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(54) **STEEL**

(57) A steel product having a specific chemical composition, in which α expressed by a following formula is 5.0 or more and 16.0 or less; having a tensile strength of 615 MPa or more and 930 MPa or less; and having a microstructure in a region that is 1/4 of a thickness from a surface that contains lower bainite and martensite, with a total of area ratios of the lower bainite and the martensite being 15.0% or more, a total of area ratios of upper bainite, the lower bainite, and the martensite being 90.0% or more, and an area ratio of residual austenite being less than 1.7%.

$$\alpha = 0.50 \times \sqrt{[C]} \times (1+0.64[Si]) \times (1+4.10[Mn]) \times (1+0.27[Cu]) \times (1+0.52[Ni]) \times (1+2.33[Cr]) \times (1+3.14[Mo])$$

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Description

Technical Field

5 **[0001]** The present disclosure relates to a steel product.

Background Art

10 **[0002]** Steel products can be used in welded structures such as buildings, bridges, ships, pipelines, offshore structures, pressure vessels and tanks. Steel products having excellent strength and adaptability to low-temperature toughness are effective in low-temperature applications.

[0003] Cryogenic steel is used in cryogenic pressure vessels such as storage tanks for liquefied gases. Al-killed steel, nickel steel, high-Mn steel, austenitic stainless steel and the like exist in a cryogenic steel, in accordance with the usage temperature. For example, nickel steel such as 3.5% Ni steel is used as a material for tanks that store liquefied ethane or liquefied ethylene whose usage temperatures are around -100°C.

15 **[0004]** As with this 3.5% Ni steel, steel products that require ensured low-temperature toughness-exemplified by those used in cryogenic pressure vessels-are often made to contain Ni.

[0005] For example, Patent Document 1 proposes a nickel-containing steel product for low temperatures that has excellent toughness and has a specific chemical composition containing 2.7% or more and 5.0% or less Ni, wherein the prior austenite grain diameter at the time of quenching heating is 20 μm or less, and the effective crystal grain diameter after a heat treatment is 12 μm or less, and the tensile strength is 450 MPa or more and 690 MPa or less.

20 **[0006]** Further, various steel products of prescribed chemical compositions and microstructures (metal structures) have been proposed for the purposes of low-temperature toughness and high strength (see, for example, Patent Documents 2 through 6).

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Patent Document 1: Japanese Patent Application Laid-Open (JP-A) No. 2019-81930

Patent Document 2: JP-A No. H06-192729

Patent Document 3: JP-A No. H07-331328

Patent Document 4: International Publication No. 2007/034576

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Patent Document 5: International Publication No. 2020/184162

Patent Document 6: International Publication No. 2014/017057

SUMMARY OF INVENTION

Technical Problem

35 **[0007]** Having both high strength and the ensuring of low-temperature toughness is desirable for cryogenic steels that are used in cryogenic pressure vessels. Further, a cryogenic pressure vessel is manufactured by welding a steel product, and, in order to eliminate residual stress that arises due to the welding, there are cases in which a post weld heat treatment (called PWHT upon occasion) is carried out. Recently, the demand for low-temperature toughness of steel products after PWHT has increased even more.

40 **[0008]** A topic of the present disclosure is the provision of a steel product that is suited to low-temperature applications and that has good low-temperature toughness regardless of whether before or after a post weld heat treatment.

Solution to Problem

45 **[0009]** The gist of the present disclosure is as follows.

50 <1> A steel product having a chemical composition including, in mass%,

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C: 0.03% or more and 0.20% or less,

Si: 0.01% or more and 0.50% or less,

Mn: 0.10% or more and 2.00% or less,

P: 0.025% or less,

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S: 0.0250% or less,

Ni: 4.51% or more and 6.10% or less,

Al: 0.001% or more and 0.100% or less,

O: 0.0100% or less,

N: 0.0100% or less,
 Cu: 0 - 1.50%,
 Cr: 0 - 3.00%,
 Mo: 0 - 2.00%,
 B: 0 - 0.0050%,
 Nb: 0 - 0.050%,
 Ti: 0 - 0.050%,
 V: 0 - 0.10%,
 Mg: 0 - 0.0200%,
 Ca: 0 - 0.0200%,
 REM: 0 - 0.0200%,
 balance: Fe and impurities,
 and in which α expressed by following formula (1) is 5.0 or more and 16.0 or less,
 wherein:

a tensile strength is 615 MPa or more and 930 MPa or less, and
 a microstructure of a region that is 1/4 of a thickness in a thickness direction from a surface of the steel product contains lower bainite and martensite, and a total of area ratios of the lower bainite and the martensite is 15.0% or more, and a total of area ratios of upper bainite and the lower bainite and the martensite is 90.0% or more, and an area ratio of residual austenite is less than 1.7%.

$$\alpha = 0.50 \times \sqrt{[C]} \times (1+0.64[Si]) \times (1+4.10[Mn]) \times (1+0.27[Cu]) \times (1+0.52[Ni]) \times (1+2.33[Cr]) \times (1+3.14[Mo]) \quad (1)$$

wherein [element symbol] in formula (1) represents content (mass%) of a respectively corresponding element contained in the steel product, and, in a case in which an element is not contained, zero is substituted in therefor.

<2> The steel product of <1>, wherein, in the microstructure of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product, an average crystal grain diameter is 20.0 μm or less.

<3> The steel product of <1> or <2>, wherein a Charpy impact absorption energy at -110°C is 150 J or more.

<4> The steel product of any one of <1> through <3>, wherein, in a case in which a heat treatment, in which a rate of temperature increase and a rate of temperature decrease in a temperature region of 425°C or more are 55°C/h and temperature is held for 2 hours at 600°C, is carried out on the steel product, a Charpy impact absorption energy at -110°C of portions where the heat treatment has been carried out is 150 J or more.

<5> The steel product of any one of <1> through <4>, wherein an aspect ratio of prior austenite crystal grains of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product is 1.5 or more.

<6> The steel product of any one of <1> through <4>, wherein an aspect ratio of prior austenite crystal grains of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product is less than 1.5.

Advantageous Effects of Invention

[0010] In accordance with the present disclosure, a steel product that is suited to low-temperature applications and that has good low-temperature toughness regardless of whether before or after a post weld heat treatment can be provided.

BRIEF DESCRIPTION OF DRAWINGS

[0011] Fig. 1 is a diagram illustrating an example of results of discriminating the microstructure.

DESCRIPTION OF EMBODIMENTS

[0012] The present disclosure is described in detail hereinafter.

[0013] The "post weld heat treatment" in the present disclosure means a post weld heat treatment based on the contents prescribed in JIS Z 3700:2009 "Method of post weld heat treatment Method", unless otherwise specified.

[0014] The "steel product" and the "base metal" in the present disclosure mean the steel product portion that does not include a surface treated layer such as a plating layer or a coated film. However, a surface treated layer such as a plating layer or a coated film may be formed on the surface of the steel product relating to the present disclosure. Further, the "base

metal" in a welded joint means the steel product portion that is not affected by welding, in contrast to the welded portion (the welded metal or the heat affected zone).

[0015] In the present disclosure, numerical ranges expressed by using "-" mean ranges in which the numerical values listed before and after the "-" are included as the lower limit value and upper limit value, respectively. However, numerical value ranges in which "exceeds" or "less than" is appended to the numerical value listed before or after the "-" mean a range in which these numerical values are not included as the lower limit value or the upper limit value.

[0016] With respect to the contents of the elements in a chemical composition, "%" means "mass%".

[0017] The term "step" is not only an independent step and includes steps that, even in a case in which that step cannot be clearly distinguished from another step, achieve the intended object of that step.

[0018] A steel product relating to an embodiment of the present disclosure is described hereinafter. The new knowledge, which was obtained as the result of studies by the inventors of the present disclosure and which was arrived at in completing the steel product relating to the present disclosure, is described in detail first.

[0019] The inventors of the present disclosure carried out studies in order to improve the strength of steel products. The tensile strength of a steel product is ensured by the configuration of the microstructure. The inventors of the present disclosure took samples from a 1/4t portion (t: thickness of the steel product) of a steel product after hot rolling and accelerated cooling, and carried out tensile test thereon, and observed the microstructures. As a result, it was learned that, at the microstructure of the 1/4t portion of a steel product having a tensile strength of 615 MPa or more and 930 MPa or less, the area ratio of ferrite is less than 10.0%, and the total of the area ratios of upper bainite, lower bainite and martensite is 90.0% or more. Note that the total of the area ratios of upper bainite, lower bainite and martensite was measured by using electron back scatter diffraction (hereinafter called "EBSD").

[0020] Further, the inventors of the present disclosure carried out studies in order to improve the toughness of steel products. The toughness of a steel product is ensured by the configuration of the microstructure. The inventors of the present disclosure took samples from the 1/4t portion of a steel product after hot rolling and accelerated cooling, and carried out Charpy impact test, and observed the microstructures. As a result, it was found that, in a steel product exhibiting a Charpy impact absorption energy of 150 J or more at -110°C, the total of the area ratios of lower bainite and martensite is 15.0% or more and the area ratio of the residual austenite is less than 1.7%. Note that the total of the area ratios of lower bainite and martensite was measured by using EBSD. Note that the area ratio of the residual austenite was measured by X-ray diffraction. The volume ratio of the residual austenite measured by the X-ray diffraction may be considered to be the area ratio.

[0021] Moreover, the inventors of the present disclosure carried out studies in order to ensure the toughness of steel products. The toughness of a steel product is ensured by making the region, at which the difference in crystal orientation is 15° or more and which is surrounded by a high angle grain boundary, small. The inventors of the present disclosure took samples from the 1/4t portion of a steel product manufactured by controlling the cooling rate and the cooling stoppage temperature after hot rolling, and measured the circle equivalent diameter of the region surrounded by a high angle grain boundary by EBSD. The circle equivalent diameter of the region surrounded by a high angle grain boundary is called the crystal grain diameter hereinafter. The sample was subjected to mechanical polishing and electrolytic polishing, and analysis was carried out on a 4 mm² region by an EBSD device equipped with an FE-SEM (field emission scanning electron microscope). The value calculated by an area weighted average that was weighted by the area per crystal grain among the crystal grain diameters measured in the 4 mm² region, was used as the average crystal grain diameter (also called "effective crystal grain diameter" upon occasion). It was learned that, if the average crystal grain diameter of a 1/4t portion of a steel product is 20.0 μm or less, there is the tendency for the toughness of the steel product to improve more regardless of whether before or after a post weld heat treatment.

[0022] Further, the inventors of the present disclosure have found that similar results can be obtained not only with steel products after hot rolling and accelerated cooling, but also with steel products after reheat quenching.

<Chemical Composition>

[0023] Alloy elements that constitute the chemical composition of the steel product relating to the present disclosure are described next. Note that, in the following description of the alloy elements, the "%" of the content means "mass%".

(C: 0.03% or more and 0.20% or less)

[0024] C is an element that improves the strength of the steel product. From the standpoint of ensuring the strength of the steel product that is used in a structure, in the present disclosure, the C content is 0.03% or more. The C content is preferably 0.05% or more, or 0.07% or more. On the other hand, C is an element that reduces toughness, and, from the standpoint of ensuring the toughness of the heat affected zone (hereinafter called "HAZ" upon occasion), in the present disclosure, the C content is 0.20% or less. The C content is preferably 0.16% or less, 0.14% or less, or 0.12% or less.

(Si: 0.01% or more and 0.50% or less)

[0025] Si is an element that is used as a deoxidizing agent, and further, that dissolves into the steel and increases the strength. From the standpoint of controlling the O concentration contained in molten steel, in the present disclosure, the Si content is 0.01% or more. The Si content is preferably 0.03% or more, 0.05% or more, 0.10% or more, or 0.12% or more. On the other hand, if the Si content is excessive, there are cases in which a hard phase forms in the HAZ, and the toughness decreases. Accordingly, from the standpoint of ensuring the toughness of the HAZ, in the present disclosure, the Si content is 0.50% or less. The Si content is preferably 0.30% or less, or 0.20% or less.

