

(19)



(11)

EP 3 940 103 A1

(12)

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

(43) Date of publication:

19.01.2022 Bulletin 2022/03

(51) International Patent Classification (IPC):

C22C 38/00 ^(2006.01) **C21D 8/02** ^(2006.01)
C22C 38/14 ^(2006.01) **C22C 38/58** ^(2006.01)

(21) Application number: **20794425.7**

(52) Cooperative Patent Classification (CPC):

C21D 8/02; C22C 38/00; C22C 38/14; C22C 38/58(22) Date of filing: **30.03.2020**

(86) International application number:

PCT/JP2020/014612

(87) International publication number:

WO 2020/217873 (29.10.2020 Gazette 2020/44)

(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 MK MT NL NO
PL PT RO RS SE SI SK SM TR**

Designated Extension States:

BA ME

Designated Validation States:

KH MA MD TN(71) Applicant: **KABUSHIKI KAISHA KOBE SEIKO SHO****(KOBE STEEL, LTD.)****Hyogo 651-8585 (JP)**(72) Inventor: **NAKO, Hidenori****Kobe-shi, Hyogo 651-2271 (JP)**(74) Representative: **Müller-Boré & Partner****Patentanwälte PartG mbB****Friedenheimer Brücke 21****80639 München (DE)**

(30) Priority: **22.04.2019 JP 2019081271**
21.01.2020 JP 2020007626

(54) **THICK STEEL PLATE**

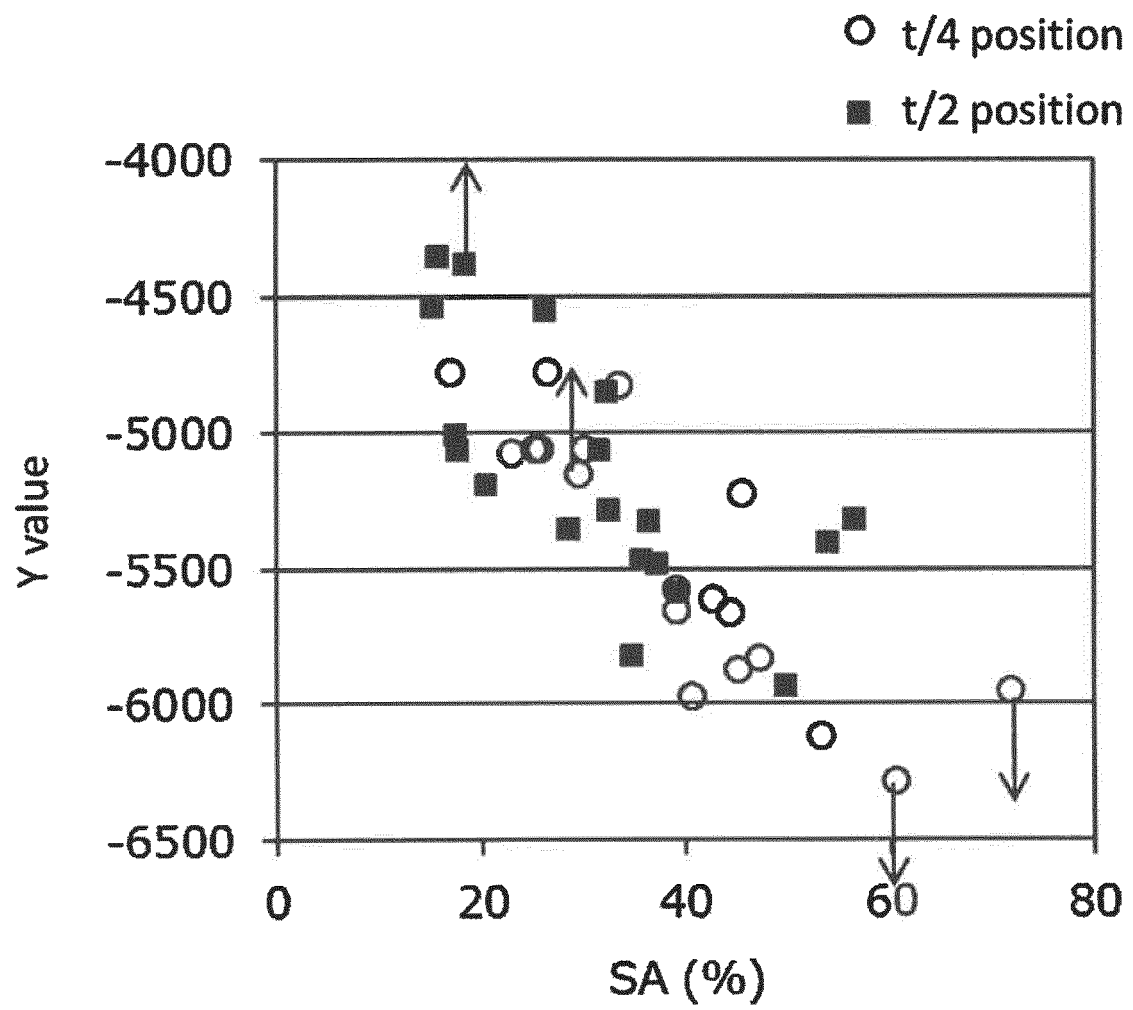
(57) Disclosed is a thick steel plate with the composition satisfying predetermined C, Si, Mn, P, S, Al, Nb, Ti, N and Ca, with the balance consisting of Fe and inevitable impurities, the composition satisfying $Di + 10Nb$: 1.20 to 2.50 determined from the equation (1) below, wherein a total area fraction SA of crystal grains having an equivalent circle diameter of 7.5 μm or less, among crystal grains surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more, is 34% or more at the 1/4 position of the plate thickness, and 27% or more at the 1/2 position of the plate thickness:

$$Di = 1.16 \times ([C]/10)^{0.5} \times (0.7 \times [Si] + 1) \times (5.1 \times ([Mn] - 1.2) + 5) \times (0.35 \times [Cu] + 1) \times (0.36 \times [Ni] + 1) \times (2.16 \times [Cr] + 1) \times (3 \times [Mo] + 1) \times (1.75 \times [V] + 1) \times (200 \times [B] + 1) \quad (1)$$

where, in the equation (1), [element] indicates the content of each element expressed in % by mass, and the content of an element not included is zero.

EP 3 940 103 A1

FIG. 1



Description

Technical Field

5 **[0001]** The present disclosure relate to a thick steel plate and a production method therefor. More particularly, it relates to a high-strength thick steel plate with excellent base metal toughness, and a method for producing the thick steel plate.

Background Art

10 **[0002]** With the increase in size of LPG tanks, there has being increasing a demand for thick steel plates with high strength, low-temperature toughness of base metal and low-temperature toughness of HAZ.

[0003] Patent Document 1 discloses, as a high-strength steel with excellent HAZ toughness, for example, a steel satisfying the prescribed composition in which the C concentration in an average chemical analytical value of the center segregation area of the steel plate is 1.2 times or less than the average C concentration of a steel material, the cleanliness of inclusions as measured by the JIS standard is 0.03% or less, and the number of oxide-based inclusions having an average diameter of 10 μm or more observed in a cross-section of the steel plate is 1 or less/1 mm^2 and the number of oxide and nitride precipitates of 0.05 to 5 μm in size is 100 or more/1 mm^2 .

[0004] Patent Document 2 mentions that a low-yield ratio high-tensile strength steel plate with excellent base metal low-temperature toughness and HAZ low-temperature toughness is obtained by satisfying a prescribed chemical composition, an acicular ferrite structure fraction of 50% or more and an island martensite (MA) structure fraction of 3 to 10% having an average equivalent circle diameter of 1 to 5 μm .

[0005] Patent Document 3 discloses a steel material satisfying the prescribed composition in which a microstructure is a bainite structure, and a yield strength is 500 N/mm^2 or more and a tensile strength is 610 N/mm^2 or more. There is also disclosed that the steel material does not require an annealing heat treatment for removal of residual stress after welding and is suitable for the production of tanks for LPG and ammonia transporting ship.

