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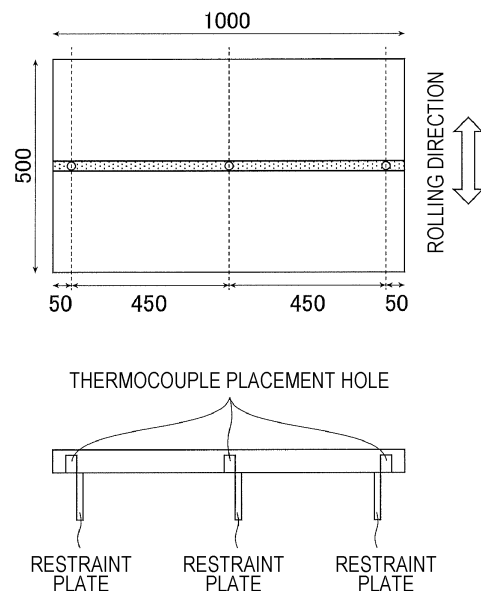
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(54) **STEEL MATERIAL AND METHOD FOR PRODUCING SAME, AND TANK AND METHOD FOR PRODUCING SAME**

(57) Provided are a steel material, a method for producing the steel material, a tank, and a method for producing the tank. A steel material of the present invention has a chemical composition containing, in mass%, C: 0.200% or more and 0.700% or less, Si: 0.05% or more and 1.00% or less, Mn: 20.0% or more and 40.0% or less, P: 0.030% or less, S: 0.0050% or less, Al: 5.00% or less, Cr: 7.0% or less, N: 0.0500% or less, O: 0.0050% or less, Ti: less than 0.005%, Nb: less than 0.005%, and one or two or more selected from Ca: 0.0100% or less, Mg: 0.0100% or less, and REM: 0.0200% or less, the balance being iron and incidental impurities, in which a microstructure has a maximum grain size of less than 200 μm at a position 1 mm below a surface of the steel material.

FIG. 1



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Description

Technical Field

5 **[0001]** The present invention relates to a steel material suitable for use in structural steels used in extremely low temperature environments such as liquid helium and liquefied gases, including, for example, tanks for storing liquid hydrogen, and to a method for producing the steel material. The present invention also relates to a tank using this steel material and a method for producing the tank.

10 Background Art

[0002] To use a hot-rolled steel plate as a material of a storage tank structure for liquid hydrogen, liquid helium, or a liquefied gas, the hot-rolled steel plate is required to have excellent toughness at a low temperature because it is used in an extremely low-temperature environment. For example, when a hot-rolled steel plate is used for a storage tank for liquid helium, it is necessary to ensure excellent toughness at a temperature equal to or lower than a boiling point of helium of -269°C. When the low-temperature toughness of the steel material is poor, there is a possibility that the safety as a structure for a cryogenic storage tank cannot be maintained. Thus, there is a high demand for improving the low-temperature toughness of the steel material used.

[0003] In response to this demand, austenitic stainless steels in the form of steel plates with austenite microstructures that do not exhibit brittleness at low temperatures, 9%-Ni steels, and 5000 series aluminum alloys have been used. However, the alloying costs and production costs are high; thus, a steel material that is inexpensive and excellent in low-temperature toughness is required.

[0004] For example, Patent Literature 1 discloses the use of a high-Mn steel containing a large amount of Mn, which is a relatively inexpensive austenite-stabilizing element, as a structural steel for a low-temperature environment, as a new steel material in place of a conventional low-temperature service steel.

[0005] Patent Literature 1 discloses a technique for ensuring low-temperature toughness in a welded heat affected zone by controlling grain size, coverage by carbides, and the like.

Citation List

Patent Literature

[0006] PTL 1: Japanese Unexamined Patent Application Publication No. 2016-196703

Summary of Invention

Technical Problem

[0007] For example, a liquefied gas storage structure (such as a liquefied gas storage tank) is produced by line heating of a steel material. Line heating is a processing method that uses plastic deformation due to local thermal stress to form a curved surface. In the Japanese Shipbuilding Quality Standard (JSQS, 2018), the line heating condition for high tensile strength steel having an equivalent carbon content (Ceq) of more than 0.38% in shipbuilding is 650°C or lower in terms of the maximum heating temperature of a surface during water cooling immediately after heating. If it is higher than that, it is specified that the maximum surface heating temperature is 900°C or lower, and water cooling is performed after natural cooling to 500°C. When carbides are formed after line heating, the low-temperature toughness is reduced. However, Patent Literature 1 does not verify the low-temperature toughness after the line heating.

[0008] The present invention has been made in view of the above disadvantages, and aims to provide a steel material having excellent low-temperature toughness after line heating, a method for producing the steel material, a tank composed of the steel material, and a method for producing the tank.

[0009] The phrase "excellent low-temperature toughness after line heating" described above indicates that, in a tank obtained by subjecting a steel material to line heat treatment described below, the absorbed energy in a Charpy impact test at -269°C or higher at a position 1 mm below the surface of the steel material (a position 1 mm from the surface of the steel material in the thickness direction) in a line-heated portion is 41 J or more. The "line-heated portion" refers to a region thermally affected after the steel material is subjected to line heating. The absorbed energy in the line-heated portion in the Charpy impact test can be measured by a method described in Examples below. Solution to Problem

[0010] To achieve the above object, the inventors have conducted intensive studies on an austenitic steel material (for example, a high-Mn steel material) with respect to the chemical composition, microstructure, and production method of the steel material (steel plate), various factors that determine the properties of the steel material, and a structure

produced by the line heating of the steel material, and have found the following findings a to c. In the present invention, the term "high-Mn steel material" refers to a steel material having a Mn content of 20% to 40% by mass.

[0011]

a. To inhibit a decrease in absorbed energy in a Charpy impact test at -269°C or higher in a line-heated portion of a structure produced by the line heating of a high-Mn steel material, it is important to set the maximum grain size at the time of production of the steel material to less than 200 μm. Preferably, the maximum grain size is less than 180 μm.

b. Austenite steel having a high Mn content contains a large amount of C and thus has a larger amount of carbides than stainless steel. Moreover, carbides are formed at the grain boundaries, and thus the grain boundary strength decreases. When the C concentration at the grain boundaries is less than 0.100% after the line heating of the high-Mn steel material, the grain boundaries serve as starting points of fracture, leading to a deterioration in low-temperature toughness. Accordingly, in order to inhibit the deterioration in low-temperature toughness after the line heating of the high-Mn steel, it is effective to increase the C concentration at the grain boundaries of the high-Mn steel. For this purpose, it is effective to make the maximum grain size less than 200 μm in the high-Mn steel material as a raw material.

c. The above a and b can be achieved, in hot rolling in the production of a steel material, by performing hot rolling at 950°C or higher and a total rolling reduction of 40% or more, performing one or more hot-rolling passes at lower than 950°C, and performing finish rolling at a finishing temperature of 750°C or higher.

[0012] The present invention has been made by further studying the above-described findings, and the gist thereof is described below.

[1] A steel material has a chemical composition containing, in mass%:

C: 0.200% or more and 0.700% or less,

Si: 0.05% or more and 1.00% or less,

Mn: 20.0% or more and 40.0% or less,

P: 0.030% or less,

S: 0.0050% or less,

Al: 5.00% or less,

Cr: 7.0% or less,

N: 0.0500% or less,

O: 0.0050% or less,

Ti: less than 0.005%,

Nb: less than 0.005%, and

one or two or more selected from Ca: 0.0100% or less, Mg: 0.0100% or less, and REM: 0.0200% or less, the balance being iron and incidental impurities, and

a microstructure having a maximum grain size of less than 200 μm at a position 1 mm below a surface of the steel material.

