



(11) **EP 4 682 286 A1**

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

(43) Date of publication:
21.01.2026 Bulletin 2026/04

(21) Application number: **24771023.9**

(22) Date of filing: **15.03.2024**

(51) International Patent Classification (IPC):
C22C 38/00 ^(2006.01) **C21D 8/00** ^(2006.01)
C21D 8/02 ^(2026.01) **C21D 9/00** ^(2006.01)
C21D 9/46 ^(2006.01) **C21D 9/50** ^(2006.01)
C22C 38/08 ^(2006.01) **C22C 38/58** ^(2006.01)

(52) Cooperative Patent Classification (CPC):
C21D 8/00; C21D 8/02; C21D 9/00; C21D 9/46;
C21D 9/50; C22C 38/00; C22C 38/08; C22C 38/58

(86) International application number:
PCT/JP2024/010387

(87) International publication number:
WO 2024/190921 (19.09.2024 Gazette 2024/38)

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

(30) Priority: **16.03.2023 JP 2023042400**
16.03.2023 JP 2023042401

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(54) **STEEL MATERIAL**

(57) A steel product having a specific chemical composition, in which α expressed by a following formula is 4.0 or more and 16.0 or less; having a tensile strength of 590 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, and a total of area ratios of upper bainite, the lower bainite, and the martensite being 90.0% or more.

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

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Description

Technical Field

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

Background Art

[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.

[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.

[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 9).

[0007]

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

Patent Document 2: International Publication No. 2014/103629

Patent Document 3: JP-A No. S52-156121

Patent Document 4: JP-A No. S55-104427

Patent Document 5: JP-A No. S58-73717

Patent Document 6: JP-A No. H07-331328

Patent Document 7: JP-A No. 2001-123222

Patent Document 8: JP-A No. 2001-123245

Patent Document 9: JP-A No. 2007-46096

SUMMARY OF INVENTION

Technical Problem

[0008] Having both high strength and the ensuring of low-temperature toughness is desirable for cryogenic steels use 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.

[0009] 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

[0010] The gist of the present disclosure is as follows.

<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 1.65% or less,

P: 0.025% or less,

S: 0.0250% or less,
 Ni: 2.65% or more and 4.45% 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 the following formula (1) is 4.0 or more and 16.0 or less, wherein:

a tensile strength is 590 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, the lower bainite, and the martensite is 90.0% or more,

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

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 -100°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 -100°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

[0011] 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

[0012] Fig. 1 is a diagram illustrating an example of results of discriminating the microstructure.

DESCRIPTION OF EMBODIMENTS

[0013] The present disclosure is described in detail hereinafter.

[0014] 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.

[0015] 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 joint or the heat affected zone).

[0016] 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.

[0017] With respect to the contents of the elements in a chemical composition, "%" means "mass%".

[0018] 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.

[0019] 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.

[0020] 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), which is the region that is 1/4 of the thickness in the thickness direction from the surface 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 590 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").

[0021] 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 -100°C, the total of the area ratios of lower bainite and martensite is 15.0% or more. Note that the total of the area ratios of lower bainite and martensite was measured by using EBSD.

[0022] 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.

[0023] 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>

[0024] 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)

[0025] 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)

[0026] 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, or 0.10% 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 1.65% or less)

[0027] 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 1.65% or less. The Mn content is preferably 1.50% or less, 1.25% or less, or 1.10% or less.

(P: 0.025% or less)

[0028] 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)

[0029] 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: 2.65% or more and 4.45% or less)

[0030] Ni is an element that is effective in improving the hardenability and toughness of the steel. Therefore, in the present disclosure, the Ni content is 2.65% or more. The Ni content is preferably 3.00% or more or 3.20% or more. However, Ni is an expensive element, and, from the standpoint of cost reduction, in the present disclosure, the Ni content is 4.45% or less. The Ni content is preferably 4.10% or less, or 3.80% or less.

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

[0031] 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)

[0032] 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)

[0033] 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.

[0034] 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%.

[0035] 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)

[0036] 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)

[0037] 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)

[0038] 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)

[0039] 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.

[0040] 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)

[0041] 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)

[0042] 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)

[0043] 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.

[0044] 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)

[0045] 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)

[0046] 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)

[0047] 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)

[0048] 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.

[0049] 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 : 4.0 or more and 16.0 or less)

[0050] Value α is computed by following formula (1).

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

[0051] 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 $[C]^{1/2}$.

[0052] In the present disclosure, the range of value α is 4.0 - 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 4.0 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.

[0053] 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 4.5 or more or 5.0 or more. Further, value α is preferably 15.5 or less or 15.0 or less.

<Microstructure>

[0054] 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.

[0055] "Bainite" is a microstructure containing bainitic ferrite ($\alpha^{\circ}B$) that has a substructure within the grain, and 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.

[0056] 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)

[0057] 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)

[0058] 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.

[0059] 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.

[0060] 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 and martensite is carried out by EBSD. The measurement magnification is 200 $\times$, and measurement of a range of 400 μm $\times$ 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 or martensite. Because the upper bainite, lower bainite and martensite in the present disclosure are determined by using the GAM of EBSD as the threshold value, not only upper bainite, lower bainite and martensite, 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.