[0006] Patent Document 4 discloses a method for producing a high-strength steel plate with excellent stress relief (SR) resistance, the method comprising heating a steel, which satisfies a prescribed composition and parameters $9 \times \text{Ceq} + 4 \times \text{P} \geq 4.8$ and $[\text{C}]/([\text{Mo}] + [\text{Ti}] + [\text{Nb}] + [\text{V}])$ is 0.6 to 1.7, to a temperature of 1,100 to 1,300°C, hot-rolling the steel at a finish rolling temperature of 750°C or higher, and then accelerated cooling is performed to a temperature of lower than 400°C at a cooling rate of 20°C/s or more, and immediately thereafter, the hot-rolled steel plate is reheated to 550 to 700°C at a temperature rise rate of 0.5°C/s or more.

Prior Art Document

35 Patent Document

[0007]

Patent Document 1: JP 8-158006 A
 40 Patent Document 2: JP 2009-127065 A
 Patent Document 3: JP 2008-025014 A
 Patent Document 4: JP 2007-270194 A

Disclosure of the Invention

45

Means or Solving the Problems

[0008] In Patent Document 1, although satisfactory balance between the strength and the toughness is obtained, consideration is made only of the plate thicknesses of 40 mm or less in Examples, and there has not been proposed the technology in which consideration is made of a thicker steel plate. In Patent Document 2, an attempt is made of achieving both low-temperature toughness and strength of the base metal and HAZ, however, the low-temperature toughness is evaluated at -60°C and it is believed that further study is required to achieve excellent toughness at lower temperature. In Patent Document 3, mechanical properties are evaluated only at the t/4 position of the plate thickness and no consideration is made of mechanical properties inside the steel plate. Patent Document 4 discloses a method for producing a thick steel plate with satisfactory mechanical properties even after SR, however, the evaluation temperature of the toughness is merely -10°C and no study is made of the toughness at lower temperature. The present disclosure has been made in light of aforementioned circumstances and an object thereof is to provide a thick steel plate which exhibits excellent strength-toughness balance throughout the interior of the steel plate even if the steel plate has

a large plate thickness, particularly a thick steel plate which exhibits high strength and excellent toughness at lower temperature than before, and a method for producing the thick steel plate.

Means for Solving the Problems

[0009] First aspect of the present invention is directed to a thick steel plate with the composition including:

C: 0.020% by mass to 0.070% by mass,
 Si: more than 0% by mass and 0.40% by mass or less,
 Mn: 1.30% by mass to 1.95% by mass,
 P: more than 0% by mass and 0.015% by mass or less,
 S: more than 0% by mass and 0.005% by mass or less,
 Al: 0.005% by mass to 0.070% by mass,
 Nb: 0.015% by mass to 0.048% by mass,
 Ti: 0.005% by mass to 0.024% by mass,
 N: 0.0030% by mass to 0.0080% by mass, and
 Ca: more than 0% by mass and 0.0040% by mass or less, with the balance consisting of Fe and inevitable impurities,
 the composition satisfying $D_i + 10Nb$: 1.20 to 2.50 determined from the equation (1) below, wherein
 a total area fraction SA of crystal grains having an equivalent circle diameter of 7.5 μm or less, among crystal grains
 surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more, is 34% or more at the
 1/4 position of the plate thickness, and 27% or more at the 1/2 position of the plate thickness:

$$D_i = 1.16 \times ([C]/10)^{0.5} \times (0.7 \times [Si] + 1) \times (5.1 \times ([Mn] - 1.2) + 5) \times (0.35 \times [Cu] + 1) \times (0.36 \times [Ni] + 1) \times (2.16 \times [Cr] + 1) \times (3 \times [Mo] + 1) \times (1.75 \times [V] + 1) \times (200 \times [B] + 1) \quad (1)$$

where, in the equation (1), [C], [Si], [Mn], [Cu], [Ni], [Cr], [Mo], [V] and [B] indicate the content of C, Si, Mn, Cu, Ni, Cr, Mo, V and B, respectively, expressed in % by mass, and the content of an element not included is zero.

[0010] Second aspect of the present invention is directed to the thick steel plate according to the first aspect, further including one or more elements selected from the group consisting of:

Cu: more than 0% by mass and 0.75% by mass or less, and
 Ni: more than 0% by mass and 1.4% by mass or less.

[0011] Third aspect of the present invention is directed to the thick steel plate according to the first or second aspect, further including one or more elements selected from the group consisting of:

Mo: more than 0% by mass and 0.50% by mass or less,
 V: more than 0% by mass and 0.060% by mass or less,
 Cr: more than 0% by mass and 0.8% by mass or less, and
 B: more than 0% by mass and 0.0007% by mass or less.

[0012] Fourth aspect of the present invention is directed to the thick steel plate according to any one of the first to third aspects, further including one or more elements selected from the group consisting of:

REM: more than 0% by mass and 0.0060% by mass or less, and
 Zr: more than 0% by mass and 0.0050% by mass or less.

[0013] Fifth aspect of the present invention is directed to a method for producing the thick steel plate according to any one of the first to fourth aspects, the method including:

a step of heating a steel piece with the composition according to any one of the first to fourth aspects to a temperature

of higher than 1,020°C and lower than 1,200°C, and a hot-rolling step after heating, wherein the hot-rolling step is a step in which the number of roll passes is set at three or more, and hot-rolling and cooling after the hot-rolling are performed so as to satisfy all of the following conditions (a) to (d):

- (a) a cumulative rolling reduction ratio in a temperature range of 850°C or lower is 40% or more,
- (b) an average rolling reduction ratio in the last three passes of rolling is 5.5% or more,
- (c) a finishing rolling temperature is 720 to 830°C, and
- (d) after hot-rolling, cooling is performed at an average cooling rate of 0.5 to 20°C/s from a start cooling temperature of the finishing rolling temperature to 690°C to a finish cooling temperature of 320 to 550°C.

Effects of the Invention

[0014] According to the present disclosure, it is possible to provide a thick steel plate which exhibits excellent strength-toughness balance throughout the interior of the steel plate even if the steel plate has a large plate thickness, particularly a thick steel plate which exhibits high strength and excellent toughness at lower temperature than before, and a production method therefor.

Brief Description of the Drawings

[0015] FIG. 1 is a graph showing the relationship between a total area fraction SA of crystal grains having an equivalent circle diameter of 7.5 μm or less, among crystal grains surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more, and a Y value.

Mode for Carrying Out the Invention

[0016] In the present disclosure, an intensive study has been made so as to obtain a thick steel plate with an improved balance between the strength and the toughness at lower temperature than before, in a state before SR, namely, as-hot rolled state. In particular, an intensive study has been made so as to obtain a thick steel plate with excellent strength-toughness balance at the 1/4 and 1/2 positions of the plate thickness even if the steel plate has a large plate thickness, specifically with sufficiently low parameter $Y (= 20 \times \sqrt{Trs} - 7 \times YP)$ related to the strength-toughness balance defined in the present disclosure.

[0017] As a result, it has been found that satisfactory properties mentioned above can be obtained by controlling the composition and securing a prescribed amount of a fine acicular ferrite structure at the 1/4 and 1/2 positions of the plate thickness, more specifically by securing a prescribed amount of an acicular ferrite having an equivalent circle diameter of 7.5 μm or less as measured by the method mentioned later. Hereinafter, the 1/4 position of the plate thickness is sometimes referred to as "t/4 position" and the 1/2 position of the plate thickness is sometimes referred to as "t/2 position".

[0018] It has been found it effective to implement all of the following (A) to (C) in order to form a prescribed amount of the above fine acicular ferrite structure. Hereinafter, the acicular ferrite is sometimes referred to as "AF".

(A) Before transformation from an austenite phase to a ferrite phase, sufficient processing strain is applied to the austenite phase by hot-rolling. A dislocation structure and a deformation zone introduced by this processing serve as nuclei for formation of AF grains, thereby realizing a microstructure.

