steel plate being 15 °C/s or higher; and
a cooling stop temperature in terms of temperatures at 0.25 mm below the surface of the steel plate and at the mid-thickness position of the steel plate being 350 °C or higher and 550 °C or lower.

[5] The method for producing a high strength steel plate for a sour-resistant line pipe according to [4], wherein the chemical composition further contains, by mass%, at least one selected from the group consisting of Cu: 0.30 % or less, Ni: 0.10 % or less, and Mo: 0.50 % or less.

[6] The method for producing a high strength steel plate for a sour-resistant line pipe according to [4] or [5], wherein the chemical composition further contains, by mass%, at least one selected from the group consisting of V: 0.005 % or

more and 0.1 % or less, Ti: 0.005 % or more and 0.1 % or less, Zr: 0.0005 % or more and 0.02 % or less, Mg: 0.0005 % or more and 0.02 % or less, and REM: 0.0005 % or more and 0.02 % or less.

[7] A high strength steel pipe or tube using the high strength steel plate for a sour-resistant line pipe according to [1] or [2].

[8] A high strength steel pipe or tube using the high strength steel plate for a sour-resistant line pipe according to [3].

(Advantageous Effect)

[0012] The high strength steel plate for a sour-resistant line pipe and the high strength steel pipe or tube using the high strength steel plate for a sour-resistant line pipe of this disclosure have excellent low-temperature toughness as well as HIC resistance and SSCC resistance. The method for manufacturing a high strength steel plate for a sour-resistant line pipe of this disclosure can produce a high strength steel plate for a sour-resistant line pipe with excellent low-temperature toughness as well as HIC and SSCC resistance.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] In the accompanying drawing:

FIG. 1 illustrates a schematic diagram for describing the method for collecting a test piece for the evaluation of SSCC resistance in the EXAMPLES section below.

DETAILED DESCRIPTION

[0014] The following is a specific description of the high strength steel plate for a sour-resistant line pipe of this disclosure.

[Chemical composition]

[0015] First, the chemical composition of the high strength steel plate of this disclosure and reasons for limitation will be described. When components are expressed in "%" in the following description, this refers to "mass%" unless otherwise noted.

C: 0.030 % or more and 0.060 % or less

[0016] C effectively contributes to strength improvement, but sufficient strength cannot be secured when the C content is less than 0.030 %, so the C content should be 0.030 % or more, preferably 0.035 % or more. On the other hand, when the C content exceeds 0.060 %, low-temperature toughness deteriorates. In addition, SSCC resistance and HIC resistance deteriorate due to the increase in hardness of the surface layer and central segregation area during accelerated cooling. Therefore, the C content should be 0.060 % or less, preferably 0.050 % or less.

Si: 0.01 % or more and 0.50 % or less

[0017] Si is added for deoxidation, but when the Si content is less than 0.01 %, the deoxidizing effect is not sufficient, so the Si content should be 0.01 % or more, preferably 0.05 % or more. On the other hand, when the Si content exceeds 0.50 %, the non-thermal stress of the steel increases and low-temperature toughness deteriorates, so the Si content should be 0.50 % or less, preferably 0.45 % or less.

Mn: 0.80 % or more and 1.80 % or less

[0018] Mn effectively contributes to the improvement of strength, but the effect is not fully realized when the Mn content is less than 0.80 %. Therefore, the Mn content should be 0.80 % or more, preferably 1.00 % or more. On the other hand, when the Mn content exceeds 1.80 %, SSCC resistance and HIC resistance deteriorate due to the increase in hardness in the surface layer and central segregation area during accelerated cooling. Weldability is also degraded. Therefore, the Mo content should be 1.80 % or less, preferably 1.70 % or less.

P: 0.015 % or less

[0019] P is an inevitable impurity element, which degrades low-temperature toughness and increases the hardness of surface layer and central segregation area, thereby degrading SSCC resistance and HIC resistance. This tendency

becomes more pronounced when the P content exceeds 0.015 %, so the P content should be 0.015 % or less, preferably 0.008 % or less. A lower P content is better, but in terms of refining cost, the P content is preferably 0.001 % or more.

S: 0.0015 % or less

[0020] S is an inevitable impurity element and should be kept low because it degrades HIC resistance by forming MnS inclusions in the steel. From this viewpoint, the S content should be 0.0015 % or less, preferably 0.0010 % or less. A lower S content is better, but in terms of refining cost, the S content is preferably 0.0002 % or more.

Al: 0.010 % or more and 0.080 % or less

[0021] Al is added as a deoxidizer, but its effect is not fully realized when the Al content is less than 0.010 %. Therefore, the Al content should be 0.010 % or more, preferably 0.015 % or more. On the other hand, when the Al content exceeds 0.080 %, the non-thermal stress of the steel increases and low-temperature toughness deteriorates. Therefore, the Al content should be 0.080 % or less, preferably 0.070 % or less.

Cr: 0.05 % or more and 0.50 % or less

[0022] Cr, like Mn, is an effective element for obtaining sufficient strength even with low C content, and to obtain this effect, the Cr content must be 0.05 % or more. However, when the Cr content is too high, the hardness of surface layer and central segregation area increases during accelerated cooling due to excessive hardenability, resulting in deterioration of SSCC resistance and HIC resistance. Weldability is also degraded. Therefore, the Cr content should be 0.50 % or less, preferably 0.45 % or less.

Nb: 0.005 % or more and 0.080 % or less

[0023] Nb, when present as solute Nb, expands non-recrystallization temperature range during controlled rolling and contributes to the improvement of low-temperature toughness, but the effect is not fully realized when the Nb content is less than 0.005 %. Therefore, the Nb content should be 0.005 % or more, preferably 0.010 % or more. On the other hand, when the Nb content exceeds 0.080 %, coarse carbides are crystallized during solidification, which deteriorates HIC resistance. Therefore, the Nb content should be 0.080 % or less, preferably 0.060 % or less.

N: 0.0010 % or more and 0.0080 % or less

[0024] N effectively contributes to the improvement of strength, but a N content of less than 0.0010 % does not ensure sufficient strength. Therefore, the N content should be 0.0010 % or more, preferably 0.0015 % or more. On the other hand, when the N content exceeds 0.0080 %, the SSCC resistance and HIC resistance deteriorate due to increased hardness in the surface layer and central segregation area during accelerated cooling. The low-temperature toughness is also degraded. Therefore, the N content should be 0.0080 % or less, preferably 0.0070 % or less.

Ca: 0.0005 % or more and 0.0050 % or less

[0025] Ca is an effective element for improving HIC resistance through morphological control of sulfide inclusions, but its addition effect is not sufficient when the Ca content is less than 0.0005 %. Therefore, the Ca content should be 0.0005 % or more, preferably 0.0008 % or more. On the other hand, when the Ca content exceeds 0.0050 %, not only does the above effect become saturated, but the HIC resistance deteriorates due to a decrease in cleanliness of the steel. Therefore, the Ca content should be 0.0050 % or less, preferably 0.0045 % or less.

[0026] The basic components of chemical composition in this disclosure have been described above. In this disclosure, at least one selected from the group consisting of Cu, Ni, and Mo can be optionally included within the range below to further improve the strength and toughness of the steel plate.

Cu: 0.30 % or less

[0027] Cu is an effective element for improving low-temperature toughness and increasing strength, and to obtain this effect, the Cu content is preferably 0.05 % or more. However, when the Cu content exceeds 0.30 %, the SSCC resistance deteriorates because micro-cracks, called fissure, are more likely to occur in environments with low hydrogen sulfide partial pressure of less than 1 bar. Therefore, when Cu is contained, the Cu content should be 0.30 % or less, preferably 0.25 % or less.