(Mn: 0.10% or more and 2.00% or less)

[0026] Mn is an element that is used as a deoxidizing agent, and further, that improves the hardenability of the steel and contributes to increasing the strength. From the standpoint of controlling the O concentration contained in molten steel, in the present disclosure, the Mn content is 0.10% or more. Moreover, due to Mn in an amount of 0.10% or more, by forming MnS, the solid-solution S is reduced, and hot cracking is prevented. From the standpoint of ensuring the strength of the steel product and the toughness of the HAZ, the Mn content is preferably 0.30% or more, or 0.50% or more. On the other hand, if the Mn content is excessive, there are cases in which the toughness after PWHT decreases due to the Mn segregating at the grain boundary at the time of PWHT. Accordingly, from the standpoint of ensuring the toughness of the steel product after PWHT, in the present disclosure, the Mn content is 2.00% or less. The Mn content is preferably 1.80% or less, or 1.50% or less.

(P: 0.025% or less)

[0027] P is an impurity element. Although the lower limit of the P content is not limited, from the standpoint of the manufacturing cost, in the present disclosure, the P content may be 0.001% or more. On the other hand, if the P content is excessive, there are cases in which the toughness after PWHT decreases due to the P segregating at the grain boundary at the time of PWHT. Accordingly, in the present disclosure, the P content is 0.025% or less. The P content is preferably 0.016% or less, 0.012% or less, or 0.008% or less.

(S: 0.0250% or less)

[0028] S is an impurity element. Although the lower limit of the S content is not limited, from the standpoint of the manufacturing cost, in the present disclosure, the S content may be 0.0001% or more. On the other hand, if the S content is excessive, there are cases in which elongated MnS is generated at the centerline segregation area, and the toughness and ductility of the steel product and the HAZ deteriorate. From the standpoint of ensuring the toughness and ductility of the steel product and the HAZ, the S content is 0.0250% or less. The S content is preferably 0.0100% or less or 0.0050% or less.

(Ni: 4.51% or more and 6.10% or less)

[0029] Ni is an element that is effective in improving the hardenability and toughness of the steel. Therefore, in the present embodiment, the Ni content is 4.51% or more. The Ni content is preferably 5.00% or more, or 5.25% or more. However, Ni is an expensive element, and, from the standpoint of cost reduction, in the present disclosure, the Ni content is 6.10% or less. The Ni content is preferably 6.00% or less, or 5.75% or less.

(Al: 0.001% or more and 0.100% or less)

[0030] Al is an element that is effective in deoxidation, and is an element that, by forming a nitride, refines the crystal grain diameter at the time of quenching. Therefore, in the present disclosure, the Al content is 0.001% or more. However, if Al is excessively contained, there is the concern that the Al will generate a coarse nitride, and the toughness of the steel product and the HAZ will decrease. Accordingly, the Al content is 0.100% or less. The Al content is preferably 0.080%, or 0.050% or less.

(O: 0.0100% or less)

[0031] O is an impurity element. Although the lower limit of the O content is not limited, from the standpoint of the manufacturing cost, in the present disclosure, the O content may be 0.0001% or more. On the other hand, if the O content is excessive, there are cases in which a coarse oxide is generated, and the toughness and ductility of the steel product and

the HAZ deteriorate. From the standpoint of ensuring the toughness and ductility of the steel product and the HAZ, the O content is 0.0100% or less. The O content is preferably 0.0060% or less, or 0.0040% or less.

(N: 0.0100% or less)

[0032] N is an impurity element. Although the lower limit of the N content is not limited, from the standpoint of the manufacturing cost, in the present disclosure, the N content may be 0.0001% or more. From the standpoint of ensuring the properties of the steel product and the toughness of the HAZ, in the present disclosure, the N content is 0.0100% or less. The N content is preferably 0.0050% or less, or 0.0040% or less.

[0033] The steel product relating to the present disclosure may contain other elements (optional elements) instead of some of the Fe. The following optional elements are given as examples, but the contents of these elements may be 0%.

[0034] In order to improve the strength and toughness, as needed, the steel product relating to the present disclosure may be made to contain one or two or more of the optional elements Cu, Cr, Mo, and B that are described hereinafter and have the effect of improving the hardenability.

(Cu: 1.50% or less)

[0035] Cu is an element that is sometimes mixed into the steel product in the manufacturing process. However, the lower limit value of the Cu content is not limited and may be 0%. Further, Cu has little adverse effect on the weldability and on the toughness of the HAZ, and has the effect of improving the hardenability of steel, and therefore, is an element that improves the strength of the steel product. Thus, in the present disclosure, the Cu content may be 0.01% or more. The Cu content is preferably 0.10% or more. However, from the standpoint of suppressing the occurrence of Cu cracking at the time of hot rolling of the steel product, in the present disclosure, the Cu content is 1.50% or less. The Cu content is preferably 1.00% or less, 0.80% or less, 0.60% or less, or 0.50% or less.

(Cr: 3.00% or less)

[0036] Cr is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the Cr content is not limited, and may be 0%. Further, Cr is also an element that improves the strength of a steel product because it has the effect of increasing the hardenability of the steel. Therefore, in the present disclosure, the Cr content may be 0.01% or more. The Cr content is preferably 0.10% or more. However, from the standpoint of suppressing deterioration in the toughness and weldability of the HAZ, in the present disclosure, the Cr content is 3.00% or less. The Cr content is preferably 2.20% or less, 1.40% or less, or 0.80% or less.

(Mo: 2.00% or less)

[0037] Mo is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the Mo content is not limited, and may be 0%. Further, Mo is also an element that improves the strength of a steel product because it has the effect of increasing the hardenability of the steel. Therefore, in the present disclosure, the Mo content may be 0.01% or more. The Mo content is preferably 0.05% or more, 0.10% or more, 0.20% or more or 0.30% or more. However, from the standpoints of suppressing deterioration in the toughness and weldability of the HAZ, and suppressing an increase in the alloy cost, in the present disclosure, the Mo content is 2.00% or less. The Mo content is preferably 1.20% or less, or 0.80% or less.

(B: 0.0050% or less)

[0038] B is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the B content is not limited, and may be 0%. Further, B is also an element that exhibits a marked effect of increasing the hardenability of steel and improves the strength of a steel product. Therefore, in the present disclosure, the B content may be 0.0003% or more. However, from the standpoint of suppressing deterioration in the surface quality of a steel slab manufactured in continuous casting, in the present disclosure, the B content is 0.0050% or less. The B content is preferably 0.0030% or less, or 0.0020% or less.

[0039] In order to improve the strength, as needed, the steel product relating to the present disclosure may be made to contain one or two or more of the optional elements Nb, Ti, and V that are described hereinafter and have the effect of increasing the strength of the steel product by precipitates such as carbides or nitrides.

(Nb: 0.050% or less)

[0040] Nb is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the Nb content is not limited, and may be 0%. Further, Nb is also an element that forms a carbide or a nitride, and has the effect of refining the microstructure, and improves the strength of the steel product. Therefore, in the present disclosure, the Nb content may be 0.001% or more. However, from the standpoint of suppressing deterioration in the toughness and weldability of the HAZ, the Nb content is 0.050% or less. The Nb content is preferably 0.040% or less, or 0.030% or less. In particular, from the standpoint of ensuring the toughness of the steel product after PWHT, the Nb content may be 0.004% or less.

(Ti: 0.050% or less)

[0041] Ti is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the Ti content is not limited, and may be 0%. Further, Ti is also an element that forms a carbide or a nitride, and has the effect of refining the microstructure, and improves the strength of the steel product. Therefore, in the present disclosure, the Ti content may be 0.001% or more. However, from the standpoint of suppressing deterioration in the toughness and weldability of the HAZ, the Ti content is 0.050% or less. The Ti content is preferably 0.040% or less, or 0.030% or less. In particular, from the standpoint of ensuring the toughness of the steel product after PWHT, the Ti content may be 0.004% or less, or 0.002% or less.

(V: 0.10% or less)

[0042] V is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the V content is not limited, and may be 0%. Further, V is also an element that forms a carbide or a nitride, and improves the strength of the steel product. Therefore, in the present disclosure, the V content may be 0.01% or more. However, from the standpoints of suppressing deterioration in the toughness and weldability of the HAZ, and suppressing an increase in the alloy cost, the V content is 0.10% or less. The V content is preferably 0.08% or less, or 0.05% or less.

[0043] In order to improve the toughness of the HAZ, as needed, the steel product relating to the present disclosure may be made to contain one or two or more of the optional elements Mg, Ca, and REM that are described hereinafter.

(Mg: 0.0200% or less)

[0044] Mg is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the Mg content is not limited, and may be 0%. Further, Mg is also an element that forms an oxide and improves the toughness of the heat affected zone. Therefore, in the present disclosure, the Mg content may be 0.0003% or more, 0.0006% or more, or 0.0010% or more. On the other hand, if the Mg content is excessive, there are cases in which the Mg forms a coarse oxide and decreases the toughness of the steel. Accordingly, from the standpoint of ensuring the toughness, in the present disclosure, the Mg content is 0.0200% or less. The Mg content is preferably 0.0100% or less, 0.0060% or less, or 0.0040% or less.

(Ca: 0.0200% or less)

[0045] Ca is an element that is sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the Ca content is not limited, and may be 0%. Further, Ca is also an element that, by spheroidizing the sulfide within the steel product, mitigates the effect of the MnS that decreases the toughness of the steel product and the heat affected zone. Therefore, in the present disclosure, the Ca content may be 0.0003% or more, 0.0006% or more, or 0.0010% or more. On the other hand, if the Ca content is excessive, there are cases in which the Ca forms a coarse oxide and decreases the toughness of the steel. Accordingly, from the standpoint of ensuring the toughness, in the present disclosure, the Ca content is 0.0200% or less. The Ca content is preferably 0.0100% or less, 0.0060% or less, or 0.0040% or less.

(REM: 0.0200% or less)

[0046] Rare earth metal (REM) is a collective term for a total of 17 elements that are the two elements of Sc and Y and fifteen lanthanoid elements such as La, Ce, Nd. The REM content means the total content of the aforementioned 17 elements. REMs are elements that are sometimes mixed into a steel product in the manufacturing process. However, the lower limit value of the REM content is not limited, and may be 0%. Further, REMs are also elements that form oxides and improve the toughness of the heat affected zone. Therefore, in the present disclosure, the REM content may be 0.0003%

or more, 0.0006% or more, or 0.0010% or more. On the other hand, if the REM content is excessive, there are cases in which the REMs form coarse oxides and decrease the toughness of the steel. Accordingly, from the standpoint of ensuring the toughness, in the present disclosure, the REM content is 0.0200% or less. The REM content is preferably 0.0100% or less, 0.0060% or less, or 0.0040% or less.

(Balance: Fe and Impurities)

[0047] The balance of the chemical composition of the steel product relating to the present disclosure is iron (Fe) and impurities. Impurities mean components that are mixed due to raw materials such as ore and scrap, and other factors, at the time of industrially manufacturing the steel product.

[0048] In addition to the limits on the contents of the respective elements, in the present disclosure, the range of value α is limited as follows.

(Value α : 5.0 or more and 16.0 or less)

[0049] Value α is computed by following formula (1).

$$\alpha = 0.50 \times \sqrt{[C]} \times (1+0.64[Si]) \times (1+4.10[Mn]) \times (1+0.27[Cu]) \times (1+0.52[Ni]) \times (1+2.33[Cr]) \times (1+3.14[Mo]) \quad (1)$$

[0050] Wherein [C], [Si], [Mn], [Cu], [Ni], [Cr] and [Mo] are the contents (mass%) of C, Si, Mn, Cu, Ni, Cr and Mo in the steel. In a case in which a given element is not contained, zero is substituted in. Note that $\sqrt{[C]}$ has the same meaning as $[C]^{1/2}$.