[2] In the steel material described in [1], the chemical composition further contains, in mass%:

one or two or more selected from

Cu: 1.0% or less,

Ni: 1.0% or less,

Mo: 2.0% or less,

V: 2.0% or less, and

W: 2.0% or less.

[3] In the steel material described in [1] or [2], the microstructure has a number density of grains having a grain size of 50 μm or more of 1.0 grain/mm² or more at the position 1 mm below the surface of the steel material.

[4] In the steel material described in any one of [1] to [3], in the microstructure, an inclusion particle size in a top 10% of an inclusion particle size distribution at the position 1 mm below the surface of the steel material is 3.5 μm or less.

[5] A method for producing the steel material described in any one of [1] to [4] includes:

heating a raw steel material having the chemical composition to a temperature range of 1,100°C or higher and

1,300°C or lower;

performing hot rolling at a total rolling reduction of 40% or more at 950°C or higher, a number of hot rolling passes of one or more at lower than 950°C, and a finishing temperature of 750°C or higher; and then performing cooling.

[6] A tank obtained by welding the steel material described in any one of [1] to [4], in which a C concentration at a grain boundary at a position 1 mm below a surface of a base metal zone subjected to line heating is 0.100% or more, and an absorbed energy in a Charpy impact test at -269°C or higher at a position 1 mm below a surface of a line-heated portion subjected to the line heating is 41 J or more.

[7] A method for producing the tank described in [6] includes:

performing line heat treatment of the steel materials described in any one of [1] to [4] to curve the steel materials, the line heat treatment including heating surfaces of the steel materials to 900°C or lower, subjecting the steel materials to natural cooling to a surface temperature of 500°C or lower, and then performing water cooling; and subsequently welding the curved steel materials together.

[8] In the method for producing the tank described in [7], the welding is performed using a solid wire as an electrode with a shielding gas of 80% Ar + 20% CO₂ at an interpass temperature of 100°C to 150°C.

Advantageous Effects of Invention

[0013] According to the present invention, the steel material having excellent low-temperature toughness after line heating and a method for producing the steel material can be provided. The steel material of the present invention is suitably used as a material for a steel structure (for example, a tank for a liquefied gas storage tank) used in a low-temperature environment, and thus it is possible to provide the tank having excellent low-temperature toughness even after line heating and a method for producing the tank. Accordingly, it is possible to greatly contribute to the improvement of the safety and the life of the steel structure, and industrially significant effects are exhibited. The production method of the present invention does not cause a decrease in productivity or an increase in production cost; thus, it is possible to provide a production method that is also excellent in economy.

Brief Description of Drawings

[0014] [Fig. 1] Fig. 1 is a schematic view illustrating a line-heating specimen used in Examples of the present invention.

Description of Embodiments

[0015] The present invention will be described in detail below. The present invention is not limited to the following embodiments.

[0016] The technical idea of the present invention will be described in detail.

[0017] As described above, there is an austenitic steel material (for example, a high-Mn steel material) as a steel material that is inexpensive and excellent in low-temperature toughness. To use the high-Mn steel material as a material of a steel structure (for example, a tank) used in a low-temperature environment, the high-Mn steel material is required to have excellent low-temperature toughness even at a portion thermally affected in a step of subjecting the material to line heating.

[0018] As a result of studies by the inventors, it has been found that when carbides are not present, a larger grain size of a high-Mn steel material results in higher absorbed energy. However, it has been found that, when carbides are present, a larger grain size does not necessarily result in higher absorbed energy. In the line heating step, a carbide was formed in a portion thermally affected at about 600°C to 800°C, and thus the low-temperature toughness was reduced.

[0019] The inventors have conducted intensive investigation of the cause and have newly found that the C concentration at grain boundaries is responsible for a decrease in absorbed energy. The relationship between the decrease in absorbed energy and the C concentration at the grain boundaries will be described below.

[0020] One of the origins of fracture of high-Mn steels is a grain boundary. The low-temperature toughness is improved by reducing the grain boundaries, that is, by coarsening the grains. Typically, when a carbide is formed at a grain boundary under the influence of heat, C around the carbide is depleted, and the grain boundary strength decreases. However, in a high-Mn steel, since the amount of C added is large, a self-healing phenomenon occurs in which C having a high diffusion rate is sufficiently supplied from the inside of grains away from grain boundaries during the formation and growth of carbides at the grain boundaries. This can suppress steep C depletion at grain boundaries. However, when the crystal grains are excessively coarse, the supply of C from the insides of the grains is not timely, resulting in

a depletion of C at the grain boundaries.

[0021] In the present invention, the maximum grain size is set to less than 200 μm in a hot rolling step described below, so that a C concentration of 0.100% or more can be ensured even when carbides are formed, thereby inhibiting a reduction in absorbed energy.

[0022] A steel material of the present invention will be described below.

[0023] The steel material of the present invention has a chemical composition described below, and the microstructure has a maximum grain size of less than 200 μm at a position 1 mm below a surface of the steel material. Thus, even after the steel material is subjected to line heating, the C concentration at the grain boundaries can be 0.100% or more. The symbol "%" regarding the C concentration indicates "% by mass".

[Chemical Composition]

[0024] The chemical composition of the steel material (austenitic steel material) of the present invention will be described.

[0025] In the present invention, an austenitic steel material (for example, a high-Mn steel material) and a raw steel material used for the production thereof have the above-described chemical composition. The chemical composition of the austenitic steel material of the present invention and the reasons for its limitation will be described. The symbol "%" regarding the chemical composition indicates "% by mass" unless otherwise specified.

C: 0.200% or more and 0.700% or less

[0026] C is an inexpensive austenite stabilizing element and is an important element for obtaining austenite. To prevent the above-described deficiency of C at the grain boundaries, C is contained in an amount of 0.200% or more. When C is contained in an amount of more than 0.700%, Cr carbide is excessively formed, thereby deteriorating low-temperature toughness (low-temperature toughness after line heating). For these reasons, the C content is 0.200% or more and 0.700% or less. The C content is preferably 0.250% or more, more preferably 0.300% or more. The content of C is preferably 0.600% or less, more preferably 0.550% or less.

Si: 0.05% or more and 1.00% or less

[0027] Si acts as a deoxidizing agent and is necessary for steelmaking, and is also effective in strengthening the steel plate by solid solution strengthening when dissolved in the steel. To provide such effects, Si is contained in an amount of 0.05% or more. A Si content of more than 1.00% results in an excessively high non-thermal stress, thereby deteriorating the low-temperature toughness. For these reasons, the Si content is 0.05% or more and 1.00% or less. The Si content is preferably 0.07% or more, more preferably 0.10% or more, still more preferably 0.15% or more. The Si content is preferably 0.80% or less, more preferably 0.75% or less, still more preferably 0.70% or less.

Mn: 20.0% or more and 40.0% or less

[0028] Mn is a relatively inexpensive austenite-stabilizing element. In the present invention, Mn is an important element for achieving both good strength and low-temperature toughness. To provide the effect, Mn is contained in an amount of 20.0% or more. When Mn is contained in an amount of more than 40.0%, the low-temperature toughness deteriorates. Furthermore, weldability and cuttability deteriorate. Moreover, segregation is promoted, and the occurrence of stress corrosion cracking is promoted. For these reasons, the Mn content is 20.0% or more and 40.0% or less. The Mn content is preferably 23.0% or more, more preferably 23.3% or more, still more preferably 23.5% or more. The Mn content is preferably 35.0% or less, more preferably 30.0% or less.

P: 0.030% or less

[0029] When P is contained in an amount of more than 0.030%, P is excessively segregated at the grain boundaries, thereby deteriorating the low-temperature toughness. For this reason, the upper limit is 0.030%, and it is desirable to reduce the content as much as possible. Thus, the P content is 0.030% or less.