[0061] 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 $\times$, and measurement of a range of 360 μm $\times$ 480 μm is carried out. The portion, which has a clear lath structure and at which carbide and MA are generated 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 (BL+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 (BL+M), the carbides are densely and uniformly distributed. The total of the area ratios of the lower bainite and martensite is determined by subtracting the area ratio of the upper bainite from the total of the area ratios of the upper bainite, lower bainite, and martensite, which were measured as described above.

[0062] Note that there are also cases in which, depending on the manufacturing conditions, residual austenite is included in the microstructure of the present disclosure, but this is not included in computing the area ratio because there is a trace amount thereof.

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

[0063] 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)

[0064] 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 average crystal grain diameter. The aspect ratio of prior austenite grains is usually 4.0 or less, and may be 3.5 or less.

[0065] 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.

[0066] 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.

[0067] 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>

[0068] 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 -100°C in particular, the steel product can exhibit excellent low-temperature toughness after PWHT as well.

(Tensile Strength: 590 MPa or more and 930 MPa or less)

[0069] In the present disclosure, the tensile strength of the steel product is 590 - 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)

[0070] The yield ratio (YR = yield strength / 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 -100°C)

[0071] In order to ensure high toughness at low temperatures, the Charpy impact absorption energy at -100°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 -100°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. Note that the Charpy impact absorption energy at -100°C is a numerical value measured by using a sample taken from a position of 1/4 of the thickness.

(Charpy Impact Absorption Energy at -100°C after PWHT)

[0072] There are cases in which PWHT is carried out on the welded portions of low temperature 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 -100°C is preferably 150 J or more. The Charpy impact absorption energy at -100°C after PWHT may be 100 J or more. The Charpy impact absorption energy at -100°C after PWHT also is a numerical value measured by using a sample taken from a position of 1/4 of the thickness.

(Charpy Impact Absorption Energy at -100°C after Thermal Cycling)

[0073] 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 -100°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 -100°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 -100°C after thermal cycling may be 40 J or more. Note that the Charpy impact absorption energy at -100°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 -100°C after Thermal Cycling and PWHT)

[0074] There are cases in which PWHT is carried out on the welded portions of low temperature 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 -100°C is preferably 50 J or more. The Charpy impact absorption energy at -100°C of the portion at which PWHT is carried out after the above-described thermal cycling test may be 40 J or more.

[0075] 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.

[0076] The tensile strength (TS) and the yield strength (YS) in the Examples are measured in accordance with a tensile test that is based on JIS Z2241:2011. The tensile test uses a JIS 14A 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.

[0077] The Charpy impact absorption energy is measured by a Charpy impact test at -100°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.

[0078] 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.

[0079] 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)

[0080] 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, an intermediate heat treatment (L) and tempering (T) may also be carried out. The manufacturing process after the hot rolling is selected from combinations of the above-described DQ, RQ, L and T, and is, for example, DQT, RQT, DQLT, or RQLT.

[0081]

- (1) DQT: direct quenching (DQ) and tempering (T)
- (2) RQT: air cooling or water cooling, reheat quenching (RQ), and tempering (T)
- (3) DQLT: direct quenching (DQ), intermediate heat treatment (L), and tempering (T)
- (4) RQLT: air cooling or water cooling, reheat quenching (RQ), intermediate heat treatment (L), and tempering (T)

(1) DQT

[0082] 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.

[0083] 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.

[0084] $A_{c3} = 937.2 - 436.5C + 56Si - 19.7Mn - 16.3Cu - 26.6Ni - 4.9Cr + 38.1Mo + 124.8V + 136.3Ti - 19.1Nb + 198.4Al + 3315B$

[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 rolled steel at the time of the hot rolling on the mechanical properties of the steel product are small. However, if the heating temperature of the rolled steel is too low, the deformation resistance increases, and therefore, the heating temperature of the rolled steel 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 Ac_3 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 steel product relating to 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,

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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.

[0099] The underlines mean that the value is outside of the scope of the present disclosure.

5 [Table 1]