[0051] In the present disclosure, the range of value α is 5.0 - 16.0. This is an index expressing the hardenability of the steel product. The greater the value α , the more that lower bainite and martensite microstructures having a superior balance of strength and toughness can be formed. When α is in the appropriate range, in the microstructure of the HAZ as well, the ratio of the lower bainite and martensite microstructures having a superior balance of strength and toughness becomes high, and the HAZ toughness also can be ensured. When α is 5.0 or more, the hardenability of the base metal is ensured, and the ratio of the lower bainite and martensite having a favorable balance of strength and toughness increases, and a deterioration in toughness is suppressed. Further, in the microstructure of the HAZ as well, it is easy for the ratio of the lower bainite and martensite to increase, and the HAZ toughness also improves. On the other hand, if value α is 16.0 or less, toughness can be ensured without the strength of the steel product becoming too high. Further, when value α is 16.0 or less, the toughness after PWHT also can be ensured. Moreover, the HAZ toughness also is ensured without the HAZ becoming too hard.

[0052] Due to the aforementioned numerical value range relating to value α being satisfied, there can be provided a nickel-containing steel product for low temperatures that has excellent strength and toughness. Value α is preferably 5.5 or more, 6.0 or more, or 7.0 or more. Further, value α is preferably 15.5 or less or 15.0 or less.

<Microstructure>

[0053] The microstructure of the steel product relating to the present disclosure is described next. The microstructure of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product relating to the present disclosure contains lower bainite and martensite. Further, in addition to lower bainite, upper bainite also may be contained as bainite.

[0054] "Bainite" is a collective term for upper bainite and lower bainite. "Upper bainite" is one of or both of upper bainite that contains residual austenite or an MA phase (martensite-austenite mixed phase) between the laths, and upper bainite that contains a carbide between the laths. "Lower bainite" is lath-shaped lower bainite containing a carbide within the laths.

[0055] There are four forms of "martensite" that are lath, butterfly, lenticular and plate-shaped, but mainly lath martensite is generated in the components of the present disclosure. Lath martensite is a microstructure that is composed of packets and blocks formed from groups of laths having a specific arrangement, and in which a single austenite grain is divided into plural packets.

(Total of Area Ratios of Lower Bainite and Martensite: 15.0% or more)

[0056] Lower bainite and martensite are hard phases and increase the toughness of the steel product. From the standpoint of ensuring the toughness of the steel product, the area ratio of lower bainite and martensite at the 1/4t portion is 15.0% or more. The area ratio of lower bainite and martensite at the 1/4t portion is preferably 20.0% or more, or 30.0% or more. The total of the area ratio of the lower bainite and the area ratio of the martensite at the 1/4t portion may be 100%.

(Total of Area Ratios of Upper Bainite, Lower Bainite, and Martensite: 90.0% or more)

[0057] From the standpoint of ensuring the strength of the steel product, the total of the area ratios of upper bainite and lower bainite and martensite at the 1/4t portion is 90.0% or more. The total of the area ratios of upper bainite, lower bainite and martensite at the 1/4t portion may be 100%. Further, the upper bainite of the 1/4t portion may be 1.0% or more.

(Area Ratio of Residual Austenite: less than 1.7%)

[0058] From the standpoint of ensuring the toughness of the steel product, the area ratio of the residual austenite of the 1/4t portion is less than 1.7%. The area ratio of the residual austenite of the 1/4t portion is preferably 1.0% or less, and may be 0%. This is thought to be because, in the Ni-containing, steel plate of the present disclosure, the Ni content is lower than conventional 9% Ni steel, and therefore, even if residual austenite were to exist at -110°C, it would be unstable, and, if the steel structure were to incur plastic deformation at the crack tip, the residual austenite would change into martensite due to plasticity-induced martensitic transformation. Thus, the residual austenite at room temperature is made to be less than 1.7% as a volume ratio.

[0059] Further, the higher the Ni content, the easier it is for the volume ratio of the residual austenite to increase as well. However, an increase in the Ni content is also not preferable in that it leads to an increase in cost.

[0060] Observation of the microstructure of the steel product is carried out by using a sample in which a 1/4t portion of the steel product serves as the observed surface. Two types of samples on which (a) electrolytic polishing or (b) nital etching is carried out are prepared. Each sample of (a) and (b) is measured at three places by the following method, and the average value of the three places is used as the area ratio of the microstructure of that steel product. Note that three of each sample of (a) and (b) may be prepared, and the averages of the respective samples may be computed. Or, three places of one sample of each may be measured in a visual field, and the average of each computed.

[0061] By using an electrolytically polished sample that, after mirror finishing by mechanical polishing, is subjected to electrolytic polishing that removes the strained layers arising due to the mechanical polishing, measurement of the total of the area ratios of the upper bainite, lower bainite, martensite and residual austenite is carried out by EBSD. The measurement magnification is 200×, and measurement of a range of 400 μm × 400 μm is carried out at a pitch of 0.4 μm. The measuring is carried out in a state in which the beam diameter of the electron beam is 0.4 μm or less. The confidence index (hereinafter called "CI value") is set to 0.1 or more. The determination of ferrite, and upper bainite, lower bainite and martensite, is carried out by setting the threshold value of the Grain Average Misorientation (hereinafter called "GAM") to 0.5. Note that the GAM value is an index defined in OIM Analysis (EBSD crystal orientation analyzing software manufactured by TSL, United States). The region in which the GAM is 0.5 or less is ferrite. The region in which the GAM exceeds 0.5 is upper bainite, lower bainite, martensite or residual austenite. Because the upper bainite, lower bainite, martensite and residual austenite in the present disclosure are determined by using the GAM of EBSD as the threshold value, not only upper bainite, lower bainite, martensite and residual austenite, but also tempered upper bainite, tempered lower bainite and tempered martensite are included. Comparing the microstructures of direct quenching (DQ) and (DQT) that is carried out thereafter up to tempering (T), although dissolution of the MA and coarsening of carbide occur after tempering, the way of looking at the microstructure does not vary greatly.

[0062] Measurement of the area ratio of the upper bainite by SEM observation is carried out by using a nital etched sample. The measurement magnification is 500×, and measurement of a range of 360 μm × 480 μm is carried out. The portion, which has a clear lath structure and at which carbide and MA have formed along the lath boundary, is upper bainite. The microstructure of the region, at which the internal structure of the microstructure is relatively coarse, and the density of carbide is low and both sparse and dense, is upper bainite. An example of the results of discriminating the microstructures is shown in Fig. 1. (A) and (B) are SEM images of the same region of a steel product that is manufactured by DQT and whose value α is 9.9. In (B), the regions surrounded by the white lines are upper bainite (Bu), and the other regions are lower bainite + martensite (B_L+M). In the portions identified as upper bainite (Bu), carbides appearing white are sparsely distributed, and regions with varying density are present. On the other hand, at the portions identified as lower bainite + martensite (B_L+M), the carbides are densely and uniformly distributed. The total of the area ratios of the lower bainite, martensite and residual austenite is determined by subtracting the area ratio of the upper bainite from the total of the area ratios of the upper bainite, lower bainite, martensite and residual austenite, which were measured as described above. Moreover, the area ratio of the residual austenite is determined by the measuring method described hereinafter, and the total of the area ratios of the lower bainite and martensite is determined by subtracting the area ratio of the residual austenite from the total of the area ratios of the lower bainite, martensite and residual austenite.

(Area Ratio of Residual Austenite)

[0063] The area ratio of the residual austenite is measured by X-ray diffraction. Measurement of the area ratio of the residual austenite is carried out by using a sample at which the region, which is 1/4 of the thickness in the thickness

direction from the surface of the steel product (also called "1/4t portion" in the present specification), is the measured area. The sample is a 2-mm thick test piece, and is taken from a position that is 1/4 of the width from a width direction end portion of the steel product, and chemical polishing is carried out thereon, and the sample is used in measuring the volume ratio of the residual austenite by X-ray diffraction using an Mo tube. Quantification is carried out on the basis of the ratios of the integrated intensities of the (200), (211) diffraction peaks of the ferrite phase and the integrated intensities of the (200), (220), (311) diffraction peaks of the austenite phase, and the average values of the six combinations are employed. The integrated intensities of the diffraction peaks are determined by fitting the backgrounds on the basis of the signals before and after the peaks, and subtracting the signal differences. The volume ratio measured by the X-ray diffraction is considered to be the area ratio.

(Average Crystal Grain Diameter of 1/4t Portion of Steel Product)

[0064] In the present disclosure, the average crystal grain diameter (effective crystal grain diameter) of the 1/4t portion of the steel product is preferably 20.0 μm or less. This is because it was learned that, if the average crystal grain diameter of the 1/4t portion of the steel product is 20.0 μm or less, the toughness of the steel product tends to improve even more regardless of whether before or after PWHT. However, the average crystal grain diameter of the 1/4t portion of the steel product may exceed 20.0 μm. The smaller the average crystal grain diameter of the steel product, the more preferable, and therefore, the lower limit value thereof is not limited. Usually, the average crystal grain diameter is 10 μm or more. The effective crystal grain diameter is determined by a weighted average. Effective crystal grain diameter D_{area} that is determined by a weighted average is calculated by the following formula by using, of the crystal grain diameters that are measured in a 4 mm² region, area S_i and grain diameter d_i of the i th crystal grain detected at the time of measurement.

$$D_{\text{area}} = \sum S_i \cdot d_i / \sum S_i$$

(Aspect Ratio of Prior Austenite Crystal Grains of 1/4t Portion of Steel Product)

[0065] The form of the prior austenite crystal grains (called prior austenite grains or prior γ grains upon occasion) of the steel product of the present disclosure may be a form that is flat in the rolling direction. If the prior austenite grains of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product are made to be flat grains of an aspect ratio of 1.5 or more, an even greater improvement in the toughness of the steel product is possible. This is because, by increasing the grain boundary area by making the prior austenite grains flat, there is a substantial refining of the austenite grains, and this is effective in refining the effective crystal grain diameter. The aspect ratio of prior austenite grains is usually 4.0 or less, and may be 3.5 or less.

[0066] On the other hand, from the standpoint of ensuring the homogeneity of the microstructure, the aspect ratio of the prior austenite crystal grains of the 1/4t portion may be less than 1.5. The aspect ratio of the prior austenite crystal grains of the 1/4t portion may be 1.4 or less, or 1.3 or less.

[0067] The aspect ratio of the prior austenite crystal grains (hereinafter called prior austenite grains upon occasion) of the steel product is determined as follows. An L cross-section (a cross-section parallel to the rolling direction and the thickness direction of the steel product) of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product is mirror polished, and corrosion is carried out by a corrosive liquid of a saturated solution base of 2 - 4% picric acid, and the prior austenite grain boundaries of an arbitrary region of 1.0 mm in the rolling direction $\times$ 0.5 mm in the thickness direction are made to appear.

[0068] Next, the long diameters and short diameters of the individual prior austenite grains are measured, and the aspect ratio of each prior austenite grain is calculated by long diameter $\div$ short diameter. The arithmetic mean of the calculated aspect ratios of all of the prior austenite grains is determined as the "aspect ratio of the prior austenite grains". Note that the maximum length of the prior austenite grain is used as the long diameter, and the maximum interval between two lines, which contact the grain and are parallel to the long diameter direction, is used as the short diameter.

<Mechanical Properties>

[0069] The steel product relating to the present disclosure has mechanical properties that are such that the steel product has both strength and low-temperature toughness. In addition to having excellent toughness at -110°C in particular, the steel product can exhibit excellent low-temperature toughness after PWHT as well.

(Tensile Strength: 615 MPa or more and 930 MPa or less)

[0070] In the present disclosure, the tensile strength of the steel product is 615 - 930 MPa. In order to reduce the weight of

large welded structures such as transport tanks, a steel product that can ensure strength of a structure even if the thickness is thin is necessary. Because steel products that are selected as steel products to be used in such applications usually are steel products having the aforementioned tensile strength, the steel product relating to the present disclosure also is manufactured to have the aforementioned tensile strength.