[0030] An excessive reduction in P content causes an increase in refining cost, which is economically disadvantageous. Thus, the P content is preferably 0.002% or more. The P content is more preferably 0.005% or more, still more preferably 0.007% or more. The P content is preferably 0.028% or less, more preferably 0.024% or less, still more preferably 0.020% or less.

S: 0.0050% or less

[0031] S deteriorates the low-temperature toughness and ductility of the base material. Thus, the upper limit is 0.0050%, and it is desirable to reduce it as much as possible. Accordingly, the S content is 0.0050% or less. The S content is preferably 0.0045% or less, more preferably 0.0043% or less. An excessive reduction in S content causes an increase in refining cost, which is economically disadvantageous. Thus, the S content is preferably 0.0010% or more. The S content is more preferably 0.0012% or more.

Al: 5.00% or less

[0032] Al acts as a deoxidizing agent and is most commonly used in a molten steel deoxidizing process of a steel plate. In addition, the yield strength and the local elongation in a tensile test are improved. To provide such effects, Al is preferably contained in an amount of 0.01% or more. When Al is contained in an amount of more than 5.00%, a large amount of inclusions are present and the low-temperature toughness is deteriorated. Thus, the Al content is 5.00% or less. The Al content is preferably 0.01% or more, more preferably 0.02% or more. The Al content is preferably 4.00% or less, more preferably 3.00% or less.

Cr: 7.0% or less

[0033] Cr is an element effective in improving the low-temperature toughness because it improves the grain boundary strength. To provide the effect, Cr is preferably contained in an amount of 0.5% or more. When Cr is contained in an amount of more than 7.0%, the low-temperature toughness and the stress corrosion cracking resistance may deteriorate because of the formation of Cr carbides. Thus, the Cr content is 7.0% or less. The Cr content is preferably 0.5% or more, more preferably 1.0% or more, still more preferably 1.2% or more. The Cr content is preferably 6.7% or less, more preferably 6.5% or less. To further improve the stress corrosion cracking resistance, the Cr content is still more preferably 2.0% or more and 6.0% or less.

N: 0.0500% or less

[0034] N is an austenite-stabilizing element and is an element effective in improving low-temperature toughness. To provide such effects, N is preferably contained in an amount of 0.0050% or more. When N is contained in an amount of more than 0.0500%, nitrides or carbonitrides may be coarsened to deteriorate the low-temperature toughness. Thus, the N content is 0.0500% or less. The N content is preferably 0.0050% or more, more preferably 0.0060% or more. The N content is preferably 0.0400% or less, more preferably 0.0300% or less.

O: 0.0050% or less

[0035] O (oxygen) forms oxides to deteriorate the low-temperature toughness. Thus, the O content is in the range of 0.0050% or less. The O content is preferably 0.0045% or less, more preferably 0.0040% or less. An excessive reduction in O content increases the refining cost, which is economically disadvantageous. Thus, the O content is desirably 0.0010% or more. The O content is more preferably 0.0012% or more.

Ti: less than 0.005%, and Nb: less than 0.005%

[0036] Ti and Nb form high-melting-point carbonitrides in steel, thereby deteriorating the low-temperature toughness. Ti and Nb are components that are inevitably incorporated from raw materials and so forth. Typically, Ti is incorporated in the range of 0.005% or more to 0.010% or less, and Nb is incorporated in ranges of 0.005% or more to 0.010% or less. It is thus necessary to avoid the inevitable incorporation of Ti and Nb and to reduce each of the Ti content and the Nb content to less than 0.005% in accordance with a steelmaking method described below. A reduction in each of the Ti content and the Nb content to less than 0.005% can eliminate the above-described adverse effects of carbonitrides to ensure excellent low-temperature toughness and ductility. Each of the Ti content and the Nb content is preferably 0.003% or less, more preferably 0.002% or less. Of course, each of the Ti content and the Nb content may be 0%.

One or Two or more Selected from Ca: 0.0100% or less, Mg: 0.0100% or less, and REM: 0.0200% or less

[0037] Ca, Mg, and rare earth metals (REM) are elements useful for morphological control of inclusions. The morphological control of the inclusions indicates that flattened inclusions are formed into granular inclusions. Ductility, low-temperature toughness, and stress corrosion cracking resistance are improved by the morphological control of the

inclusions. To provide such effects, Ca and Mg are preferably contained in an amount of 0.0005% or more, and REM is preferably contained in an amount of 0.0010% or more. If any of the elements is contained in a large amount, the amount of non-metallic inclusion increases, which in turn deteriorate the ductility, the low-temperature toughness, and the stress corrosion cracking resistance. Moreover, it is economically disadvantageous.

[0038] Thus, when Ca and Mg are contained, each of the Ca content and the Mg content is 0.0100% or less, and when REM is contained, the REM content is 0.0200% or less. Preferably, the Ca content is 0.0005% or more and 0.0090% or less, the Mg content is 0.0005% or more and 0.0090% or less, and the REM content is 0.0010% or more and 0.0180% or less. More preferably, the Ca content is 0.0010% or more and 0.0080% or less, the Mg content is 0.0010% or more and 0.0080% or less, and the REM content is 0.0020% or more and 0.0150% or less. Still more preferably, the Ca content is 0.0015% or more and 0.0050% or less, the Mg content is 0.0015% or more and 0.0050% or less, and the REM content is 0.0030% or more and 0.0100% or less.

[0039] In the austenitic steel material of the present invention, the balance other than the above-described components is iron (Fe) and incidental impurities. Examples of the incidental impurities include H and B, and are acceptable if the total amount of impurity elements is 0.01% or less.

[0040] The above elements are contained as a basic chemical composition. The target properties of the present invention can be obtained by this basic chemical composition. In the present invention, for the purpose of further improving the strength and the low-temperature toughness, in addition to the above elements, the following elements can be contained as necessary.

[0041] Each component of Cu, Ni, Mo, V, and W described below can be contained as necessary, and thus these components may be 0%.

One or Two or more Selected from Cu: 1.0% or less, Ni: 1.0% or less, Mo: 2.0% or less, V: 2.0% or less, and W: 2.0% or less

Cu: 1.0% or less, and Ni: 1.0% or less

[0042] Cu and Ni are elements that increase the strength of the steel plate by solid solution strengthening, and also improve the mobility of dislocations and improve the low-temperature toughness. To provide such effects, Cu and Ni are preferably contained in an amount of 0.01% or more. When Cu and Ni are contained in an amount of more than 1.0%, the surface quality deteriorates during rolling, and in addition, the production cost is increased. For these reasons, when these alloy elements are contained, the amount of each element is preferably 1.0% or less. Each of the Cu content and the Ni content is more preferably 0.03% or more and more preferably 0.7% or less, still more preferably 0.5% or less.

Mo: 2.0% or less, V: 2.0% or less, and W: 2.0% or less

[0043] Mo, V, and W contribute to the stabilization of austenite and to an improvement in the strength of the base material. To provide such effects, each of Mo, V, and W is preferably contained in an amount of 0.001% or more. When each of Mo, V, and W is contained in an amount of more than 2.0%, coarse carbonitrides may be formed to act as starting points of fracture, and in addition, the production cost is increased. For these reasons, when these alloy elements are contained, each element is preferably contained in an amount of 2.0% or less. Each of the Mo content, the V content, and the W content is more preferably 0.003% or more, and more preferably 1.7% or less. The content is still more preferably 0.1% or more, and still more preferably 1.5% or less.

[Microstructure of Steel Material]

[0044] The reason why the microstructure is limited as described above in the present invention will be described.