Ni: 0.10 % or less

[0028] Ni is an effective element for improving low-temperature toughness and increasing strength, and to obtain this effect, the Ni content is preferably 0.01 % or more. However, when the Ni content exceeds 0.10 %, the SSCC resistance deteriorates because micro-cracks, called fissure, are more likely to occur in environments with low hydrogen sulfide partial pressure of less than 1 bar. Therefore, when Ni is contained, the Ni content should be 0.10 % or less, preferably 0.02 % or less.

Mo: 0.50 % or less

[0029] Mo is an effective element for improving low-temperature toughness and increasing strength, and to obtain this effect, the Mo content is preferably 0.01 % or more, more preferably 0.10 % or more. On the other hand, when the Mo content is too high, the SSCC resistance deteriorates because micro-cracks, called fissure, are more likely to occur in environments with low hydrogen sulfide partial pressure of less than 1 bar. Weldability is also degraded. Therefore, when Mo is contained, the Mo content should be 0.50 % or less, preferably 0.40 % or less.

[0030] The chemical composition in this disclosure may also optionally contain at least one selected from the group consisting of V, Ti, Zr, Mg, and REM within the ranges below.

[0031] At least one selected from the group consisting of V: 0.005 % or more and 0.1 % or less, Ti: 0.005 % or more and 0.1 % or less, Zr: 0.0005 % or more and 0.02 % or less, Mg: 0.0005 % or more and 0.02 % or less, and REM: 0.0005 % or more and 0.02 % or less

[0032] Both V and Ti are elements that can be optionally added to increase the strength and low-temperature toughness of the steel plate. For each element, when the content is less than 0.005 %, the effect is not fully realized. Therefore, when these elements are contained, each of their contents should be 0.005 % or more. On the other hand, when each of the contents of these elements exceeds 0.1 %, the toughness of welded portion deteriorates. Therefore, when these elements are contained, each of their contents is preferably 0.1 % or less.

[0033] Zr, Mg, and REM are elements that can be optionally contained to increase low-temperature toughness through crystal grain refinement and to increase cracking resistance through control of inclusion properties. For each element, when the content is less than 0.0005 %, the effect is not fully realized. Therefore, when these elements are contained, each of their contents should be 0.0005 % or more. On the other hand, when each of the contents of these elements exceeds 0.02 %, the effect becomes saturated, so when they are contained, it is preferable to keep the content of each element at 0.02 % or less.

[0034] This disclosure describes a technique for improving the low-temperature toughness of high strength steel pipe or tube using a high strength steel plate for a sour-resistant line pipe. Needless to say, for sour resistance, it is necessary to satisfy HIC resistance, and for example, it is preferable to set the CP value determined by the formula (1) below to 1.00 or less. For elements that are not contained, 0 may be substituted.

$$CP = 4.46[\%C] + 2.37[\%Mn]/6 + (1.74[\%Cu] + 1.7[\%Ni])/15 + (1.18[\%Cr] + 1.95[\%Mo] + 1.74[\%V])/5 + 22.36 \quad (1)$$

[%P]

where, [%X] represents the content (by mass%) of X element in the steel.

[0035] The CP value is a formula devised to estimate the material property of the central segregation area from the content of each alloying element. As the CP value in the formula (1) is larger, the concentration of components in the central segregation area is higher and the hardness of the central segregation area is increased. Therefore, by setting the CP value determined by the formula (1) to 1.00 or less, it is possible to improve the HIC resistance. Since the hardness of the central segregation area decreases with a smaller CP value, the upper limit for CP value may be set to 0.95 when higher HIC resistance is required. No lower limit is placed on CP, but the CP value can be 0.70 or more.

[0036] The balance other than the above elements is Fe and inevitable impurities. However, other trace elements may be included as long as they do not impair the effects of this disclosure. For example, O is an inevitable element contained in steel, but is acceptable in this disclosure when its content is 0.0050 % or less, preferably 0.0040 % or less.

[Microstructure at 0.25 mm below surface of steel plate]

[0037] Next, the steel microstructure of the high strength steel plate for a sour-resistant line pipe of this disclosure is described. To improve SSCC resistance and increase tensile strength to 535 MPa or more, the steel microstructure at 0.25 mm below a surface of the steel plate is made to consist of granular bainite and tempered martensite austenite constituent. When martensite austenite constituent is mixed in the steel microstructure, low-temperature toughness and SSCC resistance deteriorate. However, when the cooling stop temperature is sufficiently high, the martensite austenite constituent is tempered after cooling is stopped to become a tempered martensite austenite constituent (TMA), which

makes it possible to prevent deterioration of low-temperature toughness and SSCC resistance. In addition, the granular bainite and tempered martensite austenite constituent have lower hardness than other bainite and other martensite, which can improve SSCC resistance.

[0038] Here, the steel microstructure at 0.25 mm below a surface of the steel plate in this disclosure is preferably mainly granular bainite. Specifically, it is preferable that the area ratio of granular bainite is 90 % or more and the area ratio of tempered martensite austenite constituent is 10 % or less. On the other hand, since the presence of tempered martensite austenite constituent is also essential, the area ratio of the granular bainite is preferably 99 % or less and the area ratio of tempered martensite austenite constituent is preferably 1 % or more.

[0039] In the high strength steel plate of this disclosure, when the steel microstructure at 0.25 mm below a surface of the steel plate satisfies the above conditions, the outermost surface layer from the surface of the steel plate to a depth of 0.25 mm will also have the same steel microstructure, and as a result, the above effect of improving SSCC resistance can be obtained.

[0040] In order to obtain the effects of improving SSCC resistance and increasing strength more sufficiently, it is preferable that the overall steel microstructure of the steel plate, including areas other than the surface layer, satisfy the above conditions. Specifically, the microstructure at the mid-thickness position of the steel plate should satisfy the above conditions on behalf of the "areas other than the surface layer".

[Maximum and average grain size at mid-thickness position of steel plate]

[0041] In this disclosure, it is essential to suppress the formation of coarse crystal grains. In detail, when the maximum or average grain size is large, the low-temperature toughness deteriorates. In particular, when the maximum grain size at the mid-thickness position of the steel plate is greater than 80 μm , the low-temperature toughness is significantly degraded because the coarse crystal grain tends to be the initiation point for fracture. When the average grain size exceeds 20 μm , the low-temperature toughness is also degraded. Therefore, at the mid-thickness position of the steel plate, the maximum grain size should be 80 μm or less and the average grain size should be 20 μm or less. The maximum grain size and the average grain size at the mid-thickness position of the steel plate are preferably smaller, and therefore no lower limit is placed on them. In this disclosure, at the mid-thickness position of the steel plate, the maximum grain size can be 50 μm or more and the average grain size can be 10 μm or more. For "grain size", the grain sizes of crystal grains in the area of 1 mm $\times$ 1 mm at the mid-thickness position of the steel plate are measured, and among them, the maximum value is adopted as the "maximum grain size" and the average value as the "average grain size." The grain size is defined as circular equivalent diameter. Here, the mid-thickness position of the steel plate refers to the 1/2 position of the total thickness.

[Brittle-ductility transition temperature]

[0042] The high strength steel plate of this disclosure shall have a brittle-ductility transition temperature in the Charpy impact test of -100 °C or lower. This can ensure excellent low-temperature toughness. No lower limit is placed on the brittle-ductility transition temperature, but in this disclosure, the brittle-ductility transition temperature can be -120 °C or higher.

[Tensile strength]

[0043] The high strength steel plate of this disclosure shall have a tensile strength of 535 MPa or more, since the steel plate is for steel pipe or tube with a strength of API 5L grade X65 or more. No upper limit is placed on the tensile strength, but the tensile strength of the high strength steel plate of this disclosure can be 600 MPa or less.

[Thickness of steel plate]

[0044] The thickness of the high strength steel plate of this disclosure is not particularly limited, but those having a thickness of 12 mm to 39 mm are suitable for the above-mentioned applications.