(Yield Ratio)

[0071] The yield ratio ($YR = [\text{yield strength}] / [\text{tensile strength}] \times 100$) of the steel product relating to the present disclosure is not particularly limited and is preferably 90% or less. In a case in which there is no yield point, the yield strength is determined by using 0.2% proof stress.

(Charpy Impact Absorption Energy at -110°C)

[0072] In order to ensure high toughness at low temperatures, the Charpy impact absorption energy at -110°C of the steel product of the present disclosure is preferably 150 J or more. Due to the steel product of the present disclosure having low-temperature toughness of a Charpy impact absorption energy at -110°C of 150 J or more, a transport tank formed from the steel product of the present disclosure can be suitably used for transporting liquid carbon dioxide for example. The steel product of the present disclosure may have low-temperature toughness of a Charpy impact absorption energy at -110°C of 100 J or more. Note that the Charpy impact absorption energy at -110°C is a numerical value measured by using a sample taken from a position of 1/4 of the thickness.

(Charpy Absorption Energy at -110°C after PWHT)

[0073] There are cases in which PWHT is carried out on the welded portions of cryogenic tanks after being assembled into transport tanks, in order to prevent breakage in advance. At this time, not only the welded portions, but also the base metal portion (also simply called base metal) of the steel product that is not affected by welding are heated. If the time over which the base metal is heated in the temperature range of 425°C or more is long, the toughness of the base metal tends to decrease. In the steel product of the present disclosure, in a case in which PWHT, in which the holding temperature is 600°C, and the holding time is 2 hours, and the rate of temperature increase and the rate of temperature decrease are 55°C/h in the temperature region of 425°C or more, is carried out on the steel product, with regard to the toughness of the portion where the PWHT has been carried out, the Charpy impact absorption energy at -110°C is preferably 150 J or more. The Charpy impact absorption energy at -110°C after PWHT may be 100 J or more. The Charpy impact absorption energy at -110°C after PWHT also is a numerical value measured by using a sample taken from a position of 1/4 of the thickness.

[0074] Note that there are cases in which the toughness of the steel product decreases due to PWHT. Although the reason for this is not clear, it is assumed that P (phosphorus) and Mn diffuse at the grain boundaries, and growth or aggregation of inclusions arises within the microstructure, and due thereto, the brittleness decreases and the toughness decreases. A decrease in the toughness due to PWHT is suppressed by limiting the contents of P and Mn and making the average crystal grain diameter of the steel product small.

(Charpy Impact Absorption Energy at -110°C after Thermal Cycling)

[0075] In the steel product of the present disclosure, in order to ensure high toughness after a thermal cycling test that simulates the welded portions at a low temperature, the Charpy impact absorption energy at -110°C after thermal cycling is preferably 50 J or more. Due to the steel product of the present disclosure having low-temperature toughness that is such that the Charpy impact absorption energy at -110°C after thermal cycling is 50 J or more, a transport tank formed from the steel product of the present disclosure can be suitably used for transporting liquid carbon dioxide for example. The Charpy impact absorption energy at -110°C after thermal cycling may be 40 J or more. Note that the Charpy impact absorption energy at -110°C after thermal cycling is a numerical value measured by using a sample taken from a position of 1/4 of the thickness of the steel product as a thermal cycling test piece, and providing it with a thermal history of raising the temperature at 60°C/s to 1350°C, and, after maintenance at 1350°C for 1 s, cooling at 20°C/s to room temperature, and thereafter, taking a Charpy test piece therefrom.

(Charpy Impact Absorption Energy at -110°C after Thermal Cycling and PWHT)

[0076] There are cases in which PWHT is carried out on the welded portions of cryogenic tanks after being assembled into transport tanks, in order to prevent breakage in advance. After the above-described thermal cycling test, PWHT, in which the rate of temperature increase and the rate of temperature decrease are 55°C/h in the temperature region of 425°C or more, and the steel product is held for 2 hours at 600°C, is carried out on the steel product of the present disclosure, and

thereafter, a Charpy test piece is taken, and measurement is carried out. In this case, with regard to the toughness of the portion where the PWHT has been carried out, the Charpy impact absorption energy at -110°C is preferably 50 J or more. The Charpy impact absorption energy at -110°C of the portion at which PWHT is carried out after the above-described thermal cycling test may be 40 J or more.

[0077] Note that there are cases in which the toughness of the steel product decreases due to PWHT. Although the reason for this is not clear, it is assumed that P (phosphorus) and Mn diffuse at the grain boundaries, and growth or aggregation of inclusions arises within the microstructure, and due thereto, the brittleness decreases and the toughness decreases. A decrease in the toughness due to PWHT is suppressed by limiting the contents of P and Mn and making the average crystal grain diameter of the steel product small.

[0078] The tensile strength (TS) and the yield strength (YS) are measured in accordance with a tensile test that is based on JIS Z2241:2011. The tensile test uses a JIS14A test piece that has been taken from a position of 1/4 of the thickness and whose length direction is the direction (the C direction) parallel to the width direction of the steel product. TS and YS are computed by using three test pieces and taking the averages thereof. The yield ratio (YR, %) is computed by $(YS/TS) \times 100$, on the basis of the respective average values of TS and YS.

[0079] The Charpy impact absorption energy is measured by a Charpy impact test at -110°C on the basis of the prescriptions of JIS Z2242:2018 and by using an impact blade of a radius of 2 mm. The Charpy impact absorption energy is calculated by measuring by using three test pieces, and taking the average thereof. The Charpy impact absorption energy test uses a V-notched test piece that has been taken from a position of 1/4 of the thickness of the steel product and whose length direction is the direction (the C direction) parallel to the width direction of the steel product.

[0080] The form of the steel product relating to the present disclosure is not particularly limited, and examples are steel plates, steel strips, structural steel and steel pipes. However, steel pipes and structural steel include steel products in which steel plates are joined, e.g., in addition to welded steel pipes and welded structural steel, structural steel joined by rivets, and the like. The thickness of the steel product such as steel plates, steel strips, structural steel and steel pipes (the thickness of the flanges in the case of structural steel) is not particularly limited, and usually is 3 mm or more and 150 mm or less. The thickness of the steel product may be 6 mm or more, 10 mm or more, 15 mm or more, or 30 mm or more. Further, the thickness of the steel product may be 100 mm or less, 80 mm or less, or 60 mm or less.

[0081] Further, although the application of the steel product relating to the present disclosure also is not particularly limited, the steel product relating to the present disclosure has mechanical properties such that the steel product has both strength and low-temperature toughness, and, in particular, can exhibit excellent low-temperature toughness even after PWHT. Therefore, the steel product relating to the present disclosure can be suitably used as a tank that stores and transports liquefied gasses, and liquid carbon dioxide in particular.

(Method of Manufacturing Steel Product)

[0082] The method of manufacturing the steel product relating to the present disclosure is not particularly limited, but, for example, after melting a steel that satisfies the above-described chemical composition, a steel slab is manufactured by continuous casting. The steel slab is subjected to either direct quenching (DQ), in which it is heated, hot rolled, and then directly water-cooled, or reheat quenching (RQ), in which it is hot rolled, air-cooled, reheated, and then water-cooled, to made into a steel product. Note that, in the case of RQ, the hot rolled steel does not necessarily have to be air-cooled before reheating, but water cooling may be used. Moreover, tempering (T) may also be carried out.

(1) DQT: direct quenching (DQ) and tempering (T)

(2) RQT: air cooling or water cooling, reheat quenching (RQ), and tempering (T)

(1) DQT

[0083] From the standpoint of the manufacturing cost, DQT is preferable in the manufacturing of the steel product relating to the present disclosure. An example of a preferable manufacturing process is given hereinafter.

[0084] In the case of manufacturing the steel product relating to the present disclosure by DQ, from the standpoint of carrying out hot rolling in a temperature range in which the microstructure of the rolled steel is austenite, the heating temperature of the steel slab on which the hot rolling is carried out is A_{c3} or more. From the standpoint of decreasing the deformation resistance, the heating temperature of the steel slab is preferably 1000°C or more. On the other hand, from the standpoint of suppressing coarsening of the heated γ grains, the heating temperature of the hot rolling is 1250°C or less. The heating temperature of the hot rolling is preferably 1200°C or less. Note that A_{c3} is a value computed by the following formula.

$Ac_3 = 937.2 - 436.5C + 56Si - 19.7Mn - 16.3Cu - 26.6Ni - 4.9Cr + 38.1Mo + 124.8V + 136.3Ti - 19.1Nb + 198.4Al + 3315B$

[0085] The element symbols in the formula mean the content (mass%) of each element contained in the steel slab.

[0086] There are cases in which the hot rolling is structured by rolling in a temperature range in which recrystallization occurs (rolling in the recrystallization temperature range) and rolling in a temperature range in which recrystallization is suppressed (rolling in the non-recrystallization temperature range).

[0087] Rolling in the recrystallization temperature range is hot rolling carried out with the temperature of the rolled steel during rolling being 900°C or more. From the standpoint of refining the austenite grain diameter of the steel product, the cumulative rolling reduction ratio of the rolling in the recrystallization temperature range is preferably 20% or more, and more preferably 30% or more. The cumulative rolling reduction ratio of the rolling in the recrystallization temperature range is determined from the difference between the thickness of the steel slab before hot rolling and the thickness of the rolled steel at 900°C.

Cumulative rolling reduction ratio (%) of rolling in recrystallization temperature range = $100 \times ([\text{thickness of steel slab}] - [\text{thickness of rolled steel at 900°C}]) / [\text{thickness of steel slab}]$

[0088] Rolling in the non-recrystallization temperature range is hot rolling carried out with the temperature of the rolled steel during rolling being less than 900°C. From the standpoint of refining the average crystal grain diameter of the steel product, the cumulative rolling reduction ratio of the rolling in the non-recrystallization temperature range is preferably 20% or more, and more preferably 30% or more. The cumulative rolling reduction ratio of the rolling in the non-recrystallization temperature range is determined from the difference between the thickness of the rolled steel at 900°C and the thickness of the steel product after rolling ends.

Cumulative rolling reduction ratio (%) of rolling in non-recrystallization temperature range = $100 \times ([\text{thickness of rolled steel at 900°C}] - [\text{thickness of steel product after rolling ends}]) / [\text{thickness of rolled steel at 900°C}]$

[0089] From the standpoint of suppressing the generation of ferrite that decreases strength, the end temperature of the hot rolling is Ar_3 or more. After hot rolling ends, accelerated cooling such as water cooling is carried out on the steel product. From the standpoint of suppressing the generation of ferrite that decreases strength, the start temperature of the accelerated cooling is Ar_3 or more. Note that Ar_3 is a value computed by the following formula.

$$Ar_3 = 910 - 310C - 80Mn - 20Cu - 15Cr - 55Ni - 80Mo + 0.35(t-8)$$

[0090] The element symbols in the formula mean the content (mass%) of each element contained in the steel product, and t means the thickness (mm) of the steel product.

[0091] From the standpoint of promoting bainitic transformation and martensitic transformation, the cooling rate is 1.0°C/s or more. The cooling rate of the accelerated cooling is preferably 5.0°C/s or more, or 10.0°C/s or more. The faster the cooling rate of the accelerated cooling, the more preferable, but from standpoints such as cost and homogeneity of the accelerated cooling, the cooling rate is preferably 50.0°C/s or less, or 30.0°C/s or less. The cooling rate is a value obtained by calculating the cooling rate at a position of 1/4 of the thickness by simulation in accordance with thermal transfer calculation.

[0092] From the standpoint of improving the strength of the steel product by ensuring the upper bainite, lower bainite and martensite, the stoppage temperature of the accelerated cooling is 400°C or less. The stoppage temperature of the accelerated cooling is preferably 350°C or less. Accelerated cooling may be carried out to room temperature. From the standpoint of dehydrogenation of the steel product, the stoppage temperature is preferably 100°C or more.