Maximum Grain Size at Position 1 mm Below Surface of Steel Material: less than 200 μm

[0045] As described above, when the grain size of the steel material (base metal) is large, C is deficient at the time of carbide formation. When the maximum grain size at a position 1 mm below a surface of the steel material is less than 200 μm , the C concentration at the grain boundaries can be 0.100% or more even after the steel material has been subjected to line heating. That is, it is possible to produce a steel material having excellent low-temperature toughness in which absorbed energy in a Charpy impact test at -269°C or higher is 41 J or more in a line-heated portion of a structure (for example, a tank) obtained after line heating.

[0046] The maximum grain size is preferably 150 μm or less, more preferably 100 μm or less, still more preferably 80 μm or less. The lower limit of the maximum grain size is not particularly specified. To ensure the toughness of the hot-rolled steel sheet (steel material), the maximum grain size is preferably 50 μm or more, more preferably 60 μm or more. Here, the above-mentioned grains refer to grains exposed by etching. In the present invention, the above-mentioned

maximum grain size can be measured by a method described in Examples described below.

[0047] In the present invention, the maximum grain size of the steel material can be controlled within the above numerical range by performing hot rolling under the conditions described below. Thus, the C concentration at the grain boundaries can be sufficiently ensured even after the line heating, and the above-described absorbed energy can be achieved.

Number Density of Grains Having Grain Size of 50 μm or more at Position 1 mm Below Surface of Steel Material (Suitable Condition)

[0048] The origins of fracture of a high-Mn steel are grain boundaries. Cracks propagate through grain boundaries. Thus, the presence of coarse crystal grains can inhibit the propagation of a crack to further improve the low-temperature toughness. For this purpose, the number of austenite grains, per 1 mm^2 , having a grain size of 50 μm or more, is preferably 1.0 or more, more preferably 2.0 or more. When the number of the austenite grains is more than 10.0 per 1 mm^2 , the strength deteriorates. Thus, the number per 1 mm^2 is preferably 10.0 or less, more preferably 9.0 or less.

[0049] In the present invention, the number of austenite grains, per 1 mm^2 , having a grain size of 50 μm or more (number density) can be measured by a method described in Examples below. The number density can be controlled within the above-mentioned numerical range by performing hot rolling described below.

Inclusion Particle Size at Position 1 mm Below Surface of Steel Material (Suitable Condition)

[0050] When coarse inclusions are present at a position 1 mm below a surface of the steel material, the stress corrosion cracking resistance deteriorates. It has been found that when the inclusion particle size in the top 10% of an inclusion particle size distribution (top 10% inclusion particle size) at the position 1 mm below the surface of the steel material is more than 3.5 μm , the stress corrosion cracking resistance deteriorates. Thus, the top 10% inclusion particle size is preferably 3.5 μm or less, more preferably 3.0 μm or less. A smaller top 10% inclusion grain size is more preferable. From the viewpoint of productivity, the top 10% inclusion particle size is preferably 1.5 μm or more, more preferably 2.0 μm or more.

[0051] Here, the "top 10% inclusion particle size" is a particle size corresponding to a 10% position when the inclusion particle sizes are arranged in descending order in the inclusion particle size distribution. In the present invention, the above-mentioned inclusion particle size can be measured by a method described in Examples below.

[0052] In the present invention, the term "steel material (austenitic steel material)" refers to a steel plate having a thickness of 6 mm or more. From the viewpoint of suitable use as a material for structural steel used in extremely low-temperature environments, the plate thickness is preferably more than 9 mm, more preferably 12 mm or more. The upper limit of the plate thickness is not particularly limited, can be any thickness, and is preferably 40 mm or less.

[Method for Producing Steel Material]

[0053] A method for producing a steel material according to an embodiment of the present invention will be described below.

[0054] Regarding the steel material (austenitic steel material) of the present invention, a molten steel having the chemical composition described above can be produced by a steelmaking method using, for example, a converter or an electric arc furnace. In addition, secondary refining may be performed in a vacuum degassing furnace.

[0055] In this case, in order to limit Ti and Nb, which hinder the control of the microstructure, to the above-described numerical ranges, it is necessary to take measures to avoid the inevitable incorporation of Ti and Nb from raw materials or the like and to reduce the amounts thereof. For example, by lowering the basicity of the slag in the refining stage, these alloys are concentrated and discharged into the slag, thereby reducing the concentrations of Ti and Nb in the final slab product. Alternatively, a method may be used in which oxygen is blown for oxidation of Ti and Nb, and alloys of Ti and Nb is floated and separated at the time of reflux.

[0056] Thereafter, a raw steel material, such as a slab having a predetermined size, is preferably formed by a casting method, such as a continuous casting method or an ingot-making and blooming method.

[0057] Production conditions for forming the raw steel material into a steel material (austenitic steel material) having excellent low-temperature toughness after line heating will be described in detail below.

[0058] To obtain an austenitic steel material having the above-described composition, it is important to heat the raw steel material having the above-described chemical composition to a temperature range of 1,100°C or higher and 1,300°C or lower and then perform hot rolling in which rolling is performed at a total rolling reduction of 40% or more at 950°C or higher, then one or more hot rolling passes is performed at lower than 950°C, and finish rolling is performed at a finishing temperature of 750°C or higher. Then, after the hot rolling is finished, cooling is performed. The temperature control here is based on the surface temperature of the raw steel material.

[0059] In the following description of the production method, the symbol "°C" regarding the temperature indicates the surface temperature of the raw steel material or the steel plate, unless otherwise specified. The surface temperature can be measured with, for example, a radiation thermometer. The temperature at the center of the thickness of the slab or steel plate can be determined, for example, by attaching a thermocouple to the center of the thickness of the steel plate and measuring the temperature, or by calculating the temperature distribution in the cross-section of the steel plate using heat transfer analysis and correcting the result using the surface temperature of the steel plate.

Heating Temperature of Raw Steel Material: 1,100°C or more and 1,300°C or lower

[0060] To diffuse Mn at hot rolling, the heating temperature of the raw steel material before hot rolling is set to 1,100°C or higher. By diffusing Mn, the stability of austenite can be secured even in the Mn negative segregation zone. This can ensure austenite stability even in a line-heated portion and prevent brittle fracture. That is, the absorbed energy at -269°C can be ensured. If the heating temperature is higher than 1,300°C, the steel may begin to melt; thus, the upper limit of the heating temperature is 1,300°C. The heating temperature of the raw steel material is preferably 1,130°C or higher and preferably 1,270°C or lower. The heating temperature is more preferably 1,150°C or higher and more preferably 1,250°C or lower.

Hot Rolling

Total Rolling Reduction at 950°C or Higher: 40% or more

[0061] As described above, in the present invention, it is important that the maximum grain size at the position 1 mm below the surface of the steel material be less than 200 μm. If the equiaxed grains cannot be obtained by the rolling in the recrystallization region, the grains remain as coarse grains even in the subsequent rolling in the non-recrystallization region, resulting in a maximum grain size of 200 μm or more. In addition, the number density of grains having a grain size of 50 μm or more is more than 10.0 grains/mm². Thus, it is effective to ensure a total rolling reduction of 40% or more in a temperature range of 950°C or higher, which is a recrystallization region. The total rolling reduction in the recrystallization region is preferably 50% or more, more preferably 52% or more. The upper limit of the total rolling reduction in the recrystallization region is not particularly specified. For the reason of ensuring the strength, the total rolling reduction in the recrystallization region is preferably 85% or less, more preferably 70% or less.