(B) Before rolling at the non-recrystallization temperature, solute Nb is secured. By doing so, it becomes easier to obtain the processing strain prior to transformation, and fine AF crystal grains are easily formed as mentioned above. To secure the solute Nb, it is effective to set the pre-rolling heating temperature at higher than 1,020°C and to decrease a rolling reduction ratio during rolling at 850°C or higher, as mentioned later.

(C) The transformation temperature to the ferrite phase is appropriately controlled. If the transformation temperature to the ferrite phase is high, a grain boundary ferrite structure is formed prior to formation of AF, and the amount of AF decreases. Meanwhile, if the transformation temperature to the ferrite phase is low, a martensite structure is formed without forming the AF structure. In order to appropriately control the transformation temperature to the ferrite phase, it is necessary to control the C content, the Mn content, and when at least one of Cu and Ni is included, the content thereof in the composition and each range of $Di + 10Nb$, and to control the average cooling rate in the prescribed temperature range after hot-rolling at 0.5°C/s or higher, as mentioned later.

[0019] Hereinafter, the steel structure and composition, properties, and production method of the thick steel plate of the present disclosure will be described in order.

1. Steel Structure

[0020] The steel structure of the thick steel plate of the present disclosure will be described in detail below. In the following description of the steel structure, mechanisms capable of improving various properties are sometimes described by having such structure. It should be noted that these are the mechanisms that the inventors of the present application have considered based on the knowledge currently available, but they do not limit the technical scope of the present disclosure.

[0021] In the present disclosure, crystal grains having an equivalent circle diameter of 7.5 μm or less, among crystal grains surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more, are defined as a fine acicular ferrite (AF) structure. In the present disclosure, "forming a prescribed amount of a fine acicular ferrite (AF) structure" means that crystal grains, which are surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more and have an equivalent circle diameter of 7.5 μm or less, are secured in the proportion of 34% or more at the t/4 position and 27% or more at the t/2 position, as mentioned later.

[0022] In the present disclosure, in order to obtain a thick steel plate which exhibits excellent strength-toughness balance even if the steel plate has a large plate thickness, a total area fraction SA of crystal grains having an equivalent circle diameter of 7.5 μm or less, among crystal grains surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more, namely, an area fraction of the fine acicular ferrite (AF) structure is specified at both the t/4 and t/2 positions. Specifically, the total area fraction SA is set at 34% or more at the t/4 position and 27% or more at the t/2 position. The total area fraction SA at the t/4 position is preferably 35% or more, and more preferably 36% or more. The total area fraction SA at the t/2 position is preferably 28% or more, and more preferably 30% or more. From the viewpoint of obtaining excellent strength-toughness balance, the upper limit of the total area fraction SA at each of the t/4 and t/2 positions is not particularly limited. Considering the production conditions of the thick steel plate in the embodiment of the present invention, the upper limit of the total area fraction SA at the t/4 position is about 80%, and the upper limit of the total area fraction SA at the t/2 position is about 70%.

[0023] Examples of the structure other than the fine acicular ferrite include bainite, ferrite, cementite, residual austenite, martensite and the like. As long as the total area fraction SA is within the range specified in the embodiment of the present invention, an acicular ferrite having an equivalent circle diameter of more than 7.5 μm may exist.

2. Composition

[0024] The composition of the thick steel plate according to the present disclosure will be described below.

C: 0.020% by mass to 0.070% by mass

[0025] C has the effect of appropriately controlling the ferrite transformation temperature and suppressing formation of a grain boundary ferrite, which acts as a starting point for brittle fracture and causes deterioration of the strength-toughness balance, before AF formation. From the viewpoint of exerting the effect, the C content is 0.020% by mass or more, preferably 0.023% by mass or more, and more preferably 0.030% by mass or more. Meanwhile, excessive C content causes formation of a hard martensite structure, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance. The C content is set at 0.070% by mass or less. The C content is preferably 0.065% by mass or less, and more preferably 0.060% by mass or less.

Si: more than 0% by mass and 0.40% by mass or less

[0026] Si is a deoxidizing element, and the content thereof is more than 0% by mass. The Si content may be 0.05% by mass or more, or may be 0.10% by mass or more. Meanwhile, excessive Si content causes formation of a hard martensite structure, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance. Therefore, the Si content is 0.40% by mass or less, preferably 0.38% by mass or less, and more preferably 0.35% by mass or less.

Mn: 1.30% by mass to 1.95% by mass

[0027] Mn has the effect of appropriately controlling the ferrite transformation temperature and suppressing formation of a grain boundary ferrite, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance, before AF formation. From the viewpoint of exerting the effect, the Mn content is 1.30% by mass or more, preferably 1.40% by mass or more, and more preferably 1.45% by mass or more. Meanwhile, excessive Mn content causes formation of a hard martensite structure, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance. Therefore, the Mn content is preferably 1.95% by mass or less, preferably

EP 3 940 103 A1

1.90% by mass or less, and more preferably 1.80% by mass or less.

P: more than 0% by mass and 0.015% by mass or less

5 **[0028]** P is an impurity element, and excessive content thereof causes the embrittlement of grain boundaries, leading to deterioration of the strength-toughness balance. Therefore, the P content is set at 0.015% by mass or less. The P content is preferably 0.008% by mass or less, and more preferably 0.007% by mass or less. Meanwhile, since it is industrially difficult to decrease the P content to 0% by mass, the lower limit of the P content is more than 0% by mass.

10 S: more than 0% by mass and 0.005% by mass or less

[0029] S is an impurity element, and excessive content thereof causes the embrittlement of grain boundaries, leading to deterioration of the strength-toughness balance. Therefore, the S content is set at 0.005% by mass or less. The S content is preferably 0.004% by mass or less, and more preferably 0.003% by mass or less. Meanwhile, since it is industrially difficult to decrease the S content to 0% by mass, the lower limit of the S content is more than 0% by mass.

Al: 0.005% by mass to 0.070% by mass

20 **[0030]** Al is a deoxidizing element. In order to decrease the content of oxygen in the steel by sufficient deoxidization to suppress deterioration of the strength-toughness balance due to oxide, the Al content is set at 0.005% by mass or more. The Al content is preferably 0.010% by mass or more, and more preferably 0.015% by mass or more. Meanwhile, excessive Al content causes formation of coarse oxide, leading to deterioration of the strength-toughness balance. Therefore, the Al content is 0.070% by mass or less, preferably 0.050% by mass or less, and more preferably 0.045% by mass or less.

25 Nb: 0.015% by mass to 0.048% by mass

30 **[0031]** Nb is an element which promotes formation of AF. In order to sufficiently form a fine AF structure to obtain satisfactory strength-toughness balance, the Nb content is set at 0.015% by mass or more, preferably 0.016% by mass or more, and more preferably 0.018% by mass or more. Meanwhile, excessive Nb content causes formation of a hard martensite structure and this structure acts as a brittle fracture starting point, leading to deterioration of the strength-toughness balance. Therefore, the Nb content is 0.048% by mass or less, preferably 0.045% by mass or less, and more preferably 0.040% by mass or less.

35 Ti: 0.005% by mass to 0.024% by mass

[0032] Ti is an element which contributes to an improvement in HAZ toughness due to formation of TiN. From the viewpoint of exerting the effect, the Ti content is 0.005% by mass or more, preferably 0.007% by mass or more, and more preferably 0.009% by mass or more. Meanwhile, excessive Ti content causes formation of coarse crystallized TiN, leading to deterioration of the strength-toughness balance. Therefore, the Ti content is 0.024% by mass or less, preferably 0.022% by mass or less, and more preferably 0.020% by mass or less.

N: 0.0030% by mass to 0.0080% by mass

45 **[0033]** N is an element which contributes to an improvement in HAZ toughness due to formation of TiN. From the viewpoint of exerting the effect, the N content is 0.0030% by mass or more, preferably 0.0032% by mass or more, and more preferably 0.0035% by mass or more. Meanwhile, excessive N content increases solute N, leading to deterioration of the strength-toughness balance. Therefore, the N content is 0.0080% by mass or less, preferably 0.0075% by mass or less, and more preferably 0.0070% by mass or less.