	No.	chemical components (mass%)																			
		C	Si	Mn	P	S	Ni	Al	N	O	Ti	Nb	Mg	Ca	REM	Cu	Cr	Mo	V	B	α
10	1A	0.16	0.20	1.56	0.008	0.0055	3.80	0.035	0.0012	0.0008											5.0
	2A	0.16	0.20	1.56	0.008	0.0055	3.80	0.035	0.0012	0.0008											5.0
	3A	0.13	0.41	1.38	0.011	0.0026	4.05	0.022	0.0045	0.0015								0.05			4.7
	4A	0.18	0.21	1.22	0.009	0.0020	4.32	0.001	0.0022	0.0018	0.002			0.0011							4.7
15	5A	0.19	0.36	1.62	0.004	0.0035	4.40	0.034	0.0035	0.0035				0.0023							6.7
	6A	0.09	0.22	0.55	0.004	0.0035	3.48	0.001	0.0025	0.0022	0.001				0.30	0.51	0.40	0.04			8.4
	7A	0.10	0.19	0.69	0.007	0.0005	3.79	0.025	0.0013	0.0014		0.004				0.90					6.2
	8A	0.07	0.15	0.62	0.007	0.0031	3.72	0.033	0.0039	0.0025			0.0030		0.62	0.39	0.20				5.5
20	9A	0.11	0.22	0.51	0.006	0.0028	3.71	0.002	0.0034	0.0039						0.61	0.60				12.0
	10A	0.11	0.22	0.51	0.006	0.0028	3.71	0.002	0.0034	0.0039						0.61	0.60				12.0
	11A	0.05	0.12	0.43	0.004	0.0011	3.44	0.024	0.0015	0.0042		0.0007			0.25	0.50	0.40		0.0005		4.8
	12A	0.12	0.18	0.48	0.006	0.0021	3.52	0.039	0.0040	0.0006		0.002		0.0008	0.60	1.00					6.3
25	13A	0.10	0.25	0.58	0.006	0.0024	3.73	0.052	0.0048	0.0028	0.002					0.56	0.43	0.02			9.9
	14A	0.08	0.15	0.66	0.008	0.0028	3.31	0.043	0.0032	0.0024						0.50	0.80				11.9
	15A	0.14	0.10	0.92	0.012	0.0128	4.35	0.072	0.0028	0.0012		0.014			0.70	0.49	0.29		0.0012		15.1
	16A	0.12	0.16	1.22	0.006	0.0046	3.61	0.008	0.0065	0.0016	0.015		0.0032	0.0008		1.00	0.60		0.06		10.0
	17A	0.04	0.23	0.65	0.019	0.0064	3.33	0.012	0.0008	0.0024						2.11					6.8
	18A	0.09	0.03	1.11	0.010	0.0028	3.88	0.042	0.0045	0.0025		0.022		0.0013				1.28			12.9
	19A	0.08	0.15	0.85	0.009	0.0078	2.87	0.036	0.0037	0.0012	0.023		0.0014		0.0031	0.50	0.75	0.22	0.04		9.1
	20A	0.16	0.08	1.60	0.011	0.0022	3.51	0.058	0.0024	0.0034						0.31	0.29				14.8

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21A	0.09	0.08	0.29	0.008	0.0024	4.01	0.009	0.0034	0.0024					0.0018		1.80			0.0011	5.5
22A	0.10	0.16	0.92	0.006	0.0027	4.11	0.015	0.0035	0.0025			0.0010				0.42		0.02		5.2
23A	0.08	0.22	0.95	0.012	0.0032	3.55	0.031	0.0028	0.0048	0.001	0.001		0.0009		0.14	0.20	0.15	0.06		5.0
26A	0.05	0.15	<u>1.73</u>	0.004	0.0014	3.57	0.022	0.0026	0.0038			0.0011			0.24	0.49	0.39		0.0004	14.4
101A	0.17	0.14	1.61	0.005	0.0008	3.71	0.041	0.0023	0.0011											5.0
102A	0.08	0.32	1.18	0.009	0.0028	3.28	0.023	0.0048	0.0037						0.42	0.28	0.21			8.2
103A	0.15	0.29	1.56	0.012	0.0042	4.09	0.011	0.0039	0.0022			0.0022								5.3
104A	0.18	0.38	1.60	0.004	0.0007	4.29	0.028	0.0014	0.0009									0.06		6.4
105A	0.09	0.11	0.79	0.011	0.0034	3.57	0.045	0.0044	0.0024			0.0006			0.52	0.41	0.43	0.04		10.2
106A	0.14	0.29	1.55	0.008	0.0011	3.79	0.002	0.0022	0.0012	0.008			0.0011	0.0004						4.8
107A	0.05	0.22	1.22	0.009	0.0018	3.25	0.021	0.0058	0.0033		0.004				0.55	0.74	0.24		0.0008	11.3
108A	0.13	0.35	1.48	0.007	0.0039	3.95	0.008	0.0009	0.0037				0.0024		0.79		0.52			15.2
109A	0.15	0.19	0.98	0.012	0.0027	3.21	0.019	0.0019	0.0031							0.95		0.02		9.3
110A	0.13	0.25	0.82	0.009	0.0029	3.85	0.044	0.0038	0.0015						0.58			0.02		<u>3.2</u>
111A	0.06	0.19	1.38	0.011	0.0039	3.55	0.035	0.0062	0.0030		0.002				0.11		0.10			<u>3.5</u>
112A	0.14	0.28	1.22	0.007	0.0022	3.64	0.033	0.0044	0.0038				0.0006		0.48	0.42	0.35			<u>18.0</u>
113A	0.11	0.27	1.58	0.014	0.0025	4.09	0.054	0.0055	0.0035						0.82		0.68		0.0004	<u>17.4</u>
114A	0.12	0.22	1.35	0.015	0.0034	3.41	0.033	0.0038	0.0022		0.008				0.21		0.42			8.8