Number of Hot Rolling Passes at Lower than 950°C: One or more, and Finishing Temperature: 750°C or Higher

[0062] To refine equiaxed grains formed by hot rolling at 950°C or higher, it is important that the number of hot rolling passes at lower than 950°C be one or more. Preferably, the number of hot rolling passes is two or more. When there is no hot rolling pass at lower than 950°C, the maximum grain size is 200 μm or more. In addition, the number density of grains having a grain size of 50 μm or more is more than 10.0 grains/mm². The upper limit of the number of hot rolling passes is not particularly specified. From the viewpoint of productivity, the number of hot rolling passes is preferably 10 or less, more preferably 8 or less. When hot rolling is performed at lower than 750°C, the grain size is excessively small, thereby deteriorating the low-temperature toughness. Thus, the finishing temperature is 750°C or higher. When the finishing temperature is 775°C or lower, the grain size is small, and as a result, the maximum grain size is sometimes less than 50 μm. Thus, the finishing temperature is preferably higher than 775°C, more preferably 780°C or higher. The upper limit of the finishing temperature is not particularly specified. From the viewpoint of ensuring the strength, the finishing temperature is preferably 930°C or lower, more preferably 900°C or lower.

Cooling

[0063] After the hot rolling is completed, cooling is performed. The cooling conditions are not particularly specified. In the present invention, it is preferable to cool from a temperature of (temperature at the end of hot rolling - 100°C) or higher to 600°C or lower at an average cooling rate of 1.0 °C/s or more. Thereby, the formation of carbides and the grain boundary segregation of P are suppressed, further improving the properties of the steel material. The above "temperature at the end of hot rolling" refers to the finishing temperature.

[0064] The upper limit of the average cooling rate is not particularly specified. From the viewpoint of controlling the finish cooling temperature, the cooling rate is preferably 30.0 °C/s or less.

[0065] A steel structure (for example, a tank) produced by using the steel material of the present invention as a raw material and subjecting the raw material to line heating will be described below.

[0066] The tank of the present invention is produced by subjecting the above-described steel material to line heating under specific line heating conditions to form a curved surface, and welding the curved steel materials. The tank of the

present invention produced as described above has the same chemical composition and microstructure in the base metal zone as the steel material (austenitic steel material) described above.

[0067] For the tank of the present invention, the C concentration at the grain boundaries at a position 1 mm below a surface of the base metal zone after the line heating is 0.100% or more. When the C concentration at the grain boundaries at the above-described position of the base metal zone after the line heating is less than 0.100%, the grain boundary strength cannot be ensured. Thus, the C concentration at the grain boundaries at the above-described position of the base metal zone after the line heating is 0.100% or more, preferably 0.200% or more, more preferably 0.250% or more. The upper limit of the C concentration at the grain boundaries at the above-described position of the base metal zone after the line heating is not particularly specified. From the viewpoint of a deterioration in low-temperature toughness due to excessive formation of Cr carbide, the C concentration is preferably 0.600% or less, more preferably 0.550% or less.

[0068] For the tank of the present invention produced as described above, the absorbed energy in a Charpy impact test at -269°C or higher at a position 1 mm below a surface of the line-heated portion after the line heating can be 41 J or more. The absorbed energy in the Charpy impact test can be measured by a method described in Examples below. That is, the absorbed energy in the Charpy impact test at -269°C or higher in the line-heated portion is 41 J or more in the case of a full-size specimen, and is 27 J or more in the case of a 5-mm sub-size specimen.

[0069] According to the present invention, stress corrosion cracking resistance can also be provided.

[0070] A preferred example of a method for producing the tank will be described below.

[0071] The tank of the present invention is produced by subjecting the above steel material to line heating under the following conditions to form a curved surface, and welding the curved steel materials. The method for producing the steel material (austenitic steel material) as a raw material has already been described, and thus description thereof is omitted. Here, preferable line heating conditions and welding conditions will be described.

[Line Heating Conditions]

[0072] The steel material is subjected to line heating at a target heating temperature (heating target temperature) of a surface of the steel material of 900°C or lower. After heating, the steel material is subjected to natural cooling to a surface temperature of 500°C or lower and then water cooling. The line heat treatment including heating and natural cooling may be performed once, or may be repeated one or more times. The number of repetitions is preferably one or more in order to modify the microstructure. The number of repetitions is preferably five or less because the local thermal cycle history is complicated. The heating temperature is preferably higher than 800°C.

[Welding Conditions]

[0073] From the viewpoints of ensuring high strength, high ductility, and excellent cryogenic impact toughness, welding is performed with a solid wire (1.2 mm in diameter) as an electrode under the following conditions: no preheating, flat position, interpass temperature: 100°C to 150°C, and shielding gas: 80% Ar + 20% CO₂. The symbol "%" regarding the shielding gas indicates "% by volume".

EXAMPLES

[0074] The present invention will be described in more detail below based on Examples. The following examples indicate preferred examples of the present invention, and the present invention is not limited to these examples.

[0075] Steel slabs having chemical compositions given in Table 1 were produced by a converter-ladle refining-continuous casting method. In Table 1, the symbol "-" indicates that the element is not intentionally added, and includes both cases where the element is not contained (0%) and where the element is inevitably contained. Each of the resulting steel slabs was hot-rolled under the conditions given in Table 2-1 and cooled to produce a steel material (hot-rolled steel plate) having a plate thickness of 6 to 40 mm.

[0076] The resulting hot-rolled steel plate (steel plate) was used to evaluate the grain size and the inclusion particle size in the following procedures.

[0077] The resulting steel plate was subjected to line heating. The steel plate after the line heating was used to evaluate the C concentration, the low-temperature toughness, and the stress corrosion cracking resistance in the following procedures.

[0078] Here, the line heating will be described. As the line heating, plate line heating illustrated in Fig. 1 was performed. As illustrated in Fig. 1, a line-heating specimen having a length of 1,000 mm and a width of 500 mm was prepared from the resulting steel plate. The specimen was fixed by restraint plates at a 1/2 position in the width direction (rolling direction). The plate line heating was performed under the following conditions. As the conditions, the target heating temperature of the surface of the steel material was 900°C, and the steel material was heated to this temperature, naturally cooled to a surface temperature of the steel material of 500°C or lower, and then water-cooled. The line heating

of the same region was repeated under the conditions illustrated in Table 2-2.

[0079] The steel plates after the line heat treatment were welded together using a solid wire (1.2 mm in diameter) as an electrode, without being preheated, in a flat position, and under the conditions given in Table 2-2.

(1) Microstructure Evaluation

[Grain Size]

[0080] With respect to the resulting hot-rolled steel plate, a cross section in the rolling direction was polished and etched. A position 1 mm below a surface of the steel plate was photographed at a magnification of 200 times with an optical microscope. From the photographed image, 100 grains exposed by etching were randomly selected. The equivalent circular diameters of the grains were taken as the grain size. The maximum grain size (μm) at the position 1 mm below the surface of the steel plate was determined. The total area of 100 grains and the number of grains having a size of 50 μm or more were determined. The number density of grains having a grain size of 50 μm or more per 1 mm² (mm²/grain) was determined. Aqua regia was used as an etchant.

[Inclusion Particle Size]

[0081] The resulting hot-rolled steel plate was examined for the inclusion particle size using a scanning electron microscope (SEM). The evaluation region of 200 mm² was used. The top 10% inclusion particle size (μm) at a position 1 mm below the surface of the steel plate was determined.

[C Concentration]

[0082] A TEM sample of 12 mm × 10 mm was prepared from the resulting hot-rolled steel plate after the steel plate was subjected to line heating. The sample was subjected to composition analysis across carbide-free grain boundaries using an EDS detector attached to a transmission electron microscope (TEM), and the resulting C concentration was evaluated. A position 1 mm below the surface of the steel plate was used as an observation target. The analysis was performed on 10 grain boundaries, and the average value was determined.