[Method for producing high strength steel plate for a sour-resistant line pipe]

[0045] The following is a specific description of the method for producing the high strength steel plate for a sour-resistant line pipe and producing conditions. In the producing method of this disclosure, a steel slab and the like having the above chemical composition is heated and then hot rolled to make a steel plate, and then the steel plate is subjected to controlled cooling under predetermined conditions.

[[Slab heating temperature]]

Slab heating temperature: 1000 °C or higher and 1250 °C or lower

[0046] When the slab heating temperature is lower than 1000 °C, carbides is not sufficiently dissolved and the degree of solid solution strengthening is low, so the required strength cannot be obtained. Therefore, the slab heating temperature should be 1000 °C or higher, preferably 1030 °C or higher. On the other hand, when the slab heating temperature exceeds 1250 °C, the crystal grains extremely coarsen and toughness deteriorates. Therefore, the slab heating temperature should be 1250 °C or lower, preferably 1200 °C or lower. This temperature is the heating furnace temperature, and the slab is assumed to be heated to this temperature to the center portion.

[[Hot rolling conditions]]

Total rolling reduction in recrystallization temperature range: 35 % or more and 55 % or less

[0047] In order to make the largest crystal grains finer, hot rolling in the recrystallization temperature range should promote recrystallization of crystal grains and suppress the formation of coarse grains. When the total rolling reduction in the recrystallization temperature range is less than 35 %, recrystallization is insufficient and coarse grains remain, resulting in degradation of low-temperature toughness. Therefore, the total rolling reduction in the recrystallization temperature range should be 35 % or more, preferably 38 % or more. On the other hand, when the total rolling reduction in the recrystallization temperature range exceeds 55 %, coarsening of the largest crystal grains can be suppressed, but the average grain size cannot be 20 μm or less due to insufficient rolling reduction in the non-recrystallization temperature range, resulting in degradation of low-temperature toughness. Therefore, the total rolling reduction in the recrystallization temperature range should be 55 % or less, preferably 52 % or less. Here, the "recrystallization temperature range" means the temperature range equal to or higher than T_{nr} determined from the following formula. The surface temperature of the steel plate can be measured with a radiation thermometer or similar device and converted to the temperature of the steel plate at each position in the plate thickness direction.

$$T_{nr} (^{\circ}\text{C}) = 174 \times \log\{[\%Nb] \times ([\%C] + 12/14[\%N])\} + 1444$$

where, [%X] represents the content (by mass%) of X element in the steel.

Rolling reduction in final rolling pass in recrystallization temperature range: 10 % or more

[0048] In addition to setting the total rolling reduction in the recrystallization temperature range to 35 % or more and 55 % or less, it is necessary to ensure a sufficient rolling reduction in the final rolling pass in the recrystallization temperature range and sufficiently promote recrystallization, so that rolling in the non-recrystallization temperature range is started in a state of uniform grains without the presence of coarse grains. When the rolling reduction in the final rolling pass in the recrystallization temperature range is less than 10 %, low-temperature toughness deteriorates because recrystallization is insufficient, and the grains grow into coarse grains during the holding time between rough rolling and the start of finish rolling. Therefore, the rolling reduction in the final rolling pass in the recrystallization temperature range should be 10 % or more, preferably 11 % or more. No upper limit is placed on the rolling reduction in the final rolling pass in the recrystallization temperature range, and a higher rolling reduction is preferable, but the rolling reduction can be 20 % or less.

[0049] In the rolling in the non-recrystallization temperature range that is carried out after the rolling in the recrystallization temperature range is completed, rolling at a low temperature is more effective in refining the crystal grains because more strain is introduced. For this reason, it is preferable to perform rolling at as low a temperature as possible in the range in which the cooling start temperature of the cooling treatment described below can be observed.

[0050] In the hot rolling process, a lower rolling finish temperature is better to obtain high low-temperature toughness. On the other hand, from the viewpoint of ensuring sour resistance even in environments with high hydrogen sulfide partial pressure, it is necessary to set the rolling finish temperature based on the fact that the cooling start temperature of controlled cooling described below, must be equal to or higher than the Ar_3 point in terms of a temperature of a surface of the steel plate. The Ar_3 point refers to the temperature at which ferrite transformation begins during cooling, and can be determined, for example, from the chemical composition of the steel by the formula below. The surface temperature of the steel plate can be measured with a radiation thermometer or the like.

$$Ar_3 \text{ point } (^{\circ}\text{C}) = 910 - 310[\%C] - 80[\%Mn] - 20[\%Cu] - 15[\%Cr] - 55[\%Ni] - 80[\%Mo]$$

where, [%X] represents the content (by mass%) of X element in the steel.

[[Controlled cooling conditions]]

5 Cooling start temperature: equal to or higher than Ar_3 point in terms of temperature of surface of steel plate

[0051] When the temperature of a surface of the steel plate at the start of cooling is below the Ar_3 point, ferrite is formed before controlled cooling, resulting in a large strength loss and degradation of sour resistance. Therefore, the temperature of a surface of the steel plate at the start of cooling should be equal to or higher than the Ar_3 point. The temperature of a surface of the steel plate at the start of cooling is equal to or lower than rolling finish temperature. No upper limit is placed on the temperature of a surface of the steel plate at the start of cooling, but the temperature can be 900 °C or lower.

[0052] To achieve high strength while obtaining excellent SSCC resistance, it is necessary to control the cooling rate at 0.25 mm below a surface of the steel plate and at the mid-thickness position of the steel plate.

15 Average cooling rate in temperature range from 750 °C to 550 °C in terms of temperature of steel plate at 0.25 mm below surface of steel plate: 15 °C/s or higher and 35 °C/s or lower

[0053] It is important to slow down the average cooling rate in a temperature range from 750 °C to 550 °C in terms of a temperature of the steel plate at 0.25 mm below a surface of the steel plate as much as possible to build up granular bainite. Since the temperature range from 750 °C to 550 °C is an important temperature range for bainite transformation, it is important to control the cooling rate in this temperature range. In detail, when the average cooling rate exceeds 35 °C/s, lath bainite is formed and SSCC resistance after pipe or tube formation deteriorates. Therefore, the average cooling rate should be 35 °C/s or lower, preferably 30 °C/s or lower. On the other hand, when the average cooling rate is lower than 15 °C/s, ferrite and pearlite are formed, resulting in insufficient strength. From the viewpoint of preventing this, the average cooling rate should be 15 °C/s or higher.

[0054] For cooling at 550 °C or lower in terms of a temperature of the steel plate at 0.25 mm below a surface of the steel plate, when the cooling rate is slow, cooling does not occur in a stable nucleate boiling state, and the microstructure may vary in the outermost surface layer of the steel plate. Therefore, the average cooling rate in a temperature range from 550 °C to the cooling stop temperature in terms of a temperature of the steel plate at 0.25 mm below a surface of the steel plate is preferably 150 °C/s or higher. The average cooling rate is preferably 250 °C/s or lower because of the risk of microstructure variation.

Average cooling rate in temperature range from 750 °C to 550 °C in terms of temperature of steel plate at mid-thickness position of steel plate: 15 °C/s or higher

[0055] When the average cooling rate in a temperature range from 750 °C to 550 °C in terms of a temperature of the steel plate at the mid-thickness position of the steel plate is lower than 15 °C/s, ferrite is formed, resulting in strength reduction and deterioration of HIC resistance. Therefore, the average cooling rate should be 15 °C/s or higher. From the viewpoint of suppressing variation in low-temperature toughness, the average cooling rate is preferably 17 °C/s or higher. Although no upper limit is placed on the cooling rate, the average cooling rate is preferably 35 °C/s or lower to prevent the formation of lath bainite. Although there are no particular limitations on cooling at 550 °C or lower in terms of a temperature of the steel plate at the mid-thickness position of the steel plate, from the viewpoint of suppressing variations in low-temperature toughness, the average cooling rate is preferably 15 °C/s or higher. The average cooling rate is preferably 35 °C/s or lower.