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[0100] 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]	rolling conditions				Ar ₃ [°C]	direct quenching 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]		cooling after rolling	start temperature [°C]	stoppage temperature [°C]		cooling rate [°C/s]
1A	30	754	1100	38	59	840	534	water cooling	830	350	10.5	600
2A	45	754	1120	19	52	810	540	water cooling	800	280	4.2	500
3A	40	779	1140	48	45	840	548	water cooling	830	50	3.8	440
4A	25	732	1080	55	57	790	525	water cooling	780	25	6.7	610
5A	25	732	1040	45	48	860	485	water cooling	850	150	7.2	600
6A	45	820	1200	47	48	770	614	water cooling	760	120	5.2	620
7A	50	790	1020	60	47	820	617	water cooling	800	310	6.2	500
8A	35	806	1160	59	24	760	609	water cooling	740	300	9.5	600
9A	60	813	1200	38	41	790	592	water cooling	770	280	2.5	640
10A	50	813	1150	18	58	820	589	water cooling	800	100	4.4	640
11A	35	837	1100	55	56	770	636	water cooling	760	140	3.5	470
12A	45	785	1090	36	30	740	627	water cooling	740	360	3.7	500

(continued)

No.	plate thickness (mm)	Ac ₃ [°C]	rolling conditions				Ar ₃ [°C]	direct quenching 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]		cooling after rolling	start temperature [°C]	stoppage temperature [°C]	
13A	50	824	1150	39	36	850	water cooling	840	320	2.2	580
14A	55	846	1020	42	59	760	water cooling	750	260	8.4	600
15A	60	763	1060	59	49	730	water cooling	730	280	3.5	640
16A	50	766	1200	32	29	810	water cooling	800	290	4.5	490
17A	40	823	1120	50	39	740	water cooling	720	300	7.2	450
18A	55	831	1080	35	40	750	water cooling	730	310	4.2	570
19A	50	829	1100	59	49	890	water cooling	880	105	2.7	470
20A	60	768	1050	28	46	720	water cooling	710	270	33	600
21A	55	787	1080	12	59	740	water cooling	720	300	7.2	450
22A	60	778	1160	55	11	750	water cooling	730	310	4.2	570
23A	50	818	1050	57	41	600	water cooling	590	290	4.5	490
26A	45	809	1140	42	45	870	water cooling	850	110	4.5	580

(continued)

No.	plate thickness (mm)	Ac ₃ [°C]	rolling conditions				cooling after rolling	Ar ₃ [°C]	direct quenching 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]	
101A	35	749	1090	58	65	820	water cooling	534	810	55	9.2	580
102A	55	814	1120	41	69	780	water cooling	597	750	240	4.5	610
103A	45	751	1100	62	50	800	water cooling	527	770	155	6.7	540
104A	50	740	1160	66	47	740	water cooling	505	720	35	3.8	630
105A	40	813	1120	45	70	850	water cooling	583	840	115	6.6	500
106A	30	762	1140	69	60	800	water cooling	542	790	305	8.7	550
107A	60	818	1080	56	55	790	water cooling	595	780	255	2.4	630
108A	25	774	1150	62	73	730	water cooling	483	710	155	9.9	640
109A	45	777	1130	71	44	860	water cooling	607	850	300	7.8	510
110A	40	775	1140	68	48	780	water cooling	592	760	255	2.1	620
111A	50	809	1160	55	54	820	water cooling	590	800	185	2.5	600
112A	45	781	1090	52	69	810	water cooling	538	790	35	6.2	580

(continued)

No.	plate thickness (mm)	Ac ₃ [°C]	rolling conditions				cooling after rolling	Ar ₃ [°C]	direct quenching 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]	
113A	55	788	1100	42	60	840	water cooling	470	820	55	5.4	620
114A	45	799	1100	52	61	840	water cooling	552	820	235	0.5	610

[Measurement and Evaluation]

[0101] 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

[0102] For the toughness, the average value (KV2) of the Charpy impact absorption energy at - 100°C, and the average value of the Charpy impact absorption energy at -100°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]	YR [%]	YS [MPa]	TS [MPa]	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 [%]										
1A	16	90	3.2	18.1	80	516	642	277	182			examples of present invention
2A	22	92	3.1	22.2	82	535	655	184	153			
3A	41	94	2.4	15.8	81	589	725	270	242			
4A	75	98	3.4	14.9	85	693	820	255	231			
5A	33	97	2.0	18.2	82	600	732	241	176			
6A	25	95	2.1	16.8	84	541	641	304	305			
7A	34	92	1.9	15.0	81	557	688	324	311			
8A	28	98	1.5	16.2	80	508	632	300	298			
9A	40	94	1.7	16.9	84	564	675	285	295			
10A	55	95	2.2	23.1	82	609	743	155	152			
11A	51	96	2.2	13.9	79	584	742	305	289			
12A	65	93	1.7	16.8	81	580	716	282	288			
13A	46	90	1.8	15.5	82	601	733	292	296			
14A	68	95	3.2	15.2	82	619	755	288	295			
15A	72	92	1.8	16.9	82	641	781	245	172			
16A	96	96	1.6	16.3	79	696	885	225	170			
17A	84	97	1.8	17.0	82	664	810	238	158			
18A	90	91	1.6	19.2	80	681	855	200	155			
19A	92	95	2.2	13.3	82	691	843	288	168			
20A	90	94	1.9	16.6	82	681	830	245	201			
21A	18	91	2.7	31.1	84	505	598	145	142			
22A	20	92	1.3	34.2	84	500	592	132	122			
23A	15	<u>80</u>	1.7	18.2	82	470	<u>572</u>	105	85			comparative examples