50 Ca: more than 0% by mass and 0.0040% by mass or less

[0034] Ca is a deoxidizing element, and the content thereof is more than 0% by mass. It is considered that large content of Mn in the steel easily form coarse MnS at the t/2 position due to the concentration of Mn during casting, leading to deterioration of the toughness at the t/2 position. In order to suppress formation of MnS, the Ca content is set at preferably more than 0% by mass, more preferably 0.0008% by mass or more, and still more preferably 0.0010% by mass or more. Meanwhile, excessive Ca content causes formation of coarse oxide, leading to deterioration of the strength-toughness balance. Therefore, the Ca content is 0.0040% by mass or less, preferably 0.0028% by mass or

less, and more preferably 0.0025% by mass or less.

[0035] The balance consists of Fe and inevitable impurities. It is permitted to mix, as inevitable impurities, trace elements, for example, As, Sb, Sn, etc. introduced according to the conditions of raw materials, materials, production facilities and the like. There are elements whose content is preferably as small as possible, for example like P and S, which are therefore inevitable impurities in which the composition range is separately specified as mentioned above. Therefore, "inevitable impurities" constituting the balance as used herein means the concept excluding the elements whose composition ranges are separately defined.

[0036] The thick steel plate in the embodiment of the present invention may include the above elements in the composition. Although selected elements mentioned below may not be included, high strength can be achieved more easily by including them together with the above-mentioned elements as necessary. It is also possible to achieve the desired structure more easily, thus making it possible to achieve the strength-toughness balance required in the embodiment of the present invention more easily. The selected elements are mentioned below.

[0037] One or more elements selected from the group consisting of Cu: more than 0% by mass and 0.75% by mass or less, and Ni: more than 0% by mass and 1.4% by mass or less

These elements have the effect of appropriately controlling the ferrite transformation temperature and suppressing formation of a grain boundary ferrite, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance, before AF formation. From the viewpoint of exerting the effect, when Cu is included, the content thereof is set at preferably more than 0% by mass, more preferably 0.05% by mass or more, still more preferably 0.10% by mass or more, and yet more preferably 0.15% by mass or more. When Ni is included, the content thereof is set at preferably more than 0% by mass, more preferably 0.10% by mass or more, still more preferably 0.15% by mass or more, and yet more preferably 0.20% by mass or more. Meanwhile, excessive contents of these elements cause formation of a hard martensite structure, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance. Therefore, the Cu content is preferably 0.75% by mass or less, more preferably 0.70% by mass or less, and still more preferably 0.68% by mass or less. The Ni content is preferably 1.4% by mass or less, more preferably 1.2% by mass or less, and still more preferably 1.0% by mass or less.

[0038] One or more elements selected from the group consisting of Mo: more than 0% by mass and 0.50% by mass or less, V: more than 0% by mass and 0.060% by mass or less, Cr: more than 0% by mass and 0.8% by mass or less, and B: more than 0% by mass and 0.0007% by mass or less

[0039] These elements are effective in improving the strength. From the viewpoint of exerting the effect, when Mo is included, the content thereof is preferably more than 0% by mass, more preferably 0.05% by mass or more, still more preferably 0.10% by mass or more. When V is included, the content thereof is preferably more than 0% by mass, more preferably 0.01% by mass or more, and still more preferably 0.02% by mass or more. When Cr is included, the content thereof is preferably more than 0% by mass, more preferably 0.10% by mass or more, still more preferably 0.20% by mass or more. When B is included, the content thereof is preferably more than 0% by mass, and more preferably 0.0003% by mass or more.

[0040] Meanwhile, excessive contents of these elements cause formation of a hard martensite structure, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance. Therefore, the Mo content is preferably 0.50% by mass or less, more preferably 0.45% by mass or less, and still more preferably 0.40% by mass or less. The V content is preferably 0.060% by mass or less, more preferably 0.050% by mass or less, and still more preferably 0.045% by mass or less. The Cr content is preferably 0.8% by mass or less, more preferably 0.70% by mass or less, and still more preferably 0.60% by mass or less. The B content is preferably 0.0007% by mass or less, and more preferably 0.0006% by mass or less.

[0041] One or more elements selected from the group consisting of

REM: more than 0% by mass and 0.0060% by mass or less, and
Zr: more than 0% by mass and 0.0050% by mass or less

[0042] These elements are deoxidizing elements. In order to exert the effect, when REM is included, the content thereof is preferably more than 0% by mass, more preferably 0.0010% by mass or more, and still more preferably 0.0015% by mass or more. When Zr is included, the content thereof is preferably more than 0% by mass, more preferably 0.0010% by mass or more, and still more preferably 0.0012% by mass or more. Meanwhile, excessive contents of these elements cause formation a hard martensite structure, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance. Therefore, the REM content is preferably 0.0060% by mass or less, more preferably 0.0050% by mass or less, and still more preferably 0.0045% by mass or less. The Zr content is preferably 0.0050% by mass or less, more preferably 0.0045% by mass or less, and still more preferably 0.0040% by mass or less. The above-mentioned REM means including lanthanide elements (15 elements from La to Lu), Sc (scandium) and Y (yttrium).

[0043] $Di + 10Nb$: 1.20 to 2.50 (Di is determined from the equation (1) below)

$$\begin{aligned}
 Di = & 1.16 \times ([C]/10)^{0.5} \times (0.7 \times [Si] + 1) \times (5.1 \times \\
 & ([Mn] - 1.2) + 5) \times (0.35 \times [Cu] + 1) \times (0.36 \times [Ni] + 1) \times \\
 & (2.16 \times [Cr] + 1) \times (3 \times [Mo] + 1) \times (1.75 \times [V] + 1) \times (200 \\
 & \times [B] + 1) \quad (1)
 \end{aligned}$$

where, in the equation (1), [C], [Si], [Mn], [Cu], [Ni], [Cr], [Mo], [V] and [B] indicate the content of C, Si, Mn, Cu, Ni, Cr, Mo, V and B, respectively, expressed in % by mass, and the content of an element not included is zero.

[0044] Di + 10Nb is a parameter which exerts an influence on the ferrite transformation temperature. By appropriately controlling the ferrite transformation temperature, it is possible to suppress formation of a grain boundary ferrite prior to formation of AF, and excessive formation of pearlite and martensite structures other than AF, thus making it possible to promote formation of AF. From these points of view, Di + 10Nb was set in a range of 1.20 to 2.50 in the embodiment of the present invention. If the value of Di + 10Nb is too small, the pearlite structure is formed together with the grain boundary ferrite, leading to deterioration of the strength-toughness balance. Therefore, Di + 10Nb is set at 1.20 or more. Di + 10Nb is preferably 1.25 or more, and more preferably 1.30 or more. Meanwhile, excessive value of Di + 10Nb causes formation of a hard martensite structure, which acts as a starting point for brittle fracture, leading to deterioration of the strength-toughness balance. Therefore, Di + 10Nb is set at 2.50 or less. Di + 10Nb is preferably 2.20 or less, and more preferably 2.00 or less.

[0045] The plate thickness of the thick steel plate in the embodiment of the present invention is preferably 16 mm or more, more preferably 30 mm or more, still more preferably 40 mm or more, and particularly preferably more than 40 mm. The upper limit of the plate thickness is not particularly limited and, for example, it is preferably 80 mm or less.

[0046] The thick steel plate of the present disclosure has the following properties, and is suitable for the production of large tanks for LPG, ships and the like.

3. Properties

[0047] In the present disclosure, Y value, which is a parameter shown in the equation (2) below, is used to evaluate a balance between the strength and the toughness at a lower temperature than before. The Y value includes a yield strength YP and a brittle-ductile transition temperature vTrs, as shown in the equation (2) below. As the yield strength YP in the equation (2) below, a 0.2% proof stress (0.2YS) is used when an SS curve (also referred to as "stress-strain diagram") is a round-type SS curve with no apparent yield point, while YP is used when the curve has a yield point.