[0056] Although the temperature of the steel plate at 0.25 mm below a surface of the steel plate and in the mid-thickness position of the steel plate cannot be physically measured directly, it can be calculated in real time from the results obtained by, for example, using a process computer to calculate the temperature distribution within a cross section along the plate thickness direction by differential calculation based on the surface temperature at the start of cooling measured with a radiation thermometer and the surface temperature at the target time when cooling is to be stopped. The temperature at 0.25 mm below a surface of the steel plate in the temperature distribution is herein referred to as the "temperature of the steel plate at 0.25 mm below a surface of the steel plate" and the temperature in the mid-thickness position of the steel plate in the temperature distribution is herein referred to as the "temperature of the steel plate in the mid-thickness position of the steel plate".

Cooling stop temperature: 350 °C or higher and 550 °C or lower in terms of temperature of steel plate at 0.25 mm below surface of steel plate and in mid-thickness position of steel plate

[0057] When the cooling stop temperature exceeds 550 °C, bainite transformation is incomplete and sufficient strength cannot be obtained. Therefore, the cooling stop temperature should be 550 °C or lower. On the other hand, when the

cooling stop temperature is lower than 350 °C, the martensite austenite constituent is not sufficiently tempered, resulting in degradation of low-temperature toughness. Furthermore, when the cooling stop temperature is lower than 250 °C, even SSCC resistance is degraded. For this reason, the cooling stop temperature should be 350 °C or higher, preferably 400 °C or higher.

[High strength steel pipe or tube]

[0058] By forming the high strength steel plate of this disclosure into a tubular shape by press bend forming, roll forming, UOE forming, or the like, and subjecting the butted portions of the tubular product to welding, a high strength steel pipe or tube (such as a UOE steel pipe or tube, electric resistance welded steel pipe or tube, or spiral steel pipe or tube) for a sour-resistant line pipe with excellent material homogeneity within the steel plate that is suitable for transporting crude oil and natural gas may be formed. Further, by using the high strength steel plate of this disclosure for steel pipe or tube, a steel pipe or tube with excellent SSCC resistance can be produced even when there is a high hardness zone in the welded portion.

[0059] For example, the UOE steel pipe or tube is produced by performing groove machining on ends of the steel plate, forming the steel plate into a steel pipe or tube shape by C press, U-ing press, or O-ing press, then subjecting the butted portions to seam welding by internal and external welding, and then expanding the pipe or tube if necessary. Any welding method that provides sufficient joint strength and joint toughness is acceptable, but submerged arc welding is preferred in terms of excellent weld quality and producing efficiency. Alternatively, the steel plate may be formed into a tubular shape by press bend forming and then subjected to seam welding at the butted portions to produce a steel pipe or tube, which may be expanded.

EXAMPLES

[0060] Steels (steel sample IDs A-AE) with the chemical compositions listed in Table 1 were made into slabs by continuous casting, and then the slabs were heated, hot rolled, and subjected to controlled cooling under the conditions listed in Table 2 to obtain steel plates. Then, the ends of each steel plate were subjected to groove machining and the steel plate was formed into a steel pipe or tube shape by C press, U-ing press, or O-ing press, and then the butted portions were subjected to seam welding by performing submerged arc welding from the inner and outer surfaces, and then a pipe or tube expansion process was performed to obtain a steel pipe or tube.

[Identification of microstructure and calculation of area ratio and maximum and average grain size]

[0061] A sample for observation of metallic microstructure was taken from the center portion in the rolling direction and in the plate transverse direction of each steel plate obtained as described above. After a cross-section of this sample perpendicular to the plate transverse direction was mirror polished and etched with colloidal silica, crystal data was collected in the fields of 1 mm × 1 mm at 0.25 mm below a surface of the steel plate and in the mid-thickness position of the steel plate (1/2 position of the total plate thickness) by the Electron Backscatter Diffraction (EBSD) method (measurement step: 0.8 μm). After data collection, OIM-Analysis and image processing software (ImageJ) were used to identify the microstructures at 0.25 mm below the surface of the steel plate and in the mid-thickness position of the steel plate, and to calculate the area ratio for each phase as well as the maximum and average grain size at the mid-thickness position of the steel plate. As the grain size, the circular equivalent diameter was used. The results are listed in Table 3.

[Derivation of brittle-ductility transition temperature]

[0062] A Charpy impact test piece was taken from the 1/2 position of the plate thickness so that the longitudinal direction of the test piece coincided with the plate transverse direction and subjected to Charpy impact test to derive the brittle-ductility transition temperature based on the method described in the "New Mathematical Expression Method for Charpy Absorbed Energy Transition Curves of Steel and Evaluation of Fracture Toughness (Journal of the Japanese Society for Strength and Fracture of Materials 17 1-13, 1982)". The results are listed in Table 3.

[Measurement of tensile strength and yield stress]

[0063] A full-thickness tensile test piece was taken so that the longitudinal direction of the test piece coincided with the plate transverse direction and subjected to a tensile test to measure tensile strength and yield stress. The results are listed in Table 3.

[Evaluation of SSCC resistance]

[0064] As illustrated in FIG. 1, after flattening a test piece (coupon) cut from each steel pipe or tube obtained, SSCC test pieces with a size of 5 mm × 15 mm × 115 mm were taken from the inner surface of the steel pipe or tube. At this time, in addition to a test piece containing only base metal without welded portion, a test piece containing both welded portion and base metal was also taken. The inner surface to be tested was left intact without removing the scale in order to leave the state of the outermost layer. That is, the position at 0.25 mm below a surface of the steel plate was included in the test piece. One of the SSCC test pieces thus obtained was applied with a stress of 90 % of the actual yield stress (0.5 % YS) of the corresponding steel pipe or tube and subjected to a 4-point bending SSCC test using NACE standard TM0177 Solution A at hydrogen sulfide partial pressure of 1 bar, in accordance with the EFC 16 standard.

[0065] Similarly, a 4-point bending SSCC test was conducted using NACE standard TM0177 Solution B at hydrogen sulfide partial pressure of 0.1 bar + carbon dioxide partial pressure of 0.9 bar, in accordance with the EFC 16 standard.

[0066] In addition, a 4-point bending SSCC test was conducted using NACE standard TM0177 Solution A at hydrogen sulfide partial pressure of 16 bar + carbon dioxide partial pressure of 5 bar, in accordance with the EFC 16 standard.

[0067] After immersing the test pieces in the solutions for 720 hours, when no crack was observed in both the test piece containing only base metal without welded portion and the test piece containing both welded portion and base metal, SSCC resistance was judged to be good and evaluated as o, and when crack occurred in at least one test piece, SSCC resistance was judged to be poor and evaluated as ×. The evaluation results are listed in Table 3.

[Evaluation of HIC resistance]

[0068] HIC resistance was examined by a HIC test in which a test piece was immersed in NACE standard TM0177 Solution A for 96 hours at hydrogen sulfide partial pressure of 1 bar. HIC resistance was also examined by a HIC test in which a test piece was immersed in NACE standard TM0177 Solution B for 96 hours at hydrogen sulfide partial pressure of 0.1 bar + carbon dioxide partial pressure of 0.9 bar. For HIC resistance, when the crack area ratio (CAR) was 5 % or less in the HIC test, HIC resistance was judged to be good and evaluated as o, and when CAR exceeded 5 %, HIC resistance was judged to be poor and evaluated as ×. The evaluation results are listed in Table 3.