(continued)

No.	microstructure (area ratio)		aspect ratio average value of prior γ grains	average crystal grain diameter $[\mu\text{m}]$	YR [%]	YS [MPa]	TS [MPa]	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 [%]										
26A	88	95	1.8	19.3	82	699	851	155	15			
101A	24	91	3.2	18.4	84	524	625	255	232	113	97	examples of present invention
102A	40	93	3.5	17.2	83	567	682	272	254	185	172	
103A	35	92	2.4	19.2	82	506	618	250	192	102	89	
104A	52	94	1.9	18.2	86	645	752	246	184	152	129	
105A	62	95	3.6	15.8	81	634	779	233	205	178	157	
106A	66	94	2.8	18.8	83	597	721	218	168	109	86	
107A	90	96	2.6	15.7	88	705	804	252	232	152	148	comparative examples
108A	92	97	2.9	18.7	87	769	889	176	152	95	90	
109A	91	93	2.2	16.0	84	722	856	215	204	176	155	
110A	1	72	1.7	35.2	82	451	551	32	31	42	37	
111A	4	62	2.3	34.5	83	442	535	38	22	37	32	
112A	98	99	3.1	19.2	89	862	968	65	45	31	24	
113A	97	98	2.2	19.6	88	856	<u>976</u>	58	32	28	15	
114A	8	92	2.0	34.2	86	544	635	34	18	172	158	

[0103] Nos. 1A - 22A and 101A - 109A are Examples of the present invention, and Nos. 23A, 26A and 110A - 114A are Comparative Examples.

[0104] In No. 23A, the rolling end temperature was low, and the direct quenching start temperature was lower than Ar_3 , and therefore, sufficient strength was not obtained.

[0105] In Nos. 110A and 111A, 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.

[0106] In Nos. 112A and 113A, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive.

[0107] In No. 114A, because the cooling temperature 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.

[0108] In contrast to the Comparative Examples, in all of the Examples of the present invention (Nos. 1A - 22A and 101A - 109A), the chemical compositions and microstructures of the steel products were controlled appropriately, and the tensile strengths were in the appropriate range of 590 MPa or more and 930 MPa or less. In addition, the Charpy impact absorption energy at - 100°C was high regardless of whether before or after PWHT, and in the Examples having particularly good properties, low-temperature toughness of 150 J or more was obtained.

<Manufacturing by Reheat Quenching and Tempering>

[Manufacturing of Steel Product]

[0109] 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 components (mass%)																		
	C	Si	Mn	P	S	Ni	Al	N	O	Ti	Nb	Mg	Ca	REM	Cu	Cr	Mo	V	B
1B	0.17	0.25	1.48	0.007	0.0042	3.78	0.032	0.0024	0.0011										
2B	0.17	0.25	1.48	0.007	0.0042	3.78	0.032	0.0024	0.0011										
3B	0.14	0.35	1.25	0.018	0.0008	4.42	0.028	0.0035	0.0008									0.04	
4B	0.18	0.30	1.59	0.009	0.0024	2.99	0.001	0.0042	0.0026	0.007			0.0011						
5B	0.17	0.45	1.55	0.004	0.0022	4.40	0.012	0.0031	0.0015			0.0022							
6B	0.11	0.20	0.58	0.007	0.0036	3.74	0.024	0.0040	0.0013		0.002				0.35	0.54	0.35		
7B	0.12	0.28	0.65	0.006	0.0029	3.55	0.002	0.0015	0.0028			0.0009				0.28	0.44	0.02	
8B	0.10	0.25	0.68	0.006	0.0005	3.60	0.048	0.0028	0.0018					0.0008	0.48	0.80			
9B	0.07	0.11	0.62	0.005	0.0010	3.64	0.030	0.0037	0.0020							0.45	0.45		
10B	0.07	0.11	0.62	0.005	0.0010	3.64	0.030	0.0037	0.0020							0.45	0.45		
11B	0.07	0.10	0.66	0.006	0.0021	3.35	0.035	0.0020	0.0035						0.28	0.78	0.56		0.0005
12B	0.05	0.15	0.52	0.008	0.0045	3.50	0.043	0.0031	0.0011	0.001					0.56	0.80	0.27		
13B	0.09	0.26	0.68	0.005	0.0034	3.68	0.048	0.0045	0.0027				0.0013		0.32	1.18		0.01	
14B	0.12	0.30	0.69	0.007	0.0028	3.74	0.043	0.0032	0.0024						0.50		0.80		0.0004
15B	0.14	0.08	0.44	0.012	0.0124	4.25	0.072	0.0024	0.0050		0.014				0.80	0.60	0.60		
16B	0.04	0.16	1.28	0.004	0.0052	3.65	0.007	0.0068	0.0018	0.015			0.0007	0.0011	1.15		0.55		0.0015
17B	0.12	0.25	0.85	0.008	0.0064	3.02	0.021	0.0007	0.0029			0.0028				1.95		0.07	
18B	0.10	0.08	0.48	0.018	0.0004	4.09	0.008	0.0055	0.0022		0.020			0.0026			1.48		
19B	0.06	0.25	0.90	0.010	0.0047	2.72	0.036	0.0037	0.0012	0.022			0.0027			0.82	0.35		
20B	0.15	0.04	1.35	0.009	0.0060	3.50	0.052	0.0060	0.0065						0.28	0.22	0.28		
21B	0.13	0.08	0.40	0.009	0.0035	3.55	0.025	0.0055	0.0015			0.0014			0.39	0.52	0.45		0.0011
22B	0.09	0.25	0.72	0.007	0.0014	3.58	0.042	0.0025	0.0016						0.25	0.34			<u>3.8</u>
23B	0.08	0.28	0.85	0.009	0.0034	2.92	0.012	0.0022	0.0025	0.002			0.0011			0.55	0.35	0.06	0.0015