[0093] After accelerated cooling, a tempering treatment may be carried out on the steel product. From the standpoint of suppressing a decrease in strength, the heating temperature of the tempering treatment is preferably 650°C or less, 620°C or less, or 590°C or less. On the other hand, from the standpoint of improving the toughness, the heating temperature of the tempering treatment is preferably 350°C or more, or 400°C or more.

(2) RQT

[0094] In a case in which the steel product relating to the present disclosure is manufactured by RQ, the effects of the heating temperature and the rolling reduction ratio of the steel slab at the time of the hot rolling on the mechanical properties of the steel product are small. However, if the heating temperature of the steel slab is too low, the deformation

resistance increases, and therefore, the heating temperature of the steel slab is preferably 1000°C or more. Further, if the rolling reduction ratio is insufficient, there are cases in which initial stage defects from the time of manufacturing the steel slab remain at the thickness central portion, and the quality of the steel product decreases. Therefore, the total of the rolling reduction ratios of hot rolling (also called cumulative rolling reduction ratio) is preferably 35% or more. After the hot rolling, the steel slab may, as is, be water-cooled or air-cooled.

[0095] After the hot rolling, reheat quenching is carried out on the steel product. The reheating temperature of the steel product is A_{c3} or more, because quenching is carried out from an austenite single-phase microstructure. From the standpoint of ensuring the homogeneity of the microstructure, the reheating temperature of the steel product is preferably 750°C or more, 850°C or more, 880°C or more, or 900°C or more. On the other hand, although the upper limit temperature of the reheating temperature is not particularly stipulated, there are cases in which excessive heating to a high temperature leads to coarsening of the austenite grains and a decrease in toughness, and therefore, the upper limit temperature of the reheating temperature is preferably 1000°C or less, 950°C or less, or 930°C or less.

[0096] After the reheat quenching, a tempering treatment may be carried out on the steel product. From the standpoint of suppressing a decrease in strength, the heating temperature of the tempering treatment is preferably 660°C or less, or 640°C or less. On the other hand, from the standpoint of improving the toughness, the heating temperature of the tempering treatment is preferably 400°C or more, 450°C or more, or 500°C or more.

EXAMPLES

[0097] The steel product relating to the present disclosure is described concretely hereinafter by way of Examples. However, the conditions in the following Examples are examples of conditions that are employed in order to confirm the feasibility and the effects of the present disclosure, and the present disclosure is not limited to the following Examples.

<Manufacturing by Direct Quenching and Tempering>

[Manufacturing of Steel Product]

[0098] First, slabs having the chemical compositions shown in Table 1 were cast by continuous casting. The balance, which is other than the components listed in Table 1, is Fe and impurities. Further, blank cells mean that the alloy elements were not intentionally added in the steelmaking process. The underlines mean that the value is outside of the scope of the present disclosure.

[Table 1]

No.	chemical composition (mass%)																			
	C	Si	Mn	P	S	Ni	Al	N	O	Ti	Nb	Mg	Ca	REM	Cu	Cr	Mo	V	B	α
2A	0.14	0.14	1.81	0.011	0.0060	5.95	0.033	0.0019	0.0022											7.0
3A	0.14	0.18	1.45	0.012	0.0071	5.52	0.030	0.0021	0.0024	0.004	0.004							0.06		5.6
4A	0.11	0.19	1.47	0.004	0.0041	5.73	0.005	0.0018	0.0025	0.002			0.0013					0.04		5.2
6A	0.06	0.13	0.66	0.006	0.0029	5.88	0.036	0.0073	0.0018	0.001	0.003				0.56	0.42	0.15			6.7
7A	0.06	0.18	1.07	0.006	0.0024	5.62	0.029	0.0021	0.0015							0.22	0.18		0.0003	6.8
8A	0.15	0.26	1.20	0.008	0.0021	5.88	0.026	0.0027	0.0019			0.0023			0.20		0.11			7.7
9A	0.17	0.22	1.40	0.007	0.0027	5.90	0.020	0.0030	0.0022						0.15		0.05			7.8
10A	0.08	0.13	0.62	0.005	0.0015	5.52	0.029	0.0019	0.0036						0.47	0.20	0.51		0.0005	9.0
11A	0.12	0.15	0.80	0.005	0.0026	5.27	0.034	0.0071	0.0041				0.0014	0.0011	0.60	0.76				9.8
12A	0.10	0.12	0.75	0.006	0.0019	5.71	0.055	0.0039	0.0022	0.002		0.0014				0.32	0.43	0.02		11.3
13A	0.07	0.17	0.73	0.006	0.0032	5.44	0.046	0.0043	0.0028		0.002					0.54	0.46			12.4
14A	0.08	0.13	0.98	0.011	0.0116	5.21	0.056	0.0021	0.0015						0.65	0.43	0.25			12.0
15A	0.06	0.17	0.73	0.009	0.0032	5.44	0.046	0.0043	0.0028	0.002					0.33	0.43	0.52	0.02		11.9
16A	0.05	0.13	1.15	0.008	0.0075	5.35	0.034	0.0025	0.0019		0.002		0.0010		0.44	0.39	0.33			11.4
17A	0.11	0.12	1.28	0.007	0.0053	5.83	0.006	0.0063	0.0019						0.40	0.43	0.10			13.1
19A	0.07	0.06	1.31	0.009	0.0044	5.11	0.038	0.0038	0.0027		0.003			0.0012			1.03			13.6
20A	0.09	0.11	0.85	0.010	0.0065	5.33	0.029	0.0031	0.0015						0.43	0.71	0.22			13.6
21A	0.11	0.07	1.26	0.007	0.0038	5.30	0.035	0.0035	0.0022	0.003						0.44	0.22			13.7
22A	0.08	0.13	0.80	0.006	0.0056	5.12	0.025	0.0028	0.0017		0.002	0.0013			0.43	0.71	0.35			14.9
24A	0.14	0.14	1.69	0.013	0.0064	5.85	0.029	0.0020	0.0019		0.003									6.5
25A	0.05	0.05	0.33	0.008	0.0018	5.80	0.006	0.0028	0.0021							1.63			0.0011	5.2
26A	0.10	0.19	1.12	0.014	0.0008	5.44	0.029	0.0048	0.0029	0.002	0.003	0.0020	0.0014				0.74			12.6
28A	0.15	0.07	1.80	0.012	0.0019	5.25	0.074	0.0034	0.0023						0.15	0.23	0.25			18.0
30A	0.06	0.13	1.45	0.007	0.0051	6.34	0.025	0.0028	0.0017		0.002	0.0010			0.43	0.71	0.35			24.6
31A	0.05	0.12	2.43	0.013	0.0009	5.30	0.028	0.0023	0.0019						0.10	0.15	0.27			12.7

(continued)

No.	chemical composition (mass%)																			
	C	Si	Mn	P	S	Ni	Al	N	O	Ti	Nb	Mg	Ca	REM	Cu	Cr	Mo	V	B	α
32A	0.10	0.13	0.87	0.008	0.0022	4.98	0.022	0.0031	0.0033					0.0012	0.22	0.42	0.29	0.02		11.2
101A	0.08	0.05	1.32	0.014	0.0036	4.78	0.004	0.0021	0.0033	0.011					0.20		0.28	0.03		6.5
102A	0.14	0.08	1.41	0.008	0.0041	5.45	0.032	0.0018	0.0024											5.1
103A	0.11	0.15	1.50	0.009	0.0053	5.11	0.034	0.0032	0.0019	0.008	0.023	0.0061					0.23			8.2
104A	0.08	0.09	1.34	0.007	0.0022	4.91	0.027	0.0024	0.0018				0.0046		0.40	0.36	0.25			12.6
105A	0.09	0.07	1.22	0.005	0.0037	5.47	0.032	0.0031	0.0036	0.014					0.23	0.23	0.31			11.6
106A	0.11	0.05	0.95	0.006	0.0018	5.87	0.025	0.0039	0.0027					0.0044	0.45	0.17	0.42		0.0010	12.3
107A	0.10	0.15	0.89	0.007	0.0023	5.05	0.031	0.0041	0.0025						0.28	0.33	0.46			13.6
108A	0.08	0.11	1.17	0.008	0.0016	5.35	0.028	0.0024	0.0034	0.009					0.35	0.46	0.34			15.6
109A	0.09	0.07	1.34	0.004	0.0034	5.81	0.025	0.0019	0.0018		0.030				0.44	0.21	0.37			14.7
110A	0.11	0.17	1.32	0.011	0.0034	5.74	0.026	0.0027	0.0027		0.003					0.32				8.2
111A	0.08	0.17	1.50	0.006	0.0044	5.30	0.031	0.0032	0.0022			0.0005					0.37			9.1
112A	0.07	0.08	1.22	0.007	0.0026	4.99	0.028	0.0024	0.0017				0.0005		0.35	0.30	0.24			9.8
113A	0.12	0.05	0.98	0.005	0.0015	5.77	0.033	0.0039	0.0025					0.0005	0.40	0.10	0.36			10.4
114A	0.08	0.13	1.05	0.012	0.0036	5.21	0.033	0.0026	0.0018								0.03			3.3
115A	0.07	0.15	1.24	0.009	0.0028	5.46	0.029	0.0021	0.0022							0.04				3.7
116A	0.12	0.09	1.73	0.011	0.0025	5.67	0.032	0.0028	0.0028						0.13	0.25	0.26			17.4
117A	0.17	0.12	1.89	0.014	0.0028	5.43	0.034	0.0031	0.0022						0.17	0.23	0.17			18.3
118A	0.08	0.11	1.32	0.006	0.0051	5.12	0.033	0.0025	0.0026		0.004					0.19				5.1

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[0099] Next, steel products were manufactured from these slabs under the manufacturing conditions listed in Table 2. "Temper heat treatment" is the heating temperature in the tempering treatment after the quenching.

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[Table 2]

No.	plate thickness (mm)	Ac ₃ [°C]	hot rolling conditions				cooling after rolling	Ar ₃ [°C]	direct quenching (accelerated cooling) conditions			Temper heat treatment [°C]
			heating temperature [°C]	cumulative rolling reduction [%] ratio at 900°C or more	cumulative rolling reduction ratio [%] at less than 900°C	end temperature [°C]			start temperature [°C]	stoppage temperature [°C]	cooling rate [°C/s]	
2A	35	697	1230	23	60	820	water cooling	404	800	180	9.5	510
3A	25	725	1150	30	50	810	water cooling	453	800	160	5.3	540
4A	15	725	1150	31	59	790	water cooling	446	770	150	5.7	640
6A	35	751	1130	31	45	770	water cooling	495	750	270	12.2	610
7A	60	763	1170	32	30	780	water cooling	497	760	290	2.9	600
8A	40	712	1200	19	65	810	water cooling	443	790	250	3.1	610
9A	20	694	1100	22	43	775	water cooling	418	750	220	4.1	590
10A	35	769	1240	34	44	750	water cooling	488	720	115	3.3	580
11A	20	731	1150	38	45	730	water cooling	500	715	320	4.2	510
12A	50	762	1020	39	33	820	water cooling	480	800	360	2.7	570
13A	55	781	1080	42	31	770	water cooling	502	745	220	10.7	610
14A	60	760	1070	37	38	740	water cooling	499	710	240	3.7	620

(continued)