[0069] The target ranges of this disclosure were, as high strength steel plate for a sour-resistant line pipe, a brittle-ductility transition temperature of -100 °C or lower, a tensile strength of 535 MPa or more, a steel microstructure at 0.25 mm below a surface of the steel plate consisting of granular bainite and tempered martensite austenite constituent, a maximum grain size of 80 μm or less and an average grain size of 20 μm or less at the mid-thickness position of the steel plate, no crack observed in the SSCC test, and a crack area ratio (CAR) of 5 % or less in the HIC test.

[Table 1]

Steel sample ID		Chemical Composition (mass%)																	CP	Ar ₃ temp. (°C)	Thr temp. (°C)	
		C	Si	Mn	P	S	Al	Cr	Nb	N	Ca	Cu	Ni	Mo	V	Ti	Zr	Mg				REM
A		0.035	0.20	1.43	0.006	0.0006	0.031	0.40	0.053	0.0047	0.0024									0.95	779	977
B		0.050	0.33	1.57	0.005	0.0005	0.035	0.15	0.025	0.0040	0.0025									0.99	767	944
C		0.045	0.25	1.48	0.005	0.0005	0.027	0.10	0.036	0.0046	0.0020	0.30								0.96	770	965
D		0.041	0.28	1.45	0.005	0.0007	0.042	0.25	0.038	0.0039	0.0019		0.10							0.94	772	961
E		0.030	0.40	1.05	0.008	0.0009	0.050	0.23	0.015	0.0034	0.0030		0.50							0.98	773	869
F		0.037	0.15	1.54	0.007	0.0008	0.025	0.31	0.027	0.0042	0.0028			0.005					1.00	771	929	
G		0.042	0.30	1.45	0.006	0.0006	0.025	0.28	0.040	0.0040	0.0023				0.012				0.96	777	967	
H		0.046	0.26	1.38	0.005	0.0005	0.029	0.35	0.031	0.0038	0.0018					0.005			0.94	780	954	
I		0.040	0.23	1.60	0.004	0.0004	0.028	0.15	0.018	0.0035	0.0040							0.005	0.94	767	903	
J		0.039	0.05	1.29	0.009	0.0007	0.060	0.50	0.012	0.0060	0.0021								1.00	787	874	
K		0.028	0.21	1.38	0.008	0.0006	0.041	0.15	0.023	0.0035	0.0020								0.88	789	896	
L		0.063	0.35	1.28	0.007	0.0007	0.027	0.22	0.016	0.0041	0.0017			0.005					1.00	785	927	
M		0.047	0.51	1.37	0.008	0.0008	0.054	0.31	0.014	0.0053	0.0025				0.010				1.00	781	897	
N		0.040	0.17	0.78	0.006	0.0005	0.028	0.43	0.022	0.0039	0.0022	0.20							0.75	825	918	
O		0.030	0.05	1.81	0.009	0.0009	0.030	0.05	0.045	0.0035	0.0028		0.05						1.07	752	952	
P		0.040	0.20	1.47	0.016	0.0009	0.026	0.22	0.045	0.0043	0.0024		0.10						1.21	769	973	
Q		0.042	0.08	1.50	0.009	0.0016	0.037	0.44	0.019	0.0035	0.0029								1.08	770	910	
R		0.049	0.10	1.15	0.009	0.0007	0.081	0.28	0.023	0.0053	0.0021	0.10	0.10						0.99	789	938	
S		0.038	0.32	1.22	0.007	0.0006	0.027	0.53	0.031	0.0044	0.0026								0.93	793	942	
T		0.050	0.14	1.50	0.009	0.0009	0.030	0.15	0.081	0.0040	0.0018								1.05	772	1033	
U		0.035	0.13	1.58	0.008	0.0008	0.028	0.35	0.030	0.0082	0.0019								1.04	768	940	
V		0.043	0.21	1.42	0.008	0.0009	0.026	0.23	0.043	0.0039	0.0051		0.15						1.04	768	974	
W		0.041	0.25	1.36	0.006	0.0006	0.025	0.20	0.040	0.0043	0.0023	0.32	0.09						0.95	774	966	
X		0.040	0.20	1.45	0.006	0.0007	0.040	0.15	0.030	0.0040	0.0026	0.30	0.15						0.97	765	942	
Y		0.035	0.22	1.20	0.006	0.0006	0.036	0.10	0.034	0.0045	0.0028		0.53						0.99	759	943	
Z		0.039	0.05	1.08	0.006	0.0005	0.030	0.11	0.022	0.0009	0.0023								0.76	810	912	
AA		0.042	0.17	1.55	0.009	0.0008	0.045	0.21	0.048	0.0042	0.0004		0.08						1.06	765	981	
AB		0.060	0.21	1.31	0.004	0.0005	0.033	0.38	0.015	0.0038	0.0021								0.96	781	918	
AC		0.037	0.30	1.80	0.004	0.0004	0.028	0.15	0.025	0.0040	0.0023								1.00	752	923	
AD		0.040	0.22	0.99	0.008	0.0008	0.035	0.49	0.075	0.0060	0.0014	0.28	0.10		0.014				0.91	800	1014	
AE		0.043	0.15	1.45	0.005	0.0006	0.030	0.29	0.034	0.0080	0.0024				0.023				0.94	776	962	

Note 1: The balance is Fe and inevitable impurities.

Note 2: Underlined if outside the scope of the disclosure.

[Table 2]

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Table 2

No.	Steel sam- ple ID	Plate thick- ness (mm)	Heat- ing temp. (°C)	Hot rolling in recrystallization temperature range		Rolling finish tempera- ture (°C)	Cooling start		Average cooling rate from 750°C to 550°C (0.25m- m below surface of steel plate) (°C/s)	Average cooling rate from 750°C to 550°C (mid- thick- ness position) (°C/s)	Aver- age cooling rate of 550°C or lower (025m- m below surface of steel plate) (°C/s)	Average cooling rate of 550°C or lower (mid- thick- ness position) (°C/s)	Cooling stop tempera- ture (025mm below surface of steel plate) (°C)	Cooling stop tempera- ture (mid- thickness position) (°C)	Re- marks
				Total rolling reduc- tion (%)	Rolling reduc- tion in final pass (%)		tempera- ture (°C)	tempera- ture-Ar ₃ (°C)							
1	A	39	1000	35	10	824	794	15	15	15	150	16	350	350	Ex.
2	B	18	1150	50	13	840	770	3	30	27	230	31	510	510	Ex.
3	C	15	1200	53	14	851	771	1	33	30	240	34	530	530	Ex.
4	D	33	1060	40	11	822	782	10	18	17	190	19	400	400	Ex.
5	E	21	1120	55	10	833	778	5	28	26	220	29	490	490	Ex.
6	F	27	1090	43	12	832	777	6	22	20	200	23	450	450	Ex.
7	G	36	1030	39	11	820	785	8	17	16	170	18	380	380	Ex.
8	H	30	1060	42	10	835	785	5	20	18	190	20	420	420	Ex.
9	I	12	1250	55	14	857	767	0	35	30	250	35	550	550	Ex.
10	J	24	1120	46	11	850	790	3	25	23	210	26	470	470	Ex.
11	K	36	1130	49	12	840	800	11	16	15	160	16	490	490	Com. Ex.
12	L	33	1110	45	10	840	795	10	19	18	180	20	390	390	Com. Ex.
13	M	27	1140	45	11	852	794	13	21	19	200	22	400	400	Com. Ex.