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5	24B	0.11	0.21	1.25	0.014	0.0022	<u>2.55</u>	0.025	0.0045	0.0035					0.0012		0.19	0.31			7.6
	25B	0.09	0.24	<u>1.72</u>	0.007	0.0008	3.58	0.044	0.0026	0.0015						0.50	0.78			12.7	
	101B	0.18	0.28	1.62	0.014	0.0009	4.09	0.032	0.0046	0.0038								0.05		6.0	
	102B	0.10	0.38	1.08	0.011	0.0028	3.68	0.044	0.0033	0.0025							0.25	0.25		0.0015	8.8
	103B	0.16	0.29	1.52	0.005	0.0007	3.79	0.022	0.0022	0.0011											5.1
	104B	0.15	0.28	1.58	0.018	0.0018	3.32	0.024	0.0021	0.0045	0.002			0.0012	0.0007				0.04		4.7
	105B	0.06	0.27	0.99	0.012	0.0038	3.71	0.039	0.0044	0.0031						0.55	0.48	0.35			10.9
	106B	0.18	0.44	1.61	0.006	0.0019	4.39	0.002	0.0027	0.0022				0.0008							6.8
	107B	0.10	0.11	0.85	0.008	0.0033	2.88	0.008	0.0051	0.0032			0.0019				0.79	0.45	0.50		12.1
	108B	0.08	0.15	0.71	0.007	0.0070	3.92	0.055	0.0044	0.0041	0.012					0.0022		0.39	1.02		14.8
10	109B	0.11	0.08	1.10	0.004	0.0041	3.09	0.026	0.0012	0.0008		0.011					1.26			0.0006	9.9
	110B	0.13	0.28	1.02	0.014	0.0028	3.71	0.031	0.0035	0.0023						0.22					<u>3.4</u>
	111B	0.07	0.16	1.18	0.011	0.0034	2.99	0.062	0.0051	0.0028		0.004		0.0021			0.12	0.11			<u>3.7</u>
	112B	0.11	0.33	1.38	0.007	0.0008	3.28	0.043	0.0028	0.0033							0.70	0.27		0.0008	<u>17.6</u>
	113B	0.15	0.24	1.25	0.009	0.0046	3.55	0.021	0.0037	0.0040						0.88	0.23	0.47	0.02		<u>18.3</u>

15 **[0110]** 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]

20	No.	plate thickness (mm)	rolling conditions		cooling after hot rolling	AC ₃ [°C]	reheat quenching conditions		Temper heat treatment [°C]
25			heating temperature [°C]	hot rolling cumulative rolling reduction ratio [%]			reheat quenching temperature [°C]	cooling after reheating	
30	1B	40	1120	45	water cooling	754	920	water cooling	580
35	2B	35	1090	50	water cooling	754	1010	water cooling	600
	3B	30	1100	48	air cool- ing	764	980	water cooling	480
40	4B	25	1200	55	water cooling	766	950	water cooling	-
	5B	30	1150	68	air cool- ing	743	870	water cooling	500
45	6B	45	1140	55	water cooling	799	900	water cooling	640
	7B	30	1080	60	air cool- ing	812	920	water cooling	600
50	8B	35	1060	52	water cooling	796	910	water cooling	620
	9B	40	1130	59	air cool- ing	825	930	water cooling	590
55	10B	35	1160	47	air cool- ing	825	1020	water cooling	610
	11B	40	1120	54	air cool- ing	832	920	water cooling	640
	12B	35	1140	48	air cool- ing	826	930	water cooling	500
	13B	45	1100	65	water cooling	801	910	water cooling	590

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(continued)

5	No.	plate thickness (mm)	rolling conditions		cooling after hot 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	
10	14B	50	1080	48	air cool- ing	821	900	water cooling	620
	15B	40	1240	50	air cool- ing	780	860	water cooling	640
15	16B	35	1160	60	water cooling	817	860	water cooling	-
	17B	55	1200	52	water cooling	805	940	water cooling	620
20	18B	45	1150	48	air cool- ing	837	980	water cooling	470
	19B	25	1100	41	air cool- ing	854	900	water cooling	580
25	20B	30	1120	62	water cooling	799	920	water cooling	550
	21B	60	1110	32	air cool- ing	799	930	water cooling	620
30	22B	40	1110	55	water cooling	805	920	water cooling	520
	23B	35	1140	65	water cooling	849	840	water cooling	600
35	24B	30	1120	39	water cooling	824	900	water cooling	570
	25B	50	1080	48	water cooling	779	910	water cooling	620
40	101B	45	1090	81	air cool- ing	746	940	water cooling	580
	102B	35	1130	88	water cooling	818	910	water cooling	630
45	103B	55	1100	80	air cool- ing	757	930	water cooling	520
	104B	50	1140	79	air cool- ing	778	950	water cooling	530
50	105B	40	1080	83	air cool- ing	818	970	water cooling	620
	106B	60	1120	80	air cool- ing	735	940	water cooling	540
55	107B	25	1100	89	water cooling	812	980	water cooling	610
	108B	50	1110	79	air cool- ing	842	900	water cooling	630