No.	plate thickness (mm)	Ac ₃ [°C]	hot rolling conditions				cooling after rolling	Ar ₃ [°C]	direct quenching (accelerated cooling) conditions			Temper heat treatment [°C]
			heating temperature [°C]	cumulative rolling reduction [%] ratio at 900°C or more	cumulative rolling reduction ratio [%] at less than 900°C	end temperature [°C]			start temperature [°C]	stoppage temperature [°C]	cooling rate [°C/s]	
15A	40	786	1200	25	45	740	water cooling	490	722	320	4.5	605
16A	55	768	1100	44	37	760	water cooling	484	748	180	6.3	560
17A	50	712	1160	32	29	820	water cooling	445	800	210	4.2	530
19A	55	795	1080	33	38	760	water cooling	437	725	290	5.4	560
20A	50	749	1100	36	31	840	water cooling	499	815	105	2.2	480
21A	35	741	1200	38	50	800	water cooling	469	784	243	2.9	490
22A	40	765	1100	30	40	790	water cooling	504	779	219	3.6	590
24A	57	701	1200	35	13	780	water cooling	427	756	320	5.4	490
25A	55	754	1130	12	35	790	water cooling	541	778	290	7.8	460
26A	60	772	1200	32	11	740	water cooling	449	730	240	4.6	560
28A	55	721	1120	33	36	720	water cooling	421	700	270	4.3	550
30A	40	729	1150	35	38	750	water cooling	391	730	220	7.4	560

(continued)

No.	plate thickness (mm)	Ac ₃ [°C]	hot rolling conditions				cooling after rolling	Ar ₃ [°C]	direct quenching (accelerated cooling) conditions			Temper heat treatment [°C]
			heating temperature [°C]	cumulative rolling reduction [%] ratio at 900°C or more	cumulative rolling reduction ratio [%] at less than 900°C	end temperature [°C]			start temperature [°C]	stoppage temperature [°C]	cooling rate [°C/s]	
31A	61	747	1200	32	41	780	water cooling	401	753	227	4.1	550
32A	50	763	1100	28	29	840	water cooling	516	820	105	0.5	490
101A	50	765	1150	58	60	810	water cooling	505	790	310	12.5	510
102A	40	714	1200	60	60	820	water cooling	465	800	283	13.1	460
103A	70	748	1100	50	53	790	water cooling	478	778	216	7.9	610
104A	53	757	1170	60	56	780	water cooling	490	764	189	15.2	550
105A	45	747	1150	55	58	790	water cooling	464	768	223	10.5	420
106A	40	733	1200	58	67	810	water cooling	443	792	196	6.9	580
107A	50	768	1100	49	59	770	water cooling	497	746	143	7.9	480
108A	55	755	1070	60	54	790	water cooling	473	774	178	15.7	500
109A	48	731	1200	56	63	800	water cooling	428	769	221	18.3	530
110A	57	724	1200	12	56	810	water cooling	467	788	343	14.2	470

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(continued)

No.	plate thickness (mm)	Ac ₃ [°C]	hot rolling conditions				cooling after rolling	Ar ₃ [°C]	direct quenching (accelerated cooling) conditions			Temper heat treatment [°C]
			heating temperature [°C]	cumulative rolling reduction [%] ratio at 900°C or more	cumulative rolling reduction ratio [%] at less than 900°C	end temperature [°C]			start temperature [°C]	stoppage temperature [°C]	cooling rate [°C/s]	
111A	55	762	1200	55	58	810	water cooling	461	793	230	10.2	530
112A	45	762	1100	55	61	820	water cooling	499	806	312	12.5	420
113A	65	728	1150	52	55	790	water cooling	459	776	187	6.8	620
114A	40	758	1200	43	40	780	water cooling	523	765	253	12.1	580
115A	50	751	1100	37	45	790	water cooling	503	778	344	10.9	470
116A	55	718	1150	60	50	810	water cooling	412	722	293	8.4	580
117A	60	697	1050	50	40	800	water cooling	405	740	365	9.8	560
118A	40	752	1100	39	45	780	water cooling	506	430	341	9.8	520

[Measurement and Evaluation]

[0100] The microstructures and mechanical properties of the obtained steel products were measured by the above-described methods. The results are shown in Table 3. The meanings of the symbols of the microstructures are as follows. Note that the remainders of the microstructures were pearlite, MA phase, and ferrite.

Bu: upper bainite

BL: lower bainite

M: martensite

residual γ : residual austenite

[0101] For the toughness, the average value of the Charpy impact absorption energy at -110°C , and the average value of the Charpy impact absorption energy at -110°C after PWHT in which the holding temperature was 600°C , the holding time was 2 hours, and the rate of temperature increase and the rate of temperature decrease in the temperature region of 425°C or more were 55°C/h , respectively were measured.

[Table 3]

No.	microstructure (area ratio)			aspect ratio average value of prior γ grains	average crystal grain diameter [μm]	YS [MPa]	TS [MPa]	YR [%]	base metal toughness KV2[J]	toughness after PWHT KV2[J]	thermal cycling toughness KV2[J]	toughness after thermal cycling and PWHT KV2 [J]	notes
	BL+M [%]	Bu+BL+M [%]	residual γ [%]										
2A	27.4	92.3	0.1	2.9	22.6	564	643	88	189	151			examples of present invention
3A	22.4	92.6	0.0	2.8	17.1	534	623	86	239	196			
4A	22.8	94.1	0.1	2.6	16.7	510	624	82	239	221			
6A	35.1	92.4	0.2	3.1	17.4	568	653	87	243	225			
7A	35.7	92.8	0.3	3.3	15.6	563	661	85	312	319			
8A	33.1	92.1	0.2	3.0	23.9	582	672	87	189	188			
9A	38.4	94.3	0.2	3.2	21.6	576	678	85	179	180			
10A	50.8	94.3	0.5	2.8	13.3	615	729	84	288	285			
11A	55.1	95.2	0.4	2.7	14.8	631	765	82	282	280			
12A	65.9	93.4	0.7	3.2	12.4	659	774	85	285	268			
13A	68.3	96.1	0.4	3.4	11.3	661	759	87	312	297			
14A	65.4	93.9	0.5	3.2	16.5	668	752	89	228	222			
15A	64.2	95.8	0.4	3.1	15.3	665	765	87	242	221			
16A	61.9	95.1	0.3	3.0	17.1	658	748	88	229	211			
17A	91.7	96.0	0.6	3.1	17.4	723	834	87	242	239			
19A	98.1	98.1	0.7	3.0	17.9	715	834	86	252	234			
20A	93.2	96.3	0.8	2.9	18.3	780	910	86	210	208			
21A	94.4	98.1	0.5	2.8	15.6	723	845	86	242	221			
22A	92.5	96.8	0.7	2.7	14.3	754	866	87	253	234			
24A	81.9	91.2	0.4	1.5	27.4	534	645	83	143	101			
25A	46.3	93.0	0.3	3.2	28.7	534	673	79	140	138			
26A	82.1	91.2	0.4	1.5	27.5	664	787	84	146	107			

(continued)

No.	microstructure (area ratio)			aspect ratio average value of prior γ grains	average crystal grain diameter [μm]	YS [MPa]	TS [MPa]	YR [%]	base metal toughness KV2[J]	toughness after PWHT KV2[J]	thermal cycling toughness KV2[J]	toughness after thermal cycling and PWHT KV2 [J]	notes
	BL+M [%]	Bu+BL+M [%]	residual γ [%]										
28A	96.4	98.1	1.5	2.6	16.3	881	991	89	156	121			comparative example
30A	95.4	97.1	1.9	2.9	17.8	912	1049	87	112	98			
31A	89.1	93.4	0.3	2.8	18.3	743	865	86	156	34			
32A	9.3	91.3	0.1	2.7	17.6	520	654	80	31	25			examples of present invention
101A	33.2	92.9	0.3	3.3	16.2	571	662	86	248	210	138	126	
102A	23.9	93.8	0.2	3.4	16.1	583	657	89	238	231	135	133	
103A	40.3	92.2	0.3	3.2	16.6	569	671	85	228	196	142	122	
104A	62.1	96.1	0.5	3.6	13.8	663	753	88	286	279	173	171	
105A	65.4	95.4	0.4	3.2	13.4	671	759	88	276	245	188	171	
106A	63.7	97.2	0.6	3.4	12.2	669	770	87	271	268	179	176	
107A	92.2	96.9	1.1	3.0	15.8	753	852	88	249	243	164	167	
108A	98.3	98.3	0.9	3.4	14.8	746	864	86	253	228	157	138	
109A	95.4	98.2	0.8	3.3	15.1	751	870	86	244	216	161	145	
110A	39.1	93.1	0.4	2.7	27.1	585	673	87	133	105	145	128	comparative example
111A	53.4	94.0	0.5	2.8	13.2	618	734	84	288	285	177	175	
112A	56.8	95.2	0.4	2.7	12.2	632	764	83	282	280	183	182	
113A	63.2	95.1	0.5	2.8	12.0	639	770	83	288	285	189	188	
114A	17.1	76.2	0.2	2.9	38.5	515	588	88	80	75	45	42	
115A	18.4	77.4	0.2	3.0	37.9	516	590	87	77	74	42	43	
116A	97.2	97.9	1.2	2.8	16.1	878	982	89	142	138	39	33	
117A	96.3	98.2	1.1	2.7	15.8	880	988	89	138	135	36	32	
118A	22.4	68.1	0.3	2.8	15.8	412	523	79	148	133	116	103	

[0102] Nos. 2A - 26A, 101A - 113A are Examples of the present invention, and Nos. 28A - 32A, 114A - 118A are Comparative Examples.

[0103] In No. 28A, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive.

[0104] In No. 30A, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive. Because there was also too much residual γ , sufficient low-temperature toughness was not obtained.

[0105] In No. 31A, because Mn fell outside of the upper limit, the low-temperature toughness after PWHT was low.

[0106] In No. 32A, because the cooling rate of the direct quenching was low, the total area ratio of the lower bainite and martensite was insufficient, and sufficient low-temperature toughness was not obtained.

[0107] In Nos. 114A and 115A, value α was less than the lower limit value of the present disclosure, and the hardenability was insufficient, and the strength was insufficient. Sufficient low-temperature toughness also was not obtained.

[0108] In Nos. 116A and 117A, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive.

[0109] In No. 118A, the start temperature of the direct quenching was too low, and the total area ratio of the upper bainite, lower bainite and martensite was insufficient, and the strength was insufficient.

[0110] In contrast to the Comparative Examples, in the Examples of the present invention, the chemical compositions and microstructures of the steel products were controlled appropriately, and the tensile strengths were in the appropriate range of 615 MPa or more and 930 MPa or less. In addition, low-temperature toughness at -110°C of 100 J or more was obtained regardless of whether before or after PWHT.

<Manufacturing by Reheat Quenching and Tempering>

[Manufacturing of Steel Product]

[0111] First, slabs having the chemical compositions shown in Table 4 were cast by continuous casting. The balance, which is other than the components listed in Table 4, is Fe and impurities. Further, blank cells mean that the alloy elements were not intentionally added in the steelmaking process. The underlines mean that the value is outside of the scope of the present disclosure.