[0048] The thick steel plate according to the embodiment of the present invention is evaluated as having excellent strength-toughness balance if it is in the as-hot rolled state, and the Y at the t/4 position is less than -5,200 and the Y at the t/2 position is less than -4,700 in the C direction perpendicular to the rolling direction.

$$Y = 20 \times vTrs - 7 \times YP \quad (2)$$

[0049] The Y value at the t/4 position is preferably -5,300 or less, and more preferably -5,400 or less, and the Y value at the t/2 position is preferably -4,800 or less, and more preferably -5,000 or less. The lower these values are, the better the strength-toughness balance is.

[0050] In the embodiment of the present invention, it is enough to achieve the above parameters as properties. For each of the yield strength YP and the brittle-ductile transition temperature vTrs, assuming that the above parameters are achieved, for example, the yield strength YP is preferably in a range of 350 to 550 MPa and the brittle-ductile transition temperature vTrs is in a range of preferably lower than -70°C, and more preferably lower than -80°C. By the measurement position, at the t/4 position, assuming that the above parameters are achieved, for example, the yield strength YP is preferably 410 MPa or more, more preferably 430 MPa or more, still more preferably 460 MPa or more, yet more preferably 480 MPa or more, and particularly 500 MPa or more. The brittle-ductile transition temperature vTrs is preferably -90°C or lower, more preferably -95°C or lower, still more preferably -100°C or lower, and yet more preferably -110°C or lower. At the t/2 position, assuming that the above parameters are achieved, for example, the yield strength YP is preferably 400 MPa or more, more preferably 430 MPa or more, still more preferably 460 MPa or more, yet more preferably 480 MPa or more, and particularly 500 MPa or more, and the brittle-ductile transition temperature vTrs is preferably -80°C or lower, more preferably -90°C or lower, still more preferably -95°C or lower, and yet more preferably -100°C or lower.

4. Production Method

[0051] The method for producing a thick steel plate according to the present disclosure is a method for producing a thick steel plate, which includes a step of heating a steel piece with the above-mentioned composition to a temperature of higher than 1,020°C and lower than 1,200°C, and a hot-rolling step after heating, wherein the hot-rolling step is a step in which the number of roll passes is set at three or more, and hot-rolling and cooling after the hot-rolling are performed so as to satisfy all of the following conditions (a) to (d):

- (a) a cumulative rolling reduction ratio in a temperature range of 850°C or lower is 40% or more,
- (b) an average rolling reduction ratio in the last three passes of rolling is 5.5% or more,
- (c) a finishing rolling temperature is 720 to 830°C, and
- (d) after hot-rolling, cooling is performed at an average cooling rate of 0.5 to 20°C/s from a start cooling temperature of the finishing rolling temperature to 690°C to a finish cooling temperature of 320 to 550°C.

[0052] The production conditions will be described in detail below.

[Step of heating steel piece with above-mentioned composition to temperature of higher than 1,020°C and lower than 1,200°C]

[0053] In heating of hot-rolling, if the heating temperature is 1,020°C or lower, NbC formed during casting does not sufficiently solid-soluted, thus failing to obtain the effect of promoting the formation of AF by solute Nb. Therefore, the heating temperature is set at higher than 1,020°C, preferably 1,040°C or higher, more preferably 1,050°C or higher, and still more preferably 1,060°C or higher. Meanwhile, if the heating temperature is 1,200°C or higher, austenite crystal grains undergoes coarsening, leading to coarsening of the entire structure. Therefore, the heating temperature is set at lower than 1,200°C, preferably 1,180°C or lower, and more preferably 1,150°C or lower.

[Hot-Rolling Step after heating]

[0054] The present disclosure is characterized in that an average rolling reduction ratio of the last three passes of rolling is controlled, as mentioned below. After heating, hot-rolling is performed with three or more roll passes. However, the total number of passes (number of roll passes) does not exert an influence on the structure and properties, and is not limited. The number of roll passes is further 7 passes or more, and still further 10 passes or more, and can be set at 60 passes or less from the viewpoint of the productivity.

[0055] In the embodiment of the present invention, hot-rolling and cooling after the hot-rolling are performed so as to satisfy all of the following conditions (a) to (d).

(a) Cumulative rolling reduction ratio at temperature range of 850°C or lower: 40% or more

[0056] In order to introduce sufficient processing strain into the austenite phase for the purpose of obtaining a sufficient AF structure, there is a need to set the cumulative rolling reduction ratio (also referred to as "total rolling reduction ratio") in a temperature range of 850°C or lower in hot-rolling at 40% or more. By the way, if the rolling reduction ratio during rolling at 850°C or higher increases, it is considered that NbC is precipitated during rolling, leading to a decrease in solute Nb. From the viewpoint of suppressing the cumulative rolling reduction ratio during rolling at 850°C or higher, the cumulative rolling reduction ratio in a temperature range of 850°C or lower is set at 40% or more. The cumulative rolling reduction ratio is preferably 50% or more, and more preferably 55% or more. The upper limit of the cumulative rolling reduction ratio is about 80% from the viewpoint of the productivity.

(b) Average rolling reduction ratio in the last three passes of rolling: 5.5% or more

[0057] Since the dislocation structure introduced during rolling reduction in the last three passes is transferred to the cooling step with relatively little recovery in progress, large AF promoting effect is exerted. In the embodiment of the present invention, the average rolling reduction ratio in the last three passes of rolling is set at 5.5% or more in order to introduce sufficient processing strain into the austenite phase for the introduction of the dislocation structure. The embodiment of the present invention differs from a conventional method in which the average rolling reduction ratio of the last three passes of rolling is not controlled, in that a desired structure with a constant or higher AF structure can be obtained even inside the steel plate, especially at the t/2 position, by controlling the average rolling reduction ratio in the last three passes of rolling. The average rolling reduction ratio is preferably 5.8% or more, and more preferably 6.0% or more. Meanwhile, from the viewpoint of rolling mill load, the upper limit of the average rolling reduction ratio is about 20%.

(c) Finishing Rolling Temperature (FRT): 720 to 830°C

[0058] When the temperature of the steel material is higher than 850°C, even if the last three passes of rolling are performed at the above average rolling reduction ratio, sufficient processing strain is not introduced into the austenite phase, leading to insufficient amount of AF structure. In the embodiment of the present invention, the finishing rolling temperature is set at 830°C or lower in order to secure a sufficient amount of the AF structure. The finishing rolling temperature is preferably 820°C or lower, and more preferably 810°C or lower. Meanwhile, if the finishing rolling temperature is lower than 720°C, coarse ferrite is formed during rolling, leading to deterioration of the toughness. Therefore, the finishing rolling temperature is set at 720°C or higher, preferably 750°C or higher, and more preferably 760°C or higher.

(d) After hot-rolling, cooling is performed at average cooling rate of 0.5 to 20°C/s from start cooling temperature of the finishing rolling temperature to 690°C to finish cooling temperature of 320 to 550°C

[0059] By cooling at an average cooling rate of 0.5 to 20°C/s in a certain temperature range, the AF structure can be sufficiently secured. It is not preferable that the average cooling rate is more than 20°C/s since martensitic transformation occurs without sufficient formation of the AF structure, unfavorably. The average cooling rate is preferably 15°C/s or less, and more preferably 12°C/s or less. As mentioned above, in order to appropriately control the transformation temperature to the ferrite phase to sufficiently secure the AF structure, it is necessary to control the C content, Mn content, and when at least one of Cu and Ni is included, the content thereof and each range of $Di + 10Nb$, and to control the average cooling rate in the prescribed temperature range at 0.5°C/s or higher. If the average cooling rate is less than 0.5°C/s, coarse grain boundary ferrite is formed during cooling, leading to insufficient amount of the AF structure. The average cooling rate is preferably 2.0°C/s or more, and more preferably 3.0°C/s or more. Examples of the method of decreasing the average cooling rate include water cooling.