(2) Low-Temperature Toughness

[0083] The low-temperature toughness of the line-heated portion was evaluated as described below.

[0084] A line-heating specimen illustrated in Fig. 1 was produced from the resulting hot-rolled steel plate. The low-temperature toughness of the line-heated portion was evaluated using a steel plate obtained by subjecting the test specimen to plate line heating under the above-described conditions. Charpy V-notch test specimens (full-size Charpy V-notch test specimens) were taken from the line-heated portion having a plate thickness of 10 mm or more in accordance with JIS Z 2242 (2005). A Charpy impact test was conducted at -196°C and -269°C using the three Charpy V-notch test specimens. An average absorbed energy value of three test specimens at each temperature was determined. In this example, in the case of the full-size Charpy V-notch test specimens, when the average absorbed energy value of the three test specimens at -269°C was 41 J or more, the steel plate was determined to have excellent low-temperature toughness.

[0085] With respect to the line-heated portion having a plate thickness of less than 10 mm, sub-size Charpy V-notch test specimens of 5 mm were taken in accordance with JIS Z 2242 (2005). A Charpy impact test was conducted at -196°C and -269°C using the three Charpy V-notch test specimens. The average absorbed energy value of the three test specimens at each temperature was determined. In Table 2, "*" is attached to each value of absorbed energy for the samples tested using the sub-sized Charpy V-notch test specimens. In the case of the sub-size Charpy V-notch test specimens, when the average absorbed energy value of the three test specimens at -269°C was 27 J or more, the steel plate was determined to have excellent low-temperature toughness.

(3) Stress Corrosion Cracking Resistance

[0086] The stress corrosion cracking resistance was evaluated by a stress corrosion cracking test in accordance with ASTM G36. A test specimen having a thickness of 2.5 mm, a width of 20 mm, and a length of 80 mm was taken from a position 1 mm below the surface of the resulting hot-rolled steel plate. A boiling MgCl₂ solution was used. The bend radius was 5 mm. The test specimen to which stress was applied was immersed in the above-described solution for 400 hours. Thereafter, whether cracking occurred was checked. When no cracking occurred, the sample was evaluated as "o (pass)" in Table 2-2. When cracking occurred, the sample was evaluated as "× (fail)" in Table 2-2.

[0087] The results obtained as above are presented in Tables 2-1 and 2-2.

[Table 1]

Steel No.	Chemical composition (% by mass)																		
	C	Si	Mn	P	S	Al	Cr	N	O	Ti	Nb	Ca	Mg	REM	Cu	Ni	Mo	V	W
1	0.358	0.10	32.6	0.013	0.0018	0.03	4.3	0.0187	0.0017	0.001	0.001	0.0020	-	-	-	-	-	-	-
2	0.550	0.07	24.0	0.014	0.0023	0.20	3.6	0.0098	0.0016	0.002	0.001	-	0.0006	-	-	-	-	-	-
3	0.402	0.38	26.6	0.014	0.0045	0.12	5.0	0.0203	0.0043	0.001	0.002	-	-	0.0010	-	-	-	-	-
4	0.555	0.25	22.9	0.012	0.0025	0.04	6.5	0.0150	0.0015	0.003	0.003	-	0.0006	-	-	1.0	-	-	-
5	0.253	0.73	24.2	0.025	0.0019	4.03	2.7	0.0215	0.0018	0.001	0.001	-	-	0.0015	-	-	1.8	-	-
6	0.204	0.98	39.6	0.012	0.0016	0.05	7.0	0.0490	0.0014	0.001	0.002	0.0015	-	-	-	-	-	0.1	-
7	0.698	0.15	20.2	0.011	0.0018	0.04	5.9	0.0102	0.0013	0.001	0.002	-	0.0011	-	-	-	-	-0.1	0.1
8	0.195	0.80	22.2	0.020	0.0023	0.36	1.5	0.0364	0.0021	0.002	0.001	0.0011	-	-	-	-	-	-	-
9	0.707	0.31	35.0	0.022	0.0030	0.60	5.8	0.0235	0.0023	0.002	0.002	-	0.0007	-	-	-	-	-	-
10	0.630	1.05	23.5	0.019	0.0020	0.03	4.7	0.0319	0.0020	0.001	0.001	-	-	0.0009	-	-	-	-	-
11	0.211	0.26	19.6	0.019	0.0019	0.12	1.9	0.0162	0.0022	0.003	0.002	0.0013	-	-	-	-	-	-	-
12	0.300	0.32	40.3	0.023	0.0025	0.05	0.7	0.0123	0.0025	0.002	0.003	-	0.0009	-	-	-	-	-	-
13	0.524	0.44	23.4	0.032	0.0018	3.50	6.6	0.0417	0.0019	0.003	0.003	-	-	0.0012	-	-	-	-	-
14	0.499	0.84	39.1	0.025	0.0051	2.35	0.9	0.0253	0.0021	0.002	0.001	0.0024	-	-	-	-	-	-	-
15	0.610	0.58	33.3	0.020	0.0021	5.02	3.4	0.0194	0.0028	0.002	0.001	-	0.0010	-	-	-	-	-	-
16	0.672	0.43	21.0	0.026	0.0019	0.21	7.2	0.0334	0.0020	0.001	0.002	0.0019	-	-	-	-	-	-	-
17	0.498	0.60	22.6	0.017	0.0022	2.27	5.5	0.0505	0.0037	0.002	0.002	-	-	0.0014	-	-	-	-	-
18	0.395	0.57	30.2	0.023	0.0020	4.00	2.3	0.0361	0.0053	0.003	0.002	0.0018	-	-	-	-	-	-	-
19	0.222	0.86	20.4	0.025	0.0040	0.04	0.8	0.0299	0.0030	0.006	0.003	-	0.0009	-	-	-	-	-	-
20	0.514	0.28	38.5	0.024	0.0035	3.48	1.1	0.0426	0.0041	0.003	0.006	-	-	0.0013	-	-	-	-	-
21	0.305	0.68	23.8	0.010	0.0014	2.90	6.0	0.0300	0.0013	0.002	0.001	0.0015	-	-	0.5	0.5	-	-	-
22	0.541	0.17	29.5	0.019	0.0040	0.05	2.0	0.0094	0.0039	0.001	0.002	-	0.0015	0.0030	-	-	1.5	-	-
23	0.210	0.31	39.3	0.020	0.0039	3.97	6.5	0.0223	0.0036	0.001	0.001	-	-	-	-	-	-	-	-

[Table 2-1]

Sample No.	Steel No.	Plate thick- ness	Method for producing steel material							Microstructure at position 1 mm below sur- face of steel plate			Remarks
			Slab heating temperature	Total rolling reduction at 950°C or higher	Number of hot rolling passes at lower than 950°C	Finishing tem- perature	Average cooling rate	Finish cooling temperature	Maximum grain size	Number density of grains with grain size of 50 μm or more	Top 10% inclusion particle size		
												(°C)	
1	1	25	1100	75	1	878	150	546	87	3.2	2.0	Example	
2	2	20	1200	65	3	842	16.2	530	76	2.4	2.3	Example	
3	3	15	1150	70	4	799	16.6	499	51	1.4	2.7	Example	
4	4	30	1250	55	4	873	12.5	541	164	6.7	2.0	Example	
5	5	10	1230	75	4	855	18.5	535	60	1.8	3.1	Example	
6	6	6	1250	85	2	891	1.2	natural cooling	79	2.7	2.6	Example	
7	7	40	1270	40	4	900	102	568	190	8.3	2.8	Example	
8	8	21	1130	65	3	808	15.7	505	96	4.2	2.0	Comparative example	
9	9	21	1130	70	2	819	15.8	524	102	5.0	2.3	Comparative example	
10	10	24	1100	65	3	757	15.5	458	49	0.0	2.9	Comparative example	
11	11	18	1090	75	2	810	16.4	515	83	3.2	3.3	Comparative example	
12	12	18	1170	70	3	806	16.2	507	97	4.2	2.8	Comparative example	
13	13	12	1150	75	3	781	17.3	477	59	1.5	3.1	Comparative example	
14	14	12	1150	85	1	894	17.7	555	181	7.7	2.6	Comparative example	