(continued)

No.	Steel sample ID	Plate thickness (mm)	Heat-ing temp. (°C)	Hot rolling in recrystallization temperature range		Rolling finish temperature (°C)	Cooling start		Average cooling rate from 750°C to 550°C (°C/s)	Average cooling rate from 750°C to 550°C (mid-thickness position) (°C/s)	Average cooling rate of 550°C or lower (mid-thickness position) (°C/s)	Cooling stop temperature (025mm below surface of steel plate) (°C)	Cooling stop temperature (mid-thickness position) (°C)	Re-marks
				Total rolling reduction (%)	Rolling reduction in final pass (%)		temperature (°C)	temperature-Ar ₃ (°C)						
14	N	39	1100	55	11	875	840	15	15	15	16	500	500	Com. Ex.
15	O	12	1200	53	13	855	755	3	31	31	35	550	550	Com. Ex.
16	P	21	1170	50	11	850	780	11	25	25	28	460	460	Com. Ex.
17	Q	39	1000	35	12	815	775	5	15	15	16	390	390	Com. Ex.
18	R	33	1110	45	10	845	800	11	18	18	20	380	380	Com. Ex.
19	S	30	1010	40	11	841	795	2	18	18	20	430	430	Com. Ex.
20	T	18	1100	40	13	845	775	3	28	28	31	500	500	Com. Ex.
21	U	36	1080	44	12	820	778	10	17	17	19	370	370	Com. Ex.
22	V	24	1070	36	12	830	770	2	22	22	25	450	450	Com. Ex.
23	W	21	1070	38	11	842	777	3	27	27	30	470	470	Com. Ex.

(continued)

No.	Steel sample ID	Plate thickness (mm)	Heat- ing temp. (°C)	Hot rolling in recrystallization temperature range		Rolling finish temperature (°C)	Cooling start		Average cooling rate from 750°C to 550°C (°C/s)	Average cooling rate from 750°C to 550°C (mid-thickness position) (°C/s)	Average cooling rate of 550°C or lower (mid-thickness position) (°C/s)	Cooling stop temperature (025mm below surface of steel plate) (°C)	Cooling stop temperature (mid-thickness position) (°C)	Re- marks
				Total rolling reduction (%)	Rolling reduction in final pass (%)		temperature (°C)	tempera- ture-Ar ₃ (°C)						
24	X <u>1</u>	21	1070	38	10	835	770	5	28	26	220	480	480	Com. Ex.
25	Y <u>1</u>	15	1150	43	13	840	760	1	32	29	230	500	500	Com. Ex.
26	H	30	<u>990</u>	52	11	847	793	13	21	19	190	490	490	Com. Ex.
27	F	27	<u>1260</u>	53	11	840	783	12	23	21	210	410	410	Com. Ex.
28	G	36	1080	<u>34</u>	11	829	787	10	17	16	160	370	370	Com. Ex.
29	D	33	1110	<u>56</u>	10	827	785	13	18	17	180	380	380	Com. Ex.
30	A	39	1050	45	9	825	789	10	15	15	150	350	350	Com. Ex.
31	E	21	1220	55	10	834	770	<u>-3</u>	28	26	200	490	490	Com. Ex.
32	B	18	1250	52	12	853	781	14	<u>14</u>	<u>14</u>	220	540	540	Com. Ex.
33	C	15	1150	43	10	855	773	3	<u>36</u>	31	240	510	510	Com. Ex.

(continued)

No.	Steel sample ID	Plate thickness (mm)	Heat-ing temp. (°C)	Hot rolling in recrystallization temperature range		Rolling finish temperature (°C)	Cooling start		Average cooling rate from 750°C to 550°C (°C/s)	Average cooling rate from 750°C to 550°C (mid-thickness position) (°C/s)	Average cooling rate of 550°C or lower (mid-thickness position) (°C/s)	Cooling stop temperature (0.25mm below surface of steel plate) (°C)	Cooling stop temperature (mid-thickness position) (°C)	Re-marks
				Total rolling reduction (%)	Rolling reduction in final pass (%)		temperature (°C)	temperature-Ar ₃ (°C)						
34	F	27	1140	45	11	842	785	14	22	20	200	340	340	Com. Ex.
35	I	12	1250	53	13	870	773	6	34	30	250	240	240	Com. Ex.
36	J	24	1220	48	11	850	790	3	26	24	210	560	560	Com. Ex.
37	Z	39	1000	35	10	854	825	15	16	15	150	520	520	Com. Ex.
38	AA	21	1150	54	10	840	766	1	25	24	210	360	360	Com. Ex.
39	AB	30	1050	40	11	840	790	9	20	18	200	400	400	Ex.
40	AC	39	1000	37	10	800	770	18	15	15	150	380	380	Ex.
41	AD	12	1250	55	13	893	803	3	35	30	250	520	520	Ex.
42	AE	20	1100	45	12	844	784	8	29	27	220	450	450	Ex.

Note 1: Underlined if outside the scope of the disclosure.

[Table 3]

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Table 3

No.	Steel sample ID	Microstructure (0.25mm below surface of steel plate)				Microstructure (mid-thickness position)				Maximum grain size (μm)	Average grain size (μm)	Brittleness transition temp. (°C)	Yield stress (MPa)	Tensile strength (MPa)	SSCC resistance of steel pipe or tube		HIC resistance of steel pipe or tube		Remarks
		Microstructure	Area ratio of GB (%)	Area ratio of 1MA (%)	Area ratio of other than GB, TMA (%)	Microstructure	Area ratio of GB (%)	Area ratio of TMA (%)	Area ratio of other than GB, TMA (%)						1bar H ₂ S	0.1bar H ₂ S +0.9bar CO ₂	16bar H ₂ S +5bar CO ₂	lbar H ₂ S	
1	A	GB+TMA	96	4	0	GB+TMA	97	3	0	79	11	-104	490	584	O	O	O	O	Ex.
2	B	GB+TMA	98	2	0	GB+TMA	99	1	0	58	16	-111	493	593	O	O	O	O	Ex.
3	C	GB+TMA	98	2	0	GB+TMA	99	1	0	59	18	-112	474	557	O	O	O	O	Ex.
4	D	GB+TMA	97	3	0	GB+TMA	97	3	0	52	13	-118	465	559	O	O	O	O	Ex.
5	E	GB+TMA	97	3	0	GB+TMA	97	3	0	75	20	-101	498	590	O	O	O	O	Ex.
6	F	GB+TMA	96	4	0	GB+TMA	97	3	0	67	15	-108	510	590	O	O	O	O	Ex.
7	G	GB+TMA	95	5	0	GB+TMA	96	4	0	52	12	-119	467	560	O	O	O	O	Ex.
8	H	GB+TMA	99	1	0	GB+TMA	99	1	0	61	16	-112	483	571	O	O	O	O	Ex.
9	I	GB+TMA	90	10	0	GB+TMA	93	7	0	66	19	-103	489	571	O	O	O	O	Ex.
10	J	GB+TMA	93	7	0	GB+TMA	95	5	0	76	19	-101	496	586	O	O	O	O	Ex.
11	K	GB+TMA	96	4	0	GB+TMA	96	4	0	72	19	-102	439	524	O	O	O	O	Com. Ex.
12	L	GB+TMA	96	4	0	GB+TMA	97	3	0	72	17	-97	450	547	×	O	×	×	Com. Ex.
13	M	GB+TMA	96	4	0	GB+TMA	97	3	0	74	18	-96	477	573	O	O	O	O	Com. Ex.
14	N	GB+TMA	98	2	0	GB+TMA	98	2	0	74	20	-102	425	521	O	O	O	O	Com. Ex.
15	O	GB+TMA	97	3	0	GB+TMA	97	3	0	65	19	-109	497	590	×	O	×	×	Com. Ex.
16	P	GB+TMA	98	2	0	GB+TMA	98	2	0	58	17	-95	496	592	×	O	×	×	Com. Ex.
17	Q	GB+TMA	97	3	0	GB+TMA	98	2	0	73	11	-107	508	591	O	O	O	×	Com. Ex.
18	R	GB+TMA	99	1	0	GB+TMA	99	1	0	73	18	-98	452	558	O	O	O	O	Com. Ex.
19	S	GB+TMA	99	1	0	GB+TMA	99	1	0	68	15	-110	489	581	×	O	×	×	Com. Ex.