[0060] The start temperature of cooling is set at any temperature between the finishing rolling temperature and 690°C. If the temperature of the steel material is lower than 710°C, problems, such as formation of the grain boundary ferrite before the start of cooling and the recovery of processing strain introduced into the austenite phase, are likely to occur. As a result, the amount of the AF structure is likely to be insufficient. In the embodiment of the present invention, the start cooling temperature (SCT) at the above average cooling rate is set at 690°C or higher in order to secure a sufficient amount of the AF structure. The cooling start temperature is preferably 710°C or higher, and more preferably 720°C or higher.

[0061] The finish cooling temperature (FCT) is set at any temperature between 320 and 550°C. If cooling at the above average cooling rate, for example, water cooling is stopped in a temperature range of higher than 550°C, the grain boundary ferrite is formed during slow cooling after stopping water cooling, thus making it difficult to sufficiently secure the AF structure. Therefore, the finish temperature is set at 550°C or lower. The finish temperature is preferably 500°C or lower, and more preferably 480°C or lower. Meanwhile, if cooling at the above average cooling rate is performed to a temperature range of lower than 320°C, martensitic transformation occurs without sufficiently forming the AF structure. Therefore, the finish temperature is set at 320°C or higher. The finish temperature is preferably 340°C or higher, and more preferably 360°C or higher.

[0062] The production method of the present disclosure is not particularly limited, except for the above-mentioned hot-rolling step, and can be implemented under conventional conditions.

[0063] A person skilled in the art, who got in touch with the method for producing a high-strength steel plate according to the embodiment of the invention which has been described above, may be able to obtain high-strength steel plate according to the embodiment of the present invention by a production method different from the above-mentioned method through trial and error.

Examples

[0064] The embodiments of present invention will be illustrated more specifically below by way of Examples. It should be noted that the present disclosure is not limited to the following Examples, and various modifications can be made to these Examples as long as they are adaptable to the above-mentioned and below-mentioned concepts and are included within the technical scope of the present disclosure.

1. Fabrication of Samples

[0065] A steel slab obtained by melting and casting a steel with the composition shown in Table 1 in a 150 kg vacuum induction furnace (VIF) or an actual converter was hot-rolled under various conditions shown in Table 2 to obtain steel plates having each thickness shown in Table 2. In the above hot-rolling, the total number of passes (the number of roll passes) was set at more than 20. In Table 1, "-" indicates that no element is intentionally added. In Table

EP 3 940 103 A1

2, FRT indicates the finishing rolling temperature, SCT indicates the start cooling temperature, and FCT indicates the finish cooling temperature. The finish cooling temperature FCT was measured at one to three points on the steel plate surface in the longitudinal direction using a radiation thermometer, and the average value was calculated. FRT and SCT were determined by measuring one point on the steel material surface using a radiation thermometer.

5

10

15

20

25

30

35

40

45

50

55

[Table 1]

Material No.	Chemical composition [% by mass]									Balance being iron and inevitable impurities										Di	Di + 10Nb
	C	Si	Mn	P	S	Al	Cu	Ni	Nb	Ti	N	Ca	Mo	V	Cr	B	REM	Zr			
A	0.040	0.30	1.55	0.0050	0.0010	0.032	0.19	0.54	0.026	0.013	0.0050	0.002	0.19	-	-	-	-	-	1.20	1.46	
B	0.040	0.30	1.51	0.005	0.0015	0.026	0.65	0.54	0.045	0.013	0.0050	0.0013	-	-	-	-	-	-	0.86	1.31	
C	0.040	0.30	1.54	0.005	0.0016	0.028	0.18	0.52	0.026	0.013	0.0051	0.0015	0.19	-	-	-	-	-	1.18	1.44	
D	0.050	0.30	1.50	0.005	0.0016	0.026	0.22	0.60	0.030	0.012	0.0047	0.0011	0.25	-	-	-	-	-	1.49	1.79	
E	0.050	0.31	1.51	0.005	0.0018	0.026	0.23	0.62	0.030	0.012	0.0054	0.0010	0.25	0.040	-	-	-	-	1.63	1.93	
F	0.036	0.30	1.53	0.005	0.0013	0.027	0.20	0.53	0.025	0.011	0.0041	0.0015	0.25	-	-	-	-	-	1.25	1.50	
G	0.039	0.31	1.55	0.005	0.0015	0.028	0.21	0.53	0.025	0.011	0.0049	0.0015	0.20	0.040	-	-	-	-	1.31	1.56	
H	0.038	0.30	1.56	0.005	0.0009	0.026	0.20	0.54	0.047	0.012	0.0044	0.0015	0.20	-	-	-	-	-	1.21	1.68	
I	0.039	0.31	1.54	0.005	0.0020	0.029	0.20	0.51	0.025	0.017	0.0047	0.0015	0.20	0.039	-	-	-	-	1.29	1.54	
J	0.038	0.30	1.53	<0.003	0.002	0.026	0.20	0.55	0.024	0.008	0.0045	0.0016	0.20	0.041	-	-	-	-	1.27	1.51	
K	0.038	0.31	1.55	0.005	0.0018	0.028	0.19	0.53	0.026	0.013	0.0058	0.0015	0.05	-	-	-	-	-	0.86	1.12	
L	0.039	0.31	1.54	0.005	0.0021	0.029	0.20	0.53	0.024	0.012	0.0048	0.0015	0.20	0.54	-	-	-	-	2.35	2.59	
M	0.039	0.31	1.54	0.005	0.0018	0.029	0.20	0.54	0.025	0.012	0.0055	0.0015	0.20	0.54	-	-	-	-	2.36	2.61	
N	0.036	0.31	1.56	0.005	0.001	0.030	0.20	0.53	0.026	0.013	0.0039	0.0016	0.20	-	-	0.0008	-	-	1.37	1.63	
O	0.036	0.30	1.52	0.005	0.002	0.029	0.20	0.53	0.018	0.012	0.0047	0.0016	0.20	-	-	-	-	-	1.14	1.32	
P	0.037	0.30	1.53	0.005	<0.001	0.030	0.19	0.53	0.014	0.013	0.0053	0.0017	0.20	-	-	-	-	-	1.16	1.30	

[Table 2]

Test No.	Material No.	Plate thickness [mm]	Heating temperature [°C]	Rolling reduction ratio at 850°C or lower [%]	Average rolling reduction ratio in last three passes [%]	FRT [°C]	SCT [°C]	FCT [°C]	Cooling rate [°C/s]	SA		Mechanical properties at t/4 position			Mechanical properties at t/2 position		
										t/4 [%]	t/2 [%]	Y	YP [MPa]	vTs [°C]	Y	YP [MPa]	vTs [°C]
1	A	63	1,100	60	8.0	822	766	390	8.4	42.6	28.5	-5,606	418	-134	-5,355	445	-112
2	A	63	1,100	60	8.0	817	698	340	9.0	45.3	32.3	-5,222	346	-140	-4,849	367	-114
3	B	63	1,100	61	6.0	796	771	437	7.1	53.1	34.7	-6,112	496	-132	-5,819	517	-110
4	C	63	1,100	61	6.0	799	771	363	8.0	39.0	36.3	-5,575	465	-116	-5,328	484	-97
5	D	63	1,100	61	6.0	798	762	407	7.7	47.1	39.2	-5,830	530	-106	-5,590	530	-94
6	E	63	1,100	61	6.0	800	770	413	7.7	44.2	35.5	-5,657	531	-97	-5,464	532	-87
7	F	63	1,100	69	10.2	800	768	460	6.8	45.0	53.8	-5,870	510	-115	-5,405	495	-97
8	G	63	1,100	69	10.2	802	768	350	7.7	71.7	56.5	-5,953	479	<-130	-5,321	483	-97
9	H	63	1,100	69	10.2	800	768	420	7.1	60.3	49.8	-6,282	526	<-130	-5,934	522	-114
10		63	1,100	61	10.2	801	772	403	8.0	40.6	31.6	-5,971	513	-119	-5,065	495	-80
11	J	63	1,100	61	10.2	798	768	403	9.1	38.9	37.2	-5,650	510	-104	-5,480	500	-99
12	A	63	1,100	32	7.7	822	741	403	8.9	22.9	15.1	-5,073	379	-121	-4,539	397	-88
13	A	63	1,100	61	10.2	833	763	377	9	30.0	17.5	-5,056	388	-117	-5,007	421	-103
14	A	63	1,100	61	10.2	832	730	360	8.8	26.4	15.7	-4,771	373	-108	-4,354	382	-84
15	K	63	1,100	61	6.0	798	765	367	8.4	-	-	-4,760	400	-98	-4,771	413	-94
16	L	63	1,100	69	10.2	801	767	413	8.9	-	-	-5,391	493	-97	-3,827	461	-30
17	M	63	1,100	61	10.2	803	770	403	8.0	-	-	-5,086	538	-66	-4,208	504	-34
18	A	63	1,020	61	10.2	831	783	377	9.0	25.1	32.4	-5,057	371	-123	-5,281	403	-123
19	A	63	1,200	61	10.2	823	780	353	8.5	25.8	20.4	-5,059	477	-86	-5,187	501	-84
20	N	63	1,100	69	7.6	802	771	493	10.3	29.5	18.4	-5,150	650	>-30	-4,380	540	>-30
21	O	63	1,100	43	4.8	800	768	443	8.8	33.4	26.3	-4,824	472	-76	-4,552	456	-68
22	P	63	1,100	32	4.8	803	772	443	7.7	16.9	17.6	-4,772	436	-86	-5,065	435	-101