(continued)

Sample No.	Steel No.	Plate thick- ness	Method for producing steel material							Microstructure at position 1 mm below sur- face of steel plate			Remarks
			Slab heating temperature	Total rolling reduction at 950°C or higher	Number of hot rolling passes at lower than 950°C	Finishing tem- perature	Average cooling rate	Finish cooling temperature	Maximum grain size	Number density of grains with grain size of 50 μm or more	Top 10% inclusion particle size		
												(°C)	
15	15	15	1270	70	3	832	16.8	530	102	5.3	2.2	Comparative example	
16	16	15	1200	75	3	811	16.6	512	90	3.6	2.0	Comparative example	
17	17	9	1170	80	3	783	1.4	natural cooling	51	1.6	2.7	Comparative example	
18	18	9	1170	85	2	768	1.4	natural cooling	48	0.0	3.2	Comparative example	
19	19	6	1200	80	4	745	10	natural cooling	36	0.0	2.1	Comparative example	
20	20	6	1200	85	3	775	1.1	natural cooling	45	0.0	2.6	Comparative example	
21	1	40	1130	35	5	800	100	501	205	10.4	3.1	Comparative example	
22	3	40	1270	70	0	953	10.4	578	213	10.9	2.9	Comparative example	
23	2	15	1220	75	3	845	16.7	532	80	2.9	3.0	Example	
24	21	20	1200	70	4	828	15.2	520	65	1.8	2.7	Example	
25	22	25	1150	65	6	800	14.7	504	53	1.4	2.6	Example	
26	23	15	1150	70	3	815	15.8	509	72	2.2	3.9	Comparative example	
27	1	25	1100	70	3	780	15.5	499	52	1.1	2.6	Example	

[Table 2-2]

Sample No.	Steel No.	Tank								Remarks
		Line heating conditions		Welding condition		Element concentration after line heating	Properties of line-heated portion			
Target heating temperature (°C)	Number of times of line heating (times)	Interpass temperature (°C)	Shielding gas	C (%)	Absorbed energy at 196°C (J)	Absorbed energy at -269°C (J)	Stress corrosion cracking resistance (-)			
1	1	900	5	100	80% Ar + 20% CO ₂	0.247	80	65	○	Example
2	2	900	5	150	80% Ar + 20% CO ₂	0.441	77	63	○	Example
3	3	900	5	130	80% Ar + 20% CO ₂	0.298	78	60	○	Example
4	4	900	5	120	80% Ar + 20% CO ₂	0.303	70	56	○	Example
5	5	900	5	140	80% Ar + 20% CO ₂	0.150	68	52	○	Example
6	6	900	5	110	80% Ar + 20% CO ₂	0.100	45*1	29*1	○	Example
7	7	900	5	130	80% Ar + 20% CO ₂	0.443	68	45	○	Example
8	8	900	5	130	80% Ar + 20% CO ₂	0.065	49	30	○	Comparative example
9	9	900	5	120	80% Ar + 20% CO ₂	0.497	50	35	○	Comparative example
10	10	900	5	140	80% Ar + 20% CO ₂	0.519	53	38	○	Comparative example
11	11	900	5	100	80% Ar + 20% CO ₂	0.105	51	30	○	Comparative example

(continued)

Sample No.	Steel No.	Tank							Remarks	
		Line heating conditions		Welding condition		Element concentration after line heating	Properties of line-heated portion			
		Target heating temperature (°C)	Number of times of line heating (times)	Interpass temperature (°C)	Shielding gas	C	Absorbed energy at 196°C (J)	Absorbed energy at -269°C (J)		Stress corrosion cracking resistance
						(%)	(J)	(J)		(-)
12	12	900	5	130	80% Ar + 20% CO ₂	0.170	55	31	○	Comparative example
13	13	900	5	150	80% Ar + 20% CO ₂	0.417	52	36	○	Comparative example
14	14	900	5	120	80% Ar + 20% CO ₂	0.248	51	37	○	Comparative example
15	15	900	5	130	80% Ar + 20% CO ₂	0.410	43	30	○	Comparative example
16	16	900	5	110	80% Ar + 20% CO ₂	0.532	50	32	○	Comparative example
17	17	900	5	110	80% Ar + 20% CO ₂	0.394	35*1	24*1	○	Comparative example
18	18	900	5	120	80% Ar + 20% CO ₂	0.293	34*1	24*1	○	Comparative example
19	19	900	5	140	80% Ar + 20% CO ₂	0.115	35*1	23*1	○	Comparative example
20	20	900	5	120	80% Ar + 20% CO ₂	0.408	38*1	26*1	○	Comparative example
21	1	900	5	130	80% Ar + 20% CO ₂	0.058	46	32	○	Comparative example
22	3	900	5	130	80% Ar + 20% CO ₂	0.092	45	30	○	Comparative example

(continued)

Sample No.	Steel No.	Tank							Remarks	
		Line heating conditions		Welding condition		Element concentration after line heating	Properties of line-heated portion			
							Absorbed energy at 196°C	Absorbed energy at -269°C		Stress corrosion cracking resistance
		Target heating temperature (°C)	Number of times of line heating (times)	Interpass temperature (°C)	Shielding gas	C (%)	(J)	(J)	(-)	
23	2	850	4	130	80% Ar + 20% CO ₂	0.475	84	70	○	
24	21	900	5	120	80% Ar + 20% CO ₂	0.209	69	53	○	
25	22	900	5	110	80% Ar + 20% CO ₂	0.438	77	64	○	
26	23	900	5	130	80% Ar + 20% CO ₂	0.114	50	39	×	
27	1	900	5	120	80% Ar + 20% CO ₂	0.258	61	44	○	
*1: Sub-size of 5 mm										

[0088] The results presented in Tables 2-1 and 2-2 indicated that the austenitic steel materials of the present invention met the above-mentioned target performance: a maximum grain size in the microstructure of less than 200 μm . The results also indicated that the line-heated portion of each of the austenitic steel materials of the present invention met the above-mentioned target performance: a C concentration at the grain boundaries of 0.100% or more and an absorbed energy (vE_{-269}) of 41 J or more or 27 J or more for the 5-mm sub-size specimen in the Charpy impact test.

[0089] In contrast, in Comparative Examples outside the scope of the present invention, the above target performance was not met.

Claims

1. A steel material having a chemical composition comprising, in mass%:

C: 0.200% or more and 0.700% or less,

Si: 0.05% or more and 1.00% or less,

Mn: 20.0% or more and 40.0% or less,

P: 0.030% or less,

S: 0.0050% or less,

Al: 5.00% or less,

Cr: 7.0% or less,

N: 0.0500% or less,

O: 0.0050% or less,

Ti: less than 0.005%,

Nb: less than 0.005%, and

one or two or more selected from Ca: 0.0100% or less, Mg: 0.0100% or less, and REM: 0.0200% or less, the balance being iron and incidental impurities, and

a microstructure having a maximum grain size of less than 200 μm at a position 1 mm below a surface of the steel material.

2. The steel material according to Claim 1, wherein the chemical composition further comprising, in mass%:

one or two or more selected from

Cu: 1.0% or less,

Ni: 1.0% or less,

Mo: 2.0% or less,

V: 2.0% or less, and

W: 2.0% or less.