(continued)

No.	plate thickness (mm)	rolling conditions		cooling after hot 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	
109B	30	1140	87	water cooling	791	920	water cooling	620
110B	40	1150	83	water cooling	780	880	water cooling	640
111B	35	1090	88	water cooling	829	890	water cooling	600
112B	55	1110	77	air cooling	811	900	water cooling	520
113B	45	1080	81	air cooling	775	950	water cooling	550

[Measurement and Evaluation]

[0111] 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 pearlite, MA phase, and ferrite.

Bu: upper bainite

BL: lower bainite

M: martensite

[0112] For the toughness, the average value (KV2) of the Charpy impact absorption energy at -100°C, and the average value of the Charpy impact absorption energy at -100°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 [um]	YR [%]	YS [Mpa]	TS [MPa]	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 [%]										
1B	22	91	1.2	16.9	82	495	602	254	221			examples of present invention
2B	17	94	1.3	22.2	84	502	596	149	125			
3B	52	98	1.2	18.8	86	608	708	235	167			
4B	78	95	1.1	17.7	87	692	795	204	169			
5B	80	91	1.4	16.8	86	636	742	215	175			
6B	38	95	1.2	13.8	85	575	675	298	289			
7B	42	93	1.3	14.8	85	542	638	275	267			
8B	45	96	1.3	15.0	84	546	652	295	296			
9B	29	95	1.2	16.2	82	532	648	315	314			
10B	65	92	1.2	24.1	84	552	655	132	132			
11B	85	94	1.3	13.5	90	688	768	308	305			
12B	72	95	1.2	15.2	86	635	742	278	284			
13B	78	96	1.3	13.9	87	661	758	285	279			
14B	62	94	1.2	14.2	89	638	720	305	310			
15B	71	95	1.2	15.5	90	695	772	234	181			
16B	97	97	1.2	13.1	85	768	905	262	205			
17B	88	97	1.3	17.4	90	792	882	198	184			
18B	90	94	1.2	17.9	88	732	834	192	152			
19B	80	92	1.2	13.3	87	712	816	262	150			
20B	90	95	1.3	17.0	86	748	865	194	162			
21B	92	96	1.1	23.5	92	762	824	138	137			
22B	<u>9</u>	<u>78</u>	1.2	19.2	83	<u>478</u>	<u>578</u>	<u>82</u>	<u>85</u>			comparative examples
23B	15	<u>70</u>	<u>1.6</u>	19.4	85	<u>475</u>	<u>560</u>	<u>27</u>	<u>18</u>			

(continued)

No.	microstructure (area ratio)		aspect ratio average value of prior γ grains	average crystal grain diameter [μm]	YR [%]	YS [Mpa]	TS [MPa]	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 [%]										
24B	54	92	1.2	18.6	89	650	731	24	19			
25B	86	94	1.2	17.3	92	776	845	156	17			
101B	25	92	1.3	15.8	83	552	666	272	218	152	120	examples of present invention
102B	32	94	1.2	14.1	82	569	691	288	271	192	184	
103B	28	93	1.2	18.4	82	532	651	212	188	118	111	
104B	55	94	1.2	18.2	84	588	702	199	154	88	72	
105B	68	94	1.3	15.3	84	657	779	222	209	172	168	
106B	71	96	1.2	14.9	83	624	755	242	217	188	178	comparative examples
107B	91	98	1.3	16.9	88	754	853	182	180	151	149	
108B	88	97	1.3	17.2	88	789	894	179	169	98	89	
109B	92	98	1.2	13.8	89	743	836	225	220	199	188	
110B	7	74	1.2	32.1	81	444	551	42	38	38	32	
111B	8	69	1.1	30.5	81	456	563	45	30	37	31	
112B	98	99	1.3	19.2	90	871	922	31	19	29	17	
113B	97	98	1.2	19.3	90	890	988	32	17	21	14	

[0113] Nos. 1B - 21B and 101B - 109B are Examples of the present invention, and Nos. 22B - 25B and 110B - 113B are Comparative Examples.

[0114] In No. 22B, α was too small, and therefore, sufficient hardenability was not obtained, sufficient strength was not obtained, and sufficient low-temperature toughness also was not obtained.

[0115] In No. 23B, the reheating temperature was low and was lower than A_{c3} , and therefore, sufficient strength was not obtained, and sufficient low-temperature toughness also was not obtained.

[0116] In No. 24B, because there was too little Ni, sufficient low-temperature toughness was not obtained.

[0117] In No. 25B, because the Mn content was too high, sufficient low-temperature toughness after PWHT was not obtained.