2. Steel Structure

[0066] Electron back scatter diffraction (EBSD) measurement was performed at the t/4 (t: thickness) and t/2 positions of a cross-section perpendicular to the rolling width direction of the above hot-rolled material. The measurement conditions are as follows.

EBSD measurement conditions

[0067]

Equipment: JEOL-5410 or JSM-IT100 manufactured by JEOL, Ltd.

Observation magnification: 400 times

Measurement area: $200\ \mu\text{m} \times 200\ \mu\text{m}$

Step (pixel) size: $0.4\ \mu\text{m}$

Phase to be considered: ferrite, austenite

[0068] EBSD data thus obtained was analyzed by analysis software OIM Analysis manufactured by TSL Solutions Ltd. In the thus obtained data, points with Confidence Index of 0.100 or less were removed, and grain boundaries with a crystal misorientation of 15° or more from the neighboring pixels were defined as high-angle grain boundaries. Of the units surrounded by these high-angle grain boundaries, units having a pixel size of 10 or more were regarded as high-angle grains. High-angle grains at the edge of the measurement field were excluded from the analysis. The average equivalent circle diameter of the high-angle grains was determined, and the total area fraction of the high-angle grains having an average equivalent circle diameter of $7.5\ \mu\text{m}$ or less to the total area of the high-angle grains, SA, was calculated.

3. Mechanical Properties

(Yield strength YS)

[0069] ASTM round bar tensile test specimens were taken at the t/4 and t/2 positions of the as-hot rolled steel plate parallel to the width direction (direction C), and a tensile test was performed in accordance with ASTM procedures to measure the yield strength YS.

(Low-temperature toughness of base metal)

[0070] V-notch Charpy test specimens were taken at the t/4 and t/2 positions of the as-hot rolled steel plate parallel to the plate width direction (C direction), and a Charpy impact test was performed in accordance with ASTM procedures. The temperature vTrs at which the percent brittle fracture reaches 50% was evaluated.

[0071] The yield strength YP and the brittle-ductile transition temperature vTrs obtained by the above measurements were substituted into the following equation (2) to obtain Y values at each of the t/4 and t/2 positions, respectively. The results are also shown in Table 2. In Table 2, when vTrs $> -30^\circ\text{C}$, vTrs $= -30^\circ\text{C}$ was used in the calculation of the Y value. When vTrs $< -130^\circ\text{C}$, vTrs $= -130^\circ\text{C}$ was used in the calculation of the Y value.

$$Y = 20 \times \text{vTrs} - 7 \times \text{YP} \quad (2)$$

[0072] From Tables 1 and 2, the followings can be seen. In tests Nos. 1 to 11, since thick steel plates were produced by satisfying the composition specified in the embodiment of the invention under the specified conditions, the thus obtained thick steel plates have excellent strength-toughness balance throughout the interior of the steel plate even if the steel plate has a large plate thickness. In particular, the thick steel plates exhibit high strength and excellent toughness at lower temperatures than before. In contrast, in tests Nos. 12 to 17, since at least one of the composition and production conditions is not in a range specified in the embodiment of the present invention, the thus obtained thick steel plates were inferior in strength-toughness balance.

[0073] In test No. 12, although the composition is in a range of the embodiment of the present invention, the cumulative rolling reduction ratio in a temperature range of 850°C or lower was insufficient in the production conditions, leading to insufficient AF structure at both t/4 and t/2 positions and inferior strength-toughness balance.

[0074] In tests Nos. 13 and 14, although the composition is in a range of the embodiments of the present invention, the finishing rolling temperature was high in the production conditions, leading to insufficient AF structure at both t/4 and t/2 positions and inferior strength-toughness balance.

[0075] In test No. 15, $Di + 10Nb$ is lower than the specified range, leading to inferior strength-toughness balance. In test No. 15, pearlite structure was formed together with grain boundary ferrite due to $Di + 10Nb$ being lower than the specified range. As a result, the AF structure was insufficient and the strength-toughness balance was inferior.

[0076] Tests Nos. 16 and 17 showed inferior strength-toughness balance since $Di + 10Nb$ exceeds the specified range. In tests Nos. 16 and 17, it is considered that a hard martensite structure was formed due to $Di + 10Nb$ exceeding the specified range. As a result, the hard martensite structure acts as a starting point for brittle fracture, leading to inferior strength-toughness balance.

[0077] In test No. 18, although the composition is in a range of the embodiment of the present invention, the heating temperature before hot-rolling was low and the finishing rolling temperature was high in the production conditions, thus failing to secure sufficient AF structure, leading to inferior strength-toughness balance.

[0078] In test No. 19, although the composition is in a range of the embodiment of the present invention, the heating temperature before hot-rolling was high in the production conditions, thus failing to secure certain level of fine AF structure beyond a certain level, leading to inferior strength-toughness balance.

[0079] In test No. 20, since the B content is 0.0008% and is more than the upper limit of 0.0007%, hard martensite was formed, leading to insufficient SA at the $t/4$ and $t/2$ positions and poor properties.

[0080] In test No. 21, although the composition is in a range of the embodiment of the present invention, the average rolling reduction ratio in the last three passes of rolling during hot-rolling was too low in the production conditions to obtain certain level of fine AF structure, leading to inferior strength-toughness balance.

[0081] In test No. 22, the Nb content is insufficient, and the cumulative rolling reduction ratio in a temperature range of 850°C or lower and the average rolling reduction ratio in the last three passes of rolling is also low in the production conditions, thus failing to secure certain level of fine AF structure beyond a certain level, leading to inferior strength-toughness balance.

[0082] FIG. 1 is a graph made based on aforementioned Examples, which shows the relationship between a total area fraction SA of crystal grains having an equivalent circle diameter of 7.5 μm or less, among crystal grains surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more, and a Y value. The downward arrow in FIG. 1 means that the Y value is estimated to be lower than the plotted value since the measured $vTrs$ is lower than -130°C, while the upward arrow means that the Y value is estimated to be higher than the plotted value since the measured $vTrs$ is higher than -30°C. Therefore, the upward arrow means that the measured $vTrs$ is higher than -30°C, so that the Y value is estimated to be higher than the plotted value.

[0083] From FIG. 1, it can be seen that there is a correlation between the total area fraction SA and the Y value at both the $t/4$ and $t/2$ positions in the steel plate, and in order to make the Y value to be less than -5,200 at the $t/4$ position, there is a need that the total area fraction SA is 34% or higher, and in order to make the Y value to be less than -4,700 at $t/2$ position, there is a need that the total area fraction SA is 27% or higher.

[0084] This application claims priority based on Japanese Patent Application No. 2019-081271 filed on April 22, 2019 and Japanese Patent Application No. 2020-007626 filed on January 21, 2020, the disclosures of which are incorporated by reference herein.