3. The steel material according to Claim 1 or 2, wherein the microstructure has a number density of grains having a grain size of 50 μm or more of 1.0 grain/ mm^2 or more at the position 1 mm below the surface of the steel material.

4. The steel material according to any one of Claims 1 to 3, wherein in the microstructure, an inclusion particle size in a top 10% of an inclusion particle size distribution at the position 1 mm below the surface of the steel material is 3.5 μm or less.

5. A method for producing the steel material according to any one of Claims 1 to 4, comprising:

heating a raw steel material having the chemical composition to a temperature range of 1,100°C or higher and 1,300°C or lower;

performing hot rolling at a total rolling reduction of 40% or more at 950°C or higher, a number of hot rolling passes of one or more at lower than 950°C, and a finishing temperature of 750°C or higher; and then performing cooling.

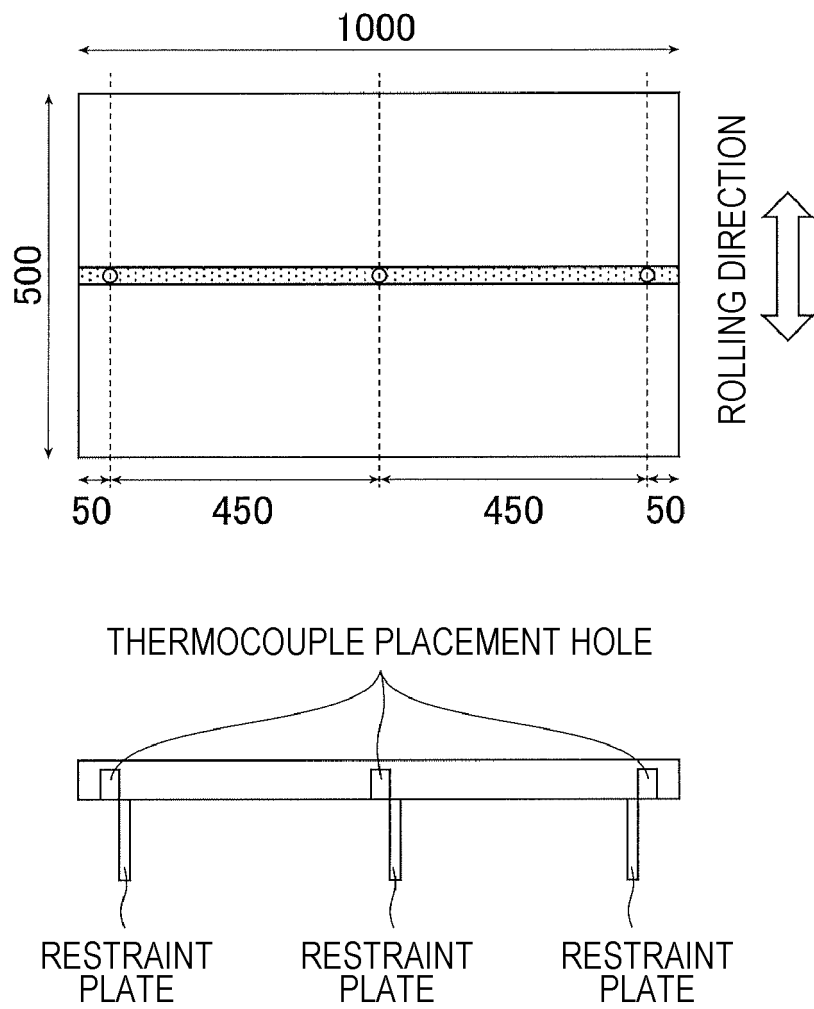
6. A tank obtained by welding the steel material according to any one of Claims 1 to 4, wherein a C concentration at a grain boundary at a position 1 mm below a surface of a base metal zone subjected to line heating is 0.100% or more, and an absorbed energy in a Charpy impact test at -269°C or higher at a position 1 mm below a surface of a line-heated portion subjected to the line heating is 41 J or more.

7. A method for producing the tank according to Claim 6, comprising:

performing line heat treatment of the steel materials according to any one of Claims 1 to 4 to curve the steel materials, the line heat treatment including heating surfaces of the steel materials to 900°C or lower, subjecting the steel materials to natural cooling to a surface temperature of 500°C or lower, and then performing water cooling; and subsequently welding the curved steel materials together.

8. The method for producing the tank according to Claim 7, wherein the welding is performed using a solid wire as an electrode with a shielding gas of 80% Ar + 20% CO₂ at an interpass temperature of 100°C to 150°C.

FIG. 1



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2022/002735

A. CLASSIFICATION OF SUBJECT MATTER <i>C22C 38/00</i> (2006.01)i; <i>B21D 51/18</i> (2006.01)i; <i>C21D 8/02</i> (2006.01)i; <i>C22C 38/38</i> (2006.01)i; <i>C22C 38/58</i> (2006.01)i; <i>F17C 3/00</i> (2006.01)i FI: C22C38/00 302B; B21D51/18 B; C21D8/02 D; C22C38/38; C22C38/58; F17C3/00 Z 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; B21D51/18; C21D8/02; F17C3/00 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Published examined utility model applications of Japan 1922-1996 Published unexamined utility model applications of Japan 1971-2022 Registered utility model specifications of Japan 1996-2022 Published registered utility model applications of Japan 1994-2022 Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)															
C. DOCUMENTS CONSIDERED TO BE RELEVANT <table border="1"> <thead> <tr> <th>Category*</th> <th>Citation of document, with indication, where appropriate, of the relevant passages</th> <th>Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>X A</td> <td>WO 2019/044928 A1 (JFE STEEL CORP.) 07 March 2019 (2019-03-07) claims, paragraphs [0042], [0045]-[0055]</td> <td>1-5 6-8</td> </tr> <tr> <td>X A</td> <td>WO 2018/105510 A1 (JFE STEEL CORP.) 14 June 2018 (2018-06-14) claims, paragraphs [0038]-[0040], [0058], [0062]-[0077]</td> <td>2-5 1, 6-8</td> </tr> <tr> <td>X A</td> <td>JP 2017-155300 A (NIPPON STEEL & SUMITOMO METAL CORP.) 07 September 2017 (2017-09-07) claims, paragraphs [0037], [0044]-[0050], fig. 1</td> <td>2-3 1, 4-8</td> </tr> <tr> <td>Y A</td> <td>JP 2020-537714 A (POSCO) 24 December 2020 (2020-12-24) claims, paragraphs [0011], [0063], [0088]-[0104]</td> <td>2-3 1, 4-8</td> </tr> </tbody> </table>	Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X A	WO 2019/044928 A1 (JFE STEEL CORP.) 07 March 2019 (2019-03-07) claims, paragraphs [0042], [0045]-[0055]	1-5 6-8	X A	WO 2018/105510 A1 (JFE STEEL CORP.) 14 June 2018 (2018-06-14) claims, paragraphs [0038]-[0040], [0058], [0062]-[0077]	2-5 1, 6-8	X A	JP 2017-155300 A (NIPPON STEEL & SUMITOMO METAL CORP.) 07 September 2017 (2017-09-07) claims, paragraphs [0037], [0044]-[0050], fig. 1	2-3 1, 4-8	Y A	JP 2020-537714 A (POSCO) 24 December 2020 (2020-12-24) claims, paragraphs [0011], [0063], [0088]-[0104]	2-3 1, 4-8
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Date of the actual completion of the international search 09 March 2022	Date of mailing of the international search report 22 March 2022														
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INTERNATIONAL SEARCH REPORT

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

International application No.

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WO 2018/199145 A1	01 November 2018	EP 3617337 A1 claim 2, paragraph [0032] CN 110573642 A KR 10-2019-0134704 A	
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