[0118] In Nos. 110B and 111B, 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.

[0119] In Nos. 112B and 113B, value α exceeded the upper limit value of the present disclosure, and the hardenability was too high, and the strength was excessive.

[0120] In contrast to the Comparative Examples, in all of the Examples of the present invention (Nos. 1B - 21B and 101B - 109B), the chemical compositions and microstructures of the steel products were controlled appropriately, and the tensile strengths were in the appropriate range of 590 MPa or more and 930 MPa or less. In addition, the Charpy impact absorption energy at - 100°C was high, at 125 J or more, regardless of whether before or after PWHT, and in the Examples having particularly good properties, low-temperature toughness of 150 J or more was obtained.

Industrial Applicability

[0121] 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.

[0122] The disclosures of Japanese Patent Application No. 2023-042400 and Japanese Patent Application No. 2023-042401 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 1.65% or less,

P: 0.025% or less,

S: 0.0250% or less,

Ni: 2.65% or more and 4.45% 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 the following formula (1) is 4.0 or more and 16.0 or less,

wherein:

a tensile strength is 590 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, the lower bainite, and the martensite is 90.0% or
more,

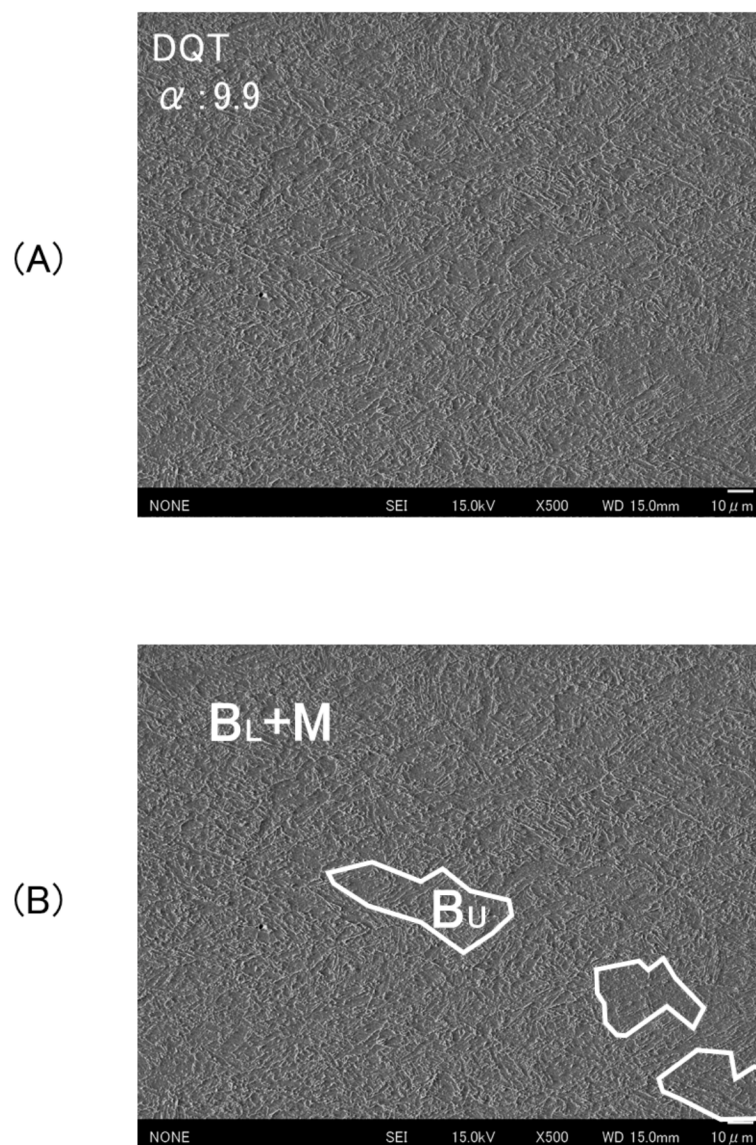
$$\alpha = 0.50 \times \sqrt{[C]} \times (1+0.64[Si]) \times (1+4.10[Mn]) \times (1+0.27[Cu]) \times (1+0.52[Ni]) \times$$

$$(1+2.33[Cr]) \times (1+3.14[Mo]) \dots(1),$$

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 -100°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
-100°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



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2024/010387

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; *C21D 8/00*(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 301B; C22C38/00 301W; C22C38/08; C22C38/58; C21D9/00 L; C21D9/50 101B; C21D9/46 S; C21D8/00 B; C21D8/02 B

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C38/00; C21D8/00; 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	JP 1-219121 A (NIPPON STEEL CORPORATION) 01 September 1989 (1989-09-01)	1-6
A	JP 2001-123245 A (NIPPON STEEL CORPORATION) 08 May 2001 (2001-05-08)	1-6
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A	JP 7-331328 A (KAWASAKI STEEL CORP.) 19 December 1995 (1995-12-19)	1-6

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

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“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

24 May 2024

Date of mailing of the international search report

04 June 2024

Name and mailing address of the ISA/JP

Japan Patent Office (ISA/JP)
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 Japan

Authorized officer

Telephone No.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2024/010387

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Form PCT/ISA/210 (patent family annex) (July 2022)

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