(continued)

No.	Steel sample ID	Microstructure (0.25mm below surface of steel plate)				Microstructure (mid-thickness position)				Maximum grain size (μm)	Average grain size (μm)	Brittle-ductility transition temp.	Yield stress (MPa)	Tensile strength (MPa)	SSCC resistance of steel pipe or tube				HIC resistance of steel pipe or tube		Remarks
		Microstructure	Area ratio of GB (%)	Area ratio of 1MA (%)	Area ratio of other than GB, TMA (%)	Microstructure	Area ratio of GB (%)	Area ratio of TMA (%)	Area ratio of other than GB, TMA (%)						1bar H ₂ S	0.1bar H ₂ S +0.9bar CO ₂	16bar H ₂ S +5bar CO ₂	lbar H ₂ S	0.1bar H ₂ S +0.9bar CO ₂		
20	<u>T</u>	GB+TMA	94	6	0	GB+TMA	96	4	0	45	16	-120	483	580	O	O	O	×	×	Com. Ex.	
21	<u>U</u>	GB+TMA	95	5	0	GB+TMA	96	4	0	62	15	-97	505	590	×	O	×	×	×	Com. Ex.	
22	<u>V</u>	GB+TMA	96	4	0	GB+TMA	96	4	0	61	12	-111	507	595	O	O	O	×	×	Com Ex.	
23	<u>W</u>	GB+TMA	98	2	0	GB+TMA	98	2	0	63	14	-114	486	575	O	×	O	O	O	Com Ex.	
24	<u>X</u>	GB+TMA	97	3	0	GB+TMA	98	2	0	69	14	-112	477	571	O	×	O	O	O	Com Ex.	
25	<u>Y</u>	GB+TMA	95	5	0	GB+TMA	96	4	0	68	16	-113	509	590	O	×	O	O	O	Com Ex.	
26	H	GB+TMA	98	2	0	GB+TMA	99	1	0	59	18	-110	440	519	O	O	O	O	O	Com Ex.	
27	F	GB+TMA	96	4	0	GB+TMA	96	4	0	82	17	-93	476	564	O	O	O	O	O	Com Ex.	
28	G	GB+TMA	96	4	0	GB+TMA	97	3	0	83	11	-94	472	566	O	O	O	O	O	Com Ex.	
29	D	GB+TMA	99	1	0	GB+TMA	99	1	0	57	22	-95	475	557	O	O	O	O	O	Com Ex.	
30	A	GB+TMA	97	3	0	GB+TMA	97	3	0	81	16	-97	480	570	O	O	O	O	O	Com Ex.	
31	E	GB+TMA+F	94	3	3	GB+TMA	98	2	0	71	17	-103	441	529	O	O	×	O	O	Com Ex.	
32	B	GB+TMA+F	93	4	3	GB+TMA+F	94	3	3	68	18	-107	433	518	O	O	×	×	O	Com Ex.	
33	C	GB+TMA+LB	93	3	4	GB+TMA	98	2	0	72	18	-112	478	570	O	O	×	O	O	Com Ex.	
34	F	GB+MA	94	0	6	GB+MA	93	0	7	73	17	-98	511	593	O	O	O	O	O	Com Ex.	
35	I	GB+MA	95	0	5	GB+MA	94	0	6	72	19	-96	493	593	O	O	×	O	O	Com Ex.	
36	J	GB+TMA+F	93	5	2	GB+TMA+F	92	4	4	78	16	-103	434	517	O	O	×	×	O	Com Ex.	
37	<u>Z</u>	GB+TMA	96	4	0	GB+TMA	96	4	0	79	14	-115	447	529	O	O	O	O	O	Com Ex.	
38	<u>AA</u>	GB+TMA	96	4	0	GB+TMA	96	4	0	57	18	-106	479	561	O	O	O	×	×	Com Ex.	
39	AB	GB+TMA	97	3	0	GB+TMA	98	2	0	68	15	-108	485	574	O	O	O	O	O	Ex.	

(continued)

No.	Steel sample ID	Microstructure (0.25mm below surface of steel plate)				Microstructure (mid-thickness position)				Maximum grain size (μm)	Average grain size (μm)	Brittle-ductility transition temp. (°C)	Yield stress (MPa)	Tensile strength (MPa)	SSCC resistance of steel pipe or tube		HIC resistance of steel pipe or tube		Remarks
		Microstructure	Area ratio of GB (%)	Area ratio of 1MA (%)	Area ratio of other than GB, TMA (%)	Microstructure	Area ratio of GB (%)	Area ratio of TMA (%)	Area ratio of other than GB, TMA (%)						1bar H ₂ S	0.1bar H ₂ S +0.9bar CO ₂	16bar H ₂ S +5bar CO ₂	0.1bar H ₂ S	
40	AC	GB+TMA	98	2	0	GB+TMA	98	2	0	78	11	-105	505	599	O	O	O	O	Ex.
41	AD	GB+TMA	97	3	0	GB+TMA	97	3	0	64	20	-110	488	569	O	O	O	O	Ex.
42	AE	GB+TMA	96	4	0	GB+TMA	97	3	0	70	17	-104	491	580	O	O	O	O	Ex.

Note 1: Underlined if outside the scope of the disclosure.

Note 2: For microstructure, GB represents granular bainite, TMA represents tempered martensite austenite constituent, MA represents martensite austenite constituent, F represents ferrite, and LB represents lath bainite.

[0072] As seen from Tables 2 and 3, Nos. 1-10 and 39-42 are our examples in which the chemical composition and producing conditions satisfy the appropriate range of this disclosure. All our examples, which had, as steel plate, a brittle-ductility transition temperature of -100 °C or lower, a tensile strength of 535 MPa or more, a steel microstructure at 0.25 mm below a surface of the steel plate consisting of granular bainite and tempered martensite austenite constituent, a maximum grain size of 80 μm or less and an average grain size of 20 μm or less at the mid-thickness position of the steel plate, had good SSCC resistance and HIC resistance.

[0073] In contrast, Nos. 11-25 and 37-38 have steel plate chemical composition outside the scope of this disclosure. No. 11, 14, and 37 did not have sufficient solid solution strengthening and lacked strength. No. 12, 15-16, 19, and 21 had poor SSCC resistance and HIC resistance due to increased hardness. Nos. 12 and 21 had a large increase in strength at low temperatures, and their low-temperature toughness deteriorated. No. 16 had lower cleanliness and degraded low-temperature toughness. No. 17, 20, 22, and 38 had poor HIC resistance due to the formation of inclusions or carbides. No. 13 and 18 had degraded low-temperature toughness due to increased non-thermal stress of steel. No. 23-25 had degraded SSCC resistance at 0.1 bar - H₂S + 0.9 bar - CO₂ due to accelerated local corrosion.

[0074] No. 26-36 are comparative examples in which the chemical composition is within the scope of this disclosure, but the producing conditions are outside the scope of this disclosure. No. 26 had low strength because the dissolution of carbides was insufficient due to low slab heating temperature. No. 27 had degraded low-temperature toughness because crystal grains were coarsened due to high slab heating temperature. No. 28 had degraded low-temperature toughness because total rolling reduction in the recrystallization temperature range was insufficient, resulting in residual coarse grains. No. 29 had degraded low-temperature toughness because total rolling reduction in the recrystallization temperature range was excessive, and the average grain size became large. No. 30 had degraded low-temperature toughness because the rolling reduction of the final pass in the recrystallization temperature range was insufficient, resulting in residual coarse grains. No. 31 had low strength and deteriorated SSCC resistance at high pressure because the cooling start temperature was low, and ferrite was partially formed in the surface layer. No. 32 had low strength and poor HIC resistance and SSCC resistance at high pressure because the average cooling rate was low, and ferrite was partially formed up to the mid-thickness position of the steel plate. No. 33 had poor SSCC resistance at high pressure because the average cooling rate was high and lath bainite was partially formed in the surface layer. No. 34 had degraded low-temperature toughness because the cooling stop temperature was low, and the martensite austenite constituent was not sufficiently tempered. No. 35 had degraded SSCC resistance at high pressure in addition to low-temperature toughness because the cooling stop temperature was even low. No. 36 had low strength and degraded HIC resistance and SSCC resistance at high pressure because the cooling stop temperature was high, and ferrite was partially formed up to the mid-thickness position of the steel plate.