[Table 4]

No.	chemical composition (mass%)																			
	C	Si	Mn	P	S	Ni	Al	N	O	Ti	Nb	Mg	Ca	REM	Cu	Cr	Mo	V	B	α
2B	0.13	0.13	1.86	0.010	0.0057	5.99	0.034	0.0022	0.0024											6.9
4B	0.12	0.21	1.50	0.006	0.0046	5.84	0.004	0.0015	0.0078	0.003			0.0071					0.03		5.7
6B	0.05	0.11	0.72	0.005	0.0035	5.76	0.035	0.0071	0.0017	0.002	0.004				0.49	0.44	0.12			6.0
7B	0.07	0.20	1.21	0.007	0.0019	5.69	0.028	0.0026	0.0014							0.21	0.21		0.0015	8.7
8B	0.14	0.22	1.18	0.007	0.0028	5.73	0.022	0.0031	0.0018			0.0013			0.23		0.15			7.7
9B	0.18	0.24	1.37	0.005	0.0031	5.98	0.026	0.0027	0.0025						0.17		0.08			8.7
10B	0.07	0.11	0.55	0.006	0.0022	5.31	0.022	0.0018	0.0031						0.51	0.26	0.46		0.0004	7.7
11B	0.14	0.14	0.76	0.008	0.0029	5.44	0.038	0.0074	0.0044				0.0012	0.0021	0.64	0.70				9.9
14B	0.07	0.15	0.92	0.010	0.0122	5.38	0.052	0.0024	0.0017						1.23	0.38	0.27			12.2
15B	0.05	0.14	0.79	0.008	0.0040	5.23	0.039	0.0047	0.0025	0.003					0.29	0.45	0.55	0.03		11.6
16B	0.06	0.16	1.03	0.009	0.0081	5.48	0.031	0.0021	0.0022		0.001		0.0013		0.48	0.36	0.31			11.1
17B	0.11	0.11	1.33	0.006	0.0062	5.89	0.008	0.0066	0.0016						0.39	0.41	0.13			14.2
19B	0.09	0.08	1.07	0.008	0.0039	5.14	0.033	0.0033	0.0022		0.002			0.0022			1.10			13.9
20B	0.08	0.13	0.91	0.011	0.0072	5.19	0.027	0.0037	0.0018						0.47	0.76	0.25			14.9
21B	0.13	0.05	1.15	0.009	0.0042	5.39	0.038	0.0031	0.0027	0.002						0.48	0.22			14.5
22B	0.07	0.10	0.85	0.007	0.0060	5.01	0.022	0.0024	0.0019		0.004	0.0022			0.45	0.66	0.31			12.8
24B	0.13	0.11	1.72	0.014	0.0079	5.91	0.025	0.0026	0.0018		0.002									6.3
25B	0.07	0.12	1.01	0.010	0.0051	5.47	0.034	0.0021	0.0015								0.08			3.5
26B	0.17	0.05	1.78	0.013	0.0016	5.06	0.071	0.0038	0.0021						0.16	0.27	0.21			18.1
29B	0.06	0.14	2.55	0.014	0.0013	5.11	0.026	0.0031	0.0018						0.14	0.07	0.22			11.4
101B	0.12	0.15	1.44	0.009	0.0034	5.54	0.028	0.0026	0.0029											5.1
102B	0.07	0.11	1.32	0.012	0.0042	4.89	0.032	0.0031	0.0032	0.019					0.25		0.44			8.2
103B	0.05	0.09	1.29	0.007	0.0028	5.98	0.033	0.0036	0.0037		0.040					0.30	0.17	0.07		8.0
104B	0.08	0.16	1.25	0.008	0.0045	4.82	0.003	0.0037	0.0026	0.012					0.42		0.50			9.6
105B	0.11	0.14	0.96	0.005	0.0058	5.43	0.027	0.0042	0.0042		0.030					0.35	0.22			10.5

(continued)

No.	chemical composition (mass%)																			
	C	Si	Mn	P	S	Ni	Al	N	O	Ti	Nb	Mg	Ca	REM	Cu	Cr	Mo	V	B	α
106B	0.15	0.13	1.14	0.007	0.0036	5.88	0.029	0.0028	0.0035						0.35	0.54		0.08		11.9
107B	0.07	0.09	1.64	0.008	0.0056	5.22	0.028	0.0046	0.0031						0.42	0.42	0.18			13.8
108B	0.09	0.14	1.36	0.006	0.0042	5.46	0.026	0.0029	0.0027	0.015		0.0031	0.0022			0.30	0.34			14.5
109B	0.06	0.11	1.28	0.009	0.0028	5.71	0.031	0.0038	0.0041						0.21	0.34	0.35			12.9
110B	0.15	0.14	1.56	0.005	0.0067	5.05	0.033	0.0019	0.0035											5.7
111B	0.07	0.14	1.25	0.008	0.0028	4.91	0.032	0.0031	0.0025			0.0005			0.44		0.53			9.4
112B	0.12	0.11	0.92	0.006	0.0052	5.48	0.031	0.0038	0.0037				0.0005			0.30	0.24			10.1
113B	0.14	0.14	1.19	0.005	0.0030	5.82	0.025	0.0032	0.0038					0.0005	0.25	0.45		0.08		10.6
114B	0.09	0.14	0.90	0.013	0.0032	5.23	0.032	0.0025	0.0023							0.07				<u>3.3</u>
115B	0.08	0.15	1.21	0.011	0.0029	5.38	0.031	0.0029	0.0034						0.14					<u>3.6</u>
116B	0.14	0.09	1.86	0.015	0.0023	5.15	0.035	0.0045	0.0025						0.12	0.29	0.19			<u>17.3</u>
117B	0.12	0.13	1.74	0.011	0.0014	5.23	0.037	0.0032	0.0033						0.16	0.31	0.28			<u>19.2</u>
118B	0.11	0.13	0.78	0.012	0.0082	5.21	0.037	0.0027	0.0029	0.002	0.002					0.45				5.7
119B	0.17	0.09	1.36	0.009	0.0056	6.08	0.029	0.0026	0.0041		0.002	0.0018			0.32	0.38	0.34			<u>25.3</u>

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[0112] Next, steel products were manufactured from these slabs under the manufacturing conditions listed in Table 5. "Temper heat treatment" is the heating temperature in the tempering treatment after the quenching.

[Table 5]

No.	plate thickness (mm)	rolling conditions		cooling after rolling	Ac ₃ [°C]	reheat quenching conditions		Temper heat treatment [°C]
		heating temperature [°C]	hot rolling cumulative rolling reduction ratio [%]			reheat quenching temperature [°C]	cooling after reheating	
2B	40	1210	55	water cooling	699	1030	water cooling	520
4B	19	1130	63	water cooling	717	880	water cooling	630
6B	40	1150	50	water cooling	756	910	water cooling	620
7B	50	1190	39	air cooling	760	930	water cooling	590
8B	35	1180	60	water cooling	719	1020	water cooling	620
9B	25	1125	45	air cooling	691	760	water cooling	580
10B	40	1220	58	air cooling	774	880	water cooling	-
11B	25	1130	55	air cooling	718	900	water cooling	530
14B	55	1050	38	air cooling	753	890	water cooling	640
15B	45	1170	42	air cooling	794	930	water cooling	590
16B	60	1130	48	water cooling	762	830	water cooling	550
17B	55	1150	38	air cooling	711	840	water cooling	520
19B	50	1050	59	air cooling	793	880	water cooling	570
20B	45	1130	50	water cooling	757	840	water cooling	470
21B	40	1150	68	air cooling	731	800	water cooling	480
22B	35	1130	45	water cooling	768	860	water cooling	600
24B	55	1220	19	air cooling	700	850	water cooling	490
25B	43	1150	43	air cooling	758	900	water cooling	570
26B	50	1100	39	water cooling	714	930	water cooling	520

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(continued)

5	No.	plate thickness (mm)	rolling conditions			Ac ₃ [°C]	reheat quenching conditions		Temper heat treatment [°C]
			heating temperature [°C]	hot rolling cumulative rolling reduction ratio [%]			reheat quenching temperature [°C]	cooling after reheating	
10	29B	57	1180	45	air cooling	744	890	water cooling	590
	101B	70	1200	70	air cooling	723	850	water cooling	-
15	102B	60	1120	80	water cooling	778	930	water cooling	590
	103B	80	1150	68	air cooling	755	900	water cooling	630
20	104B	60	1200	75	air cooling	773	880	water cooling	520
	105B	50	1100	80	water cooling	745	900	water cooling	580
25	106B	45	1150	85	air cooling	708	930	water cooling	610
	107B	60	1100	75	air cooling	744	870	water cooling	540
30	108B	50	1250	80	water cooling	752	890	water cooling	580
	109B	45	1150	85	air cooling	754	920	water cooling	620
35	110B	60	1100	65	water cooling	721	810	water cooling	520
	111B	55	1150	78	air cooling	779	860	water cooling	560
40	112B	50	1200	83	water cooling	741	910	water cooling	530
	113B	45	1100	82	air cooling	714	950	water cooling	600
45	114B	50	1100	75	water cooling	755	880	water cooling	540
	115B	40	1150	70	air cooling	748	900	water cooling	600
50	116B	60	1200	70	water cooling	718	950	water cooling	530
	117B	50	1150	67	air cooling	733	920	water cooling	550
55	118B	50	1200	75	air cooling	748	590	water cooling	480
	119B	50	1050	80	water cooling	691	830	water cooling	560

[Measurement and Evaluation]

[0113] The microstructures and mechanical properties of the obtained steel products were measured by the above-described methods. The results are shown in Table 6. The meanings of the symbols of the microstructures are as follows. Note that the remainders of the microstructures were MA phase and ferrite.

Bu: upper bainite

BL: lower bainite

M: martensite

residual γ : residual austenite

[0114] For the toughness, the average value of the Charpy impact absorption energy at -110°C, and the average value of the Charpy impact absorption energy at -110°C after PWHT in which the holding temperature was 600°C, the holding time was 2 hours, and the rate of temperature increase and the rate of temperature decrease in the temperature region of 425°C or more were 55°C/h, respectively were measured.

[Table 6]

No.	microstructure (area ratio)			aspect ratio average value of prior γ grains	average crystal grain diameter $[\mu\text{m}]$	YS [MPa]	TS [MPa]	YR [%]	base metal toughness KV2[J]	toughness after PWHT KV2[J]	thermal cycling toughness KV2[J]	toughness after thermal cycling and PWHT KV2 [J]	notes
	BL+M [%]	Bu+BL+M [%]	residual γ [%]										
2B	25.2	92.1	0.0	1.1	23.2	569	654	87	146	122			examples of present invention
4B	24.7	92.7	0.0	1.3	16.4	513	628	82	221	190			
6B	36.2	92.5	0.1	1.2	17.3	572	661	87	248	222			
7B	37.7	93.6	0.2	1.1	15.6	561	657	85	312	319			
8B	34.4	93.2	0.1	1.0	22.4	578	669	86	148	145			
9B	37.1	93.1	0.2	1.1	17.4	581	684	85	233	230			
10B	52.7	95.4	0.4	1.2	14.1	621	734	85	281	278			
11B	55.9	93.7	0.5	1.1	13.8	642	773	83	285	282			
14B	67.3	95.2	0.4	1.4	14.2	658	745	88	232	228			
15B	62.1	94.8	0.3	1.2	16.4	672	778	86	251	232			
16B	64.3	95.9	0.4	1.2	16.7	651	739	88	233	218			
17B	92.8	95.2	0.7	1.1	14.5	731	844	87	245	240			
19B	91.3	97.1	0.8	1.3	15.4	722	846	85	256	238			
20B	92.9	97.3	0.7	1.2	18.3	779	912	85	214	210			
21B	98.2	98.2	0.6	1.1	15.6	736	857	86	252	232			
22B	90.0	96.8	0.6	1.2	14.1	749	858	87	262	241			
24B	38.1	92.3	0.2	1.4	27.5	542	653	83	137	102			
25B	10.2	80.2	0.0	1.2	41.2	510	568	90	68	67			
26B	95.3	98.1	1.3	1.1	17.0	891	992	90	159	119			
29B	87.9	95.1	0.8	1.3	17.2	736	859	86	155	30			comparative example

(continued)

No.	microstructure (area ratio)			aspect ratio average value of prior γ grains	average crystal grain diameter [μm]	YS [MPa]	TS [MPa]	YR [%]	base metal toughness KV2[J]	toughness after PWHT KV2[J]	thermal cycling toughness KV2[J]	toughness after thermal cycling and PWHT KV2 [J]	notes
	BL+M [%]	Bu+BL+M [%]	residual γ [%]										
101B	26.2	92.3	0.2	1.1	19.4	605	683	89	231	220	135	118	examples of present invention
102B	36.4	93.1	0.3	1.2	17.2	573	663	86	220	197	143	131	
103B	34.8	93.0	0.2	1.1	17.5	570	659	86	227	204	142	129	
104B	57.2	94.8	0.6	1.2	16.1	645	765	84	240	218	186	161	
105B	60.2	95.7	0.7	1.1	15.6	674	770	88	252	228	192	175	
106B	63.8	96.9	0.7	1.3	15.3	680	778	87	239	235	181	178	
107B	93.4	97.1	1.1	1.2	14.2	731	856	85	245	224	162	141	
108B	93.1	98.2	1.2	1.1	15.1	752	862	87	251	236	158	142	
109B	92.0	98.1	0.9	1.3	14.8	744	858	87	254	250	172	169	
110B	25.3	90.2	0.2	1.3	26.6	528	624	85	140	123	135	114	
111B	55.8	94.3	0.4	1.2	13.8	646	759	83	279	276	182	181	
112B	64.3	94.8	0.4	1.3	14.2	661	757	88	241	240	185	182	
113B	66.1	95.2	0.5	1.2	14.3	674	775	86	255	251	195	192	comparative example
114B	9.2	78.3	0.1	1.3	40.4	501	566	89	66	63	43	32	
115B	10.1	79.1	0.0	1.2	39.8	512	573	89	68	69	41	37	
116B	96.2	98.2	0.9	1.2	16.1	873	986	89	142	138	39	33	
117B	97.3	98.1	1.2	1.1	15.8	884	995	89	138	135	36	32	
118B	11.4	53.0	0.1	1.8	16.6	437	526	83	161	142	127	112	
119B	96.2	96.8	1.9	1.2	18.2	936	1070	87	63	42	25	18	

[0115] Nos. 2B - 24B and 101B - 113B are Examples of the present invention, and Nos. 25B - 29B and 114B - 119B are Comparative Examples.