INDUSTRIAL APPLICABILITY

[0075] This disclosure can provide a high strength steel plate for a sour-resistant line pipe and high strength steel pipe or tube with excellent low-temperature toughness as well as HIC and SSCC resistance.

Claims

1. A high strength steel plate for a sour-resistant line pipe comprising a chemical composition containing, by mass%, C: 0.030 % or more and 0.060 % or less, Si: 0.01 % or more and 0.50 % or less, Mn: 0.80 % or more and 1.80 % or less, P: 0.015 % or less, S: 0.0015 % or less, Al: 0.010 % or more and 0.080 % or less, Cr: 0.05 % or more and 0.50 % or less, Nb: 0.005 % or more and 0.080 % or less, N: 0.0010 % or more and 0.0080 % or less, and Ca: 0.0005 % or more and 0.0050 % or less, with the balance being Fe and inevitable impurities, wherein

a microstructure at 0.25 mm below a surface of the steel plate consists of granular bainite and tempered martensite austenite constituent,
a maximum grain size is 80 μm or less and an average grain size is 20 μm or less at a mid-thickness position of the steel plate,
a brittle-ductility transition temperature in a Charpy impact test is -100 °C or lower, and
a tensile strength is 535 MPa or more.

2. The high strength steel plate for a sour-resistant line pipe according to claim 1, wherein the chemical composition further contains, by mass%, at least one selected from the group consisting of Cu: 0.30 % or less, Ni: 0.10 % or less, and Mo: 0.50 % or less.

3. The high strength steel plate for a sour-resistant line pipe according to claim 1 or 2, wherein the chemical composition

further contains, by mass%, at least one selected from the group consisting of V: 0.005 % or more and 0.1 % or less, Ti: 0.005 % or more and 0.1 % or less, Zr: 0.0005 % or more and 0.02 % or less, Mg: 0.0005 % or more and 0.02 % or less, and REM: 0.0005 % or more and 0.02 % or less.

- 5 **4.** A method for producing a high strength steel plate for a sour-resistant line pipe, the method comprising:

heating a slab having a chemical composition containing, by mass%, C: 0.030 % or more and 0.060 % or less, Si: 0.01 % or more and 0.50 % or less, Mn: 0.80 % or more and 1.80 % or less, P: 0.015 % or less, S: 0.0015 % or less, Al: 0.010 % or more and 0.080 % or less, Cr: 0.05 % or more and 0.50 % or less, Nb: 0.005 % or more and 0.080 % or less, N: 0.0010 % or more and 0.0080 % or less, and Ca: 0.0005 % or more and 0.0050 % or less, with the balance being Fe and inevitable impurities to a temperature of 1000 °C or higher and 1250 °C or lower; then subjecting the slab to hot rolling, which satisfies a total rolling reduction in a recrystallization temperature range being 35 % or more and 55 % or less and a rolling reduction in a final rolling pass in the recrystallization temperature range being 10 % or more to obtain a steel plate; and

then subjecting the steel plate to controlled cooling under a set of conditions including:

a temperature of a surface of the steel plate at the start of cooling being equal to or higher than A_{r3} point; an average cooling rate in a temperature range from 750 °C to 550 °C in terms of a temperature at 0.25 mm below the surface of the steel plate being 15 °C/s or higher and 35 °C/s or lower; an average cooling rate in a temperature range from 750 °C to 550 °C in terms of a temperature at a mid-thickness position of the steel plate being 15 °C/s or higher; and a cooling stop temperature in terms of temperatures at 0.25 mm below the surface of the steel plate and at the mid-thickness position of the steel plate being 350 °C or higher and 550 °C or lower.

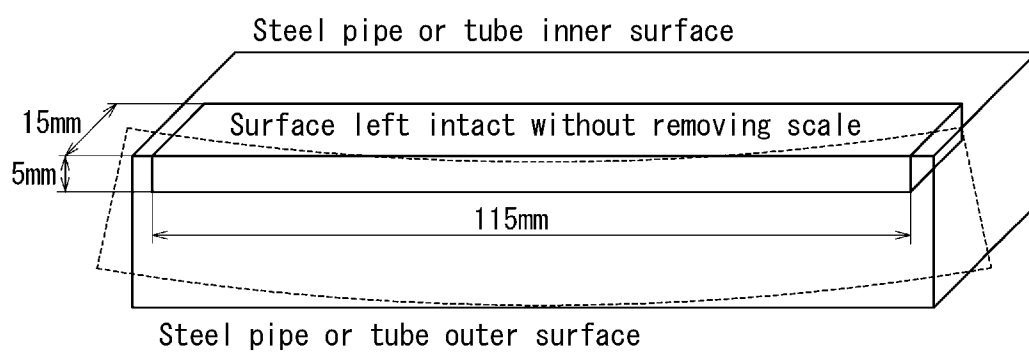
- 25 **5.** The method for producing a high strength steel plate for a sour-resistant line pipe according to claim 4, wherein the chemical composition further contains, by mass%, at least one selected from the group consisting of Cu: 0.30 % or less, Ni: 0.10 % or less, and Mo: 0.50 % or less.

- 30 **6.** The method for producing a high strength steel plate for a sour-resistant line pipe according to claim 4 or 5, wherein the chemical composition further contains, by mass%, at least one selected from the group consisting of V: 0.005 % or more and 0.1 % or less, Ti: 0.005 % or more and 0.1 % or less, Zr: 0.0005 % or more and 0.02 % or less, Mg: 0.0005 % or more and 0.02 % or less, and REM: 0.0005 % or more and 0.02 % or less.

- 35 **7.** A high strength steel pipe or tube using the high strength steel plate for a sour-resistant line pipe according to claim 1 or 2.

- 8.** A high strength steel pipe or tube using the high strength steel plate for a sour-resistant line pipe according to claim 3.

FIG. 1



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2023/017639

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; **B21B 3/00**(2006.01)i; **B21C 37/08**(2006.01)i; **C21D 8/02**(2006.01)i; **C22C 38/38**(2006.01)i;
C22C 38/58(2006.01)i

FI: C22C38/00 301F; C22C38/00 301Z; C22C38/38; C22C38/58; C21D8/02 C; B21B3/00 A; B21C37/08 A

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; B21B3/00; B21C37/08; 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.
A	WO 2020/003499 A1 (NIPPON STEEL CORP.) 02 January 2020 (2020-01-02)	1-8
A	WO 2021/020220 A1 (JFE STEEL CORP.) 04 February 2021 (2021-02-04)	1-8
A	WO 2020/067209 A1 (JFE STEEL CORP.) 02 April 2020 (2020-04-02)	1-8

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

* Special categories of cited documents:

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

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

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

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

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

“&” document member of the same patent family

Date of the actual completion of the international search

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Name and mailing address of the ISA/JP

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Authorized officer

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/JP2023/017639

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
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WO 2021/020220 A1	04 February 2021	EP 4006180 A1 CN 114174547 A KR 10-2022-0032115 A BR 112022001623 A2	
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REFERENCES CITED IN THE DESCRIPTION

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- JP 2020012168 A [0005] [0006]
- JP 2020509181 A [0005] [0006]

Non-patent literature cited in the description

- New Mathematical Expression Method for Charpy Absorbed Energy Transition Curves of Steel and Evaluation of Fracture Toughness. *Journal of the Japanese Society for Strength and Fracture of Materials*, 1982, vol. 17, 1-13 [0062]