[0116] In No. 25B, value α was less than the lower limit value of the present disclosure, and the hardenability was insufficient, and the strength was insufficient. Sufficient low-temperature toughness also was not obtained.

[0117] In No. 26B, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive.

[0118] In No. 29B, because Mn fell outside of the upper limit, the low-temperature toughness after PWHT was low.

[0119] In Nos. 114B and 115B, value α was less than the lower limit value of the present disclosure, and the hardenability was insufficient, and the strength was insufficient. Sufficient low-temperature toughness also was not obtained.

[0120] In Nos. 116B and 117B, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive.

[0121] In No. 118B, the reheating quenching temperature was too low, and the total area ratio of the upper bainite, lower bainite and martensite was insufficient, and the strength was insufficient.

[0122] In No. 119B, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive. Further, because there was also too much residual γ , sufficient low-temperature toughness was not obtained.

[0123] In contrast to the Comparative Examples, in the Examples of the present invention, the chemical compositions and microstructures of the steel products were controlled appropriately, and the tensile strengths were in the appropriate range of 615 MPa or more and 930 MPa or less. In addition, low-temperature toughness at -110°C of 100 J or more was obtained regardless of whether before or after PWHT. In particularly suitable structures of the present disclosure, low-temperature toughness at -110°C of 150 J or more was obtained regardless of whether before or after PWHT.

Industrial Applicability

[0124] The steel products relating to the present disclosure can be used mainly for transport tanks of liquefied carbon dioxide. Further, the steel products relating to the present disclosure can also be used in other welded structures such as buildings, bridges, ships, pipelines, offshore structures, pressure vessels and tanks.

[0125] The disclosures of Japanese Patent Application No. 2023-042399 and Japanese Patent Application No. 2023-042402 filed on March 16, 2023 are, in their entireties, incorporated by reference into the present specification.

All publications, patent applications, and technical standards mentioned in the present specification are incorporated by reference into the present specification to the same extent as if such individual publication, patent application, or technical standard was specifically and individually put forth herein.

Claims

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

C: 0.03% or more and 0.20% or less,
 Si: 0.01% or more and 0.50% or less,
 Mn: 0.10% or more and 2.00% or less,
 P: 0.025% or less,
 S: 0.0250% or less,
 Ni: 4.51% or more and 6.10% or less,
 Al: 0.001% or more and 0.100% or less,
 O: 0.0100% or less,
 N: 0.0100% or less,
 Cu: 0 - 1.50%,
 Cr: 0 - 3.00%,
 Mo: 0 - 2.00%,
 B: 0 - 0.0050%,
 Nb: 0 - 0.050%,
 Ti: 0 - 0.050%,
 V: 0 - 0.10%,
 Mg: 0 - 0.0200%,
 Ca: 0 - 0.0200%,
 REM: 0 - 0.0200%,
 balance: Fe and impurities,

and in which α expressed by following formula (1) is 5.0 or more and 16.0 or less, wherein:

a tensile strength is 615 MPa or more and 930 MPa or less, and a microstructure of a region that is 1/4 of a thickness in a thickness direction from a surface of the steel product contains lower bainite and martensite, and a total of area ratios of the lower bainite and the martensite is 15.0% or more, and a total of area ratios of upper bainite and the lower bainite and the martensite is 90.0% or more, and an area ratio of residual austenite is less than 1.7%.

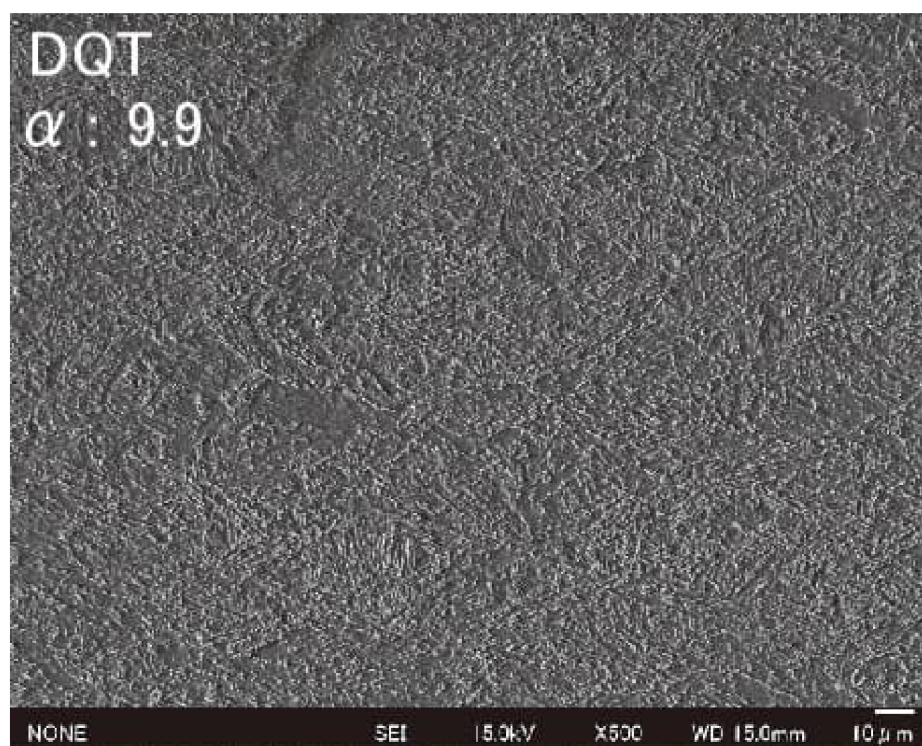
$$\alpha = 0.50 \times \sqrt{[C]} \times (1+0.64[Si]) \times (1+4.10[Mn]) \times (1+0.27[Cu]) \times (1+0.52[Ni]) \times (1+2.33[Cr]) \times (1+3.14[Mo]) \quad (1)$$

wherein [element symbol] in formula (1) represents content (mass%) of a respectively corresponding element contained in the steel product, and, in a case in which an element is not contained, zero is substituted in therefor.

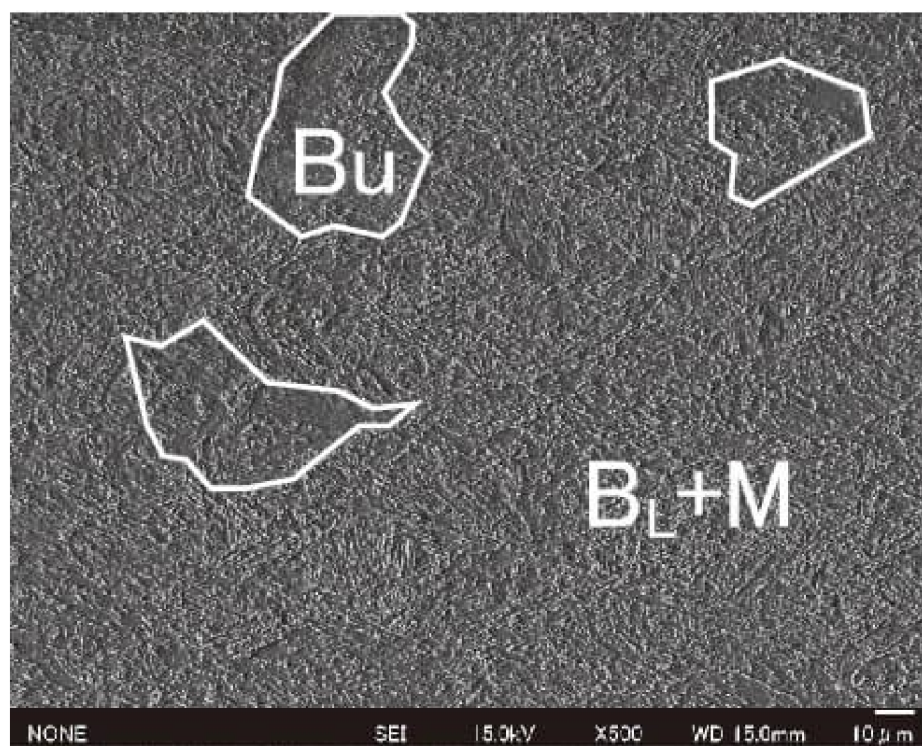
2. The steel product of Claim 1, wherein, in the microstructure of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product, an average crystal grain diameter is 20.0 μm or less.
3. The steel product of Claim 1 or Claim 2, wherein a Charpy impact absorption energy at -110°C is 150 J or more.
4. The steel product of any one of Claim 1 through Claim 3, wherein, in a case in which a heat treatment, in which a rate of temperature increase and a rate of temperature decrease in a temperature region of 425°C or more are 55°C/h and temperature is held for 2 hours at 600°C, is carried out on the steel product, a Charpy impact absorption energy at -110°C of portions where the heat treatment has been carried out is 150 J or more.
5. The steel product of any one of Claim 1 through Claim 4, wherein an aspect ratio of prior austenite crystal grains of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product is 1.5 or more.
6. The steel product of any one of Claim 1 through Claim 4, wherein an aspect ratio of prior austenite crystal grains of the region that is 1/4 of the thickness in the thickness direction from the surface of the steel product is less than 1.5.

FIG.1

(A)



(B)



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2024/010386

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; *C21D 8/02*(2006.01)i; *C21D 9/00*(2006.01)i; *C21D 9/46*(2006.01)i; *C21D 9/50*(2006.01)i;
C22C 38/08(2006.01)i; *C22C 38/58*(2006.01)i

FI: C22C38/00 302B; C22C38/00 301W; C22C38/08; C22C38/58; C21D9/00 L; C22C38/00 301B; C21D9/50 101B;
 C21D9/46 S; C21D9/46 Z; C21D8/02 B; C21D8/02 D

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; C21D8/02; C21D9/00; C21D9/46; C21D9/50; C22C38/08; C22C38/58

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 1971-2024
 Registered utility model specifications of Japan 1996-2024
 Published registered utility model applications of Japan 1994-2024

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.
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A	CN 102851611 A (BAOSHAN IRON & STEEL CO., LTD.) 02 January 2013 (2013-01-02)	1-6

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

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“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

22 May 2024

Date of mailing of the international search report

04 June 2024

Name and mailing address of the ISA/JP

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Authorized officer

Telephone No.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2024/010386

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JP 2-163342 A	22 June 1990	(Family: none)	
JP 1-219121 A	01 September 1989	(Family: none)	
JP 2001-527155 A	25 December 2001	WO 1999/032672 A1 GB 2348887 A CN 1282381 A KR 10-2001-0024757 A	
CN 102851611 A	02 January 2013	(Family: none)	

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