Claims

1. A thick steel plate with the composition comprising:

C: 0.020% by mass to 0.070% by mass,

Si: more than 0% by mass and 0.40% by mass or less,

Mn: 1.30% by mass to 1.95% by mass,

P: more than 0% by mass and 0.015% by mass or less,

S: more than 0% by mass and 0.005% by mass or less,

Al: 0.005% by mass to 0.070% by mass,

Nb: 0.015% by mass to 0.048% by mass,

Ti: 0.005% by mass to 0.024% by mass,

N: 0.0030% by mass to 0.0080% by mass, and

Ca: more than 0% by mass and 0.0040% by mass or less, with the balance consisting of Fe and inevitable impurities,

the composition satisfying $Di + 10Nb$: 1.20 to 2.50 determined from the equation (1) below, wherein

a total area fraction SA of crystal grains having an equivalent circle diameter of 7.5 μm or less, among crystal grains surrounded by high-angle grain boundaries having a crystal misorientation of 15° or more, is 34% or more at the $1/4$ position of the plate thickness, and 27% or more at the $1/2$ position of the plate thickness:

$$\begin{aligned}
 Di = & 1.16 \times ([C]/10)^{0.5} \times (0.7 \times [Si] + 1) \times (5.1 \times \\
 & ([Mn] - 1.2) + 5) \times (0.35 \times [Cu] + 1) \times (0.36 \times [Ni] + 1) \times \\
 & (2.16 \times [Cr] + 1) \times (3 \times [Mo] + 1) \times (1.75 \times [V] + 1) \times (200 \\
 & \times [B] + 1) \quad (1)
 \end{aligned}$$

where, in the equation (1), [C], [Si], [Mn], [Cu], [Ni], [Cr], [Mo], [V] and [B] indicate the content of C, Si, Mn, Cu, Ni, Cr, Mo, V and B, respectively, expressed in % by mass, and the content of an element not included is zero.

2. The high-strength plate according to claim 1, which satisfies one or more of the following (i) to (iii):

(i) further comprising one or more elements selected from the group consisting of:

Cu: more than 0% by mass and 0.75% by mass or less, and
Ni: more than 0% by mass and 1.4% by mass or less;

(ii) further comprising one or more elements selected from the group consisting of:

Mo: more than 0% by mass and 0.50% by mass or less,
V: more than 0% by mass and 0.060% by mass or less,
Cr: more than 0% by mass and 0.8% by mass or less, and
B: more than 0% by mass and 0.0007% by mass or less; and

(iii) further comprising one or more elements selected from the group consisting of:

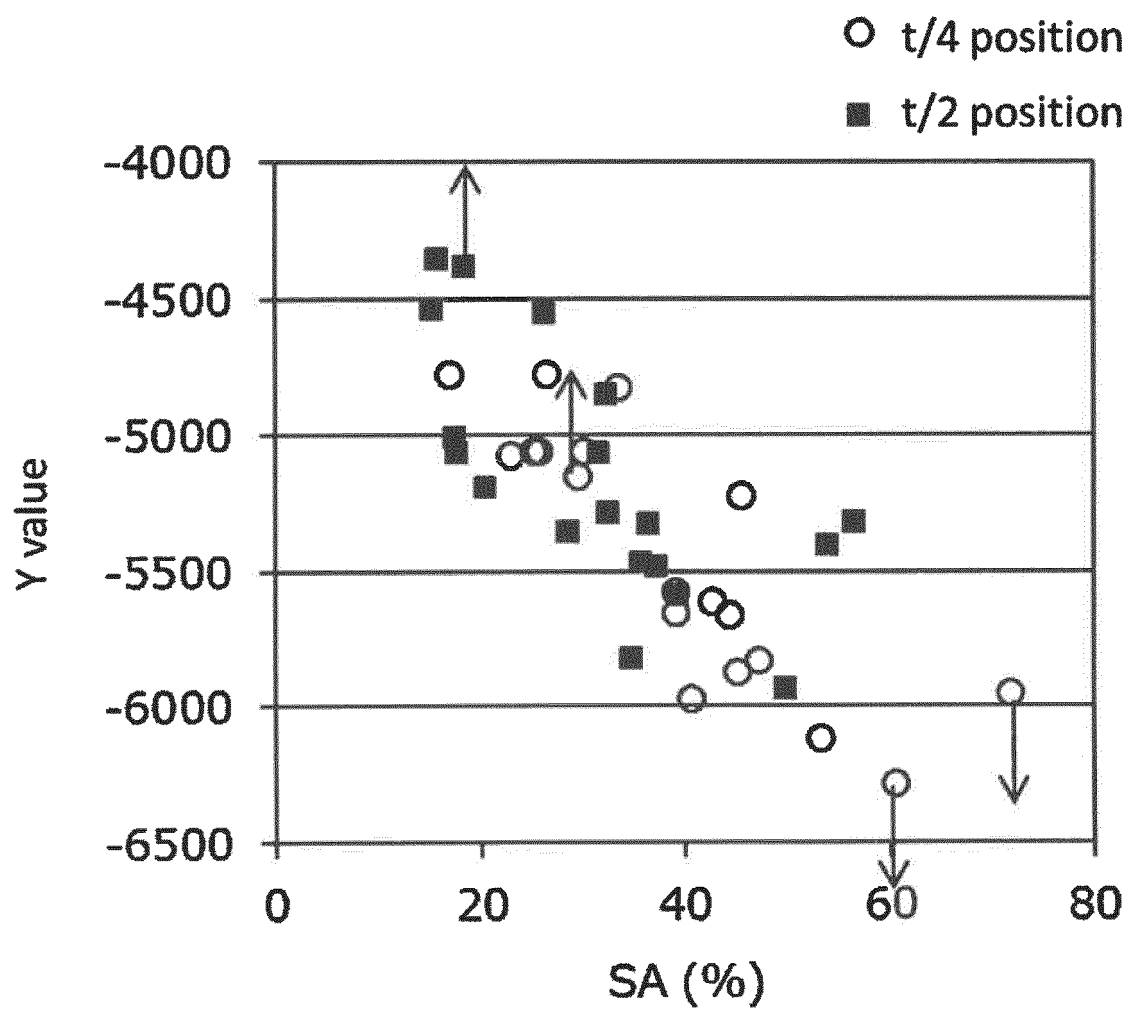
REM: more than 0% by mass and 0.0060% by mass or less, and
Zr: more than 0% by mass and 0.0050% by mass or less.

3. A method for producing the thick steel plate according to claim 1 or 2, the method comprising:

a step of heating a steel piece with the composition according to claim 1 or 2 to a temperature of higher than 1,020°C and lower than 1,200°C, and a hot-rolling step after heating, wherein the hot-rolling step is a step in which the number of roll passes is set at three or more, and hot-rolling and cooling after the hot-rolling are performed so as to satisfy all of the following conditions (a) to (d):

- (a) a cumulative rolling reduction ratio in a temperature range of 850°C or lower is 40% or more,
- (b) an average rolling reduction ratio in the last three passes of rolling is 5.5% or more,
- (c) a finishing rolling temperature is 720 to 830°C, and
- (d) after hot-rolling, cooling is performed at an average cooling rate of 0.5 to 20°C/s from a start cooling temperature of the finishing rolling temperature to 690°C to a finish cooling temperature of 320 to 550°C.

FIG. 1



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2020/014612

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. C22C38/00 (2006.01) i, C21D8/02 (2006.01) i, C22C38/14 (2006.01) i,
C22C38/58 (2006.01) i

FI: C22C38/00 301A, C22C38/14, C22C38/58, C21D8/02 B

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int. Cl. C21D8/02, C22C38/00, C22C38/14, 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 1971-2020

Registered utility model specifications of Japan 1996-2020

Published registered utility model applications of Japan 1994-2020

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.
X	JP 2013-204145 A (KOBE STEEL, LTD.) 07 October	2
Y	2013, paragraphs [0023]-[0048], [0070]-[0076],	1
A	[0110], tables 1, 3, 5, paragraphs [0023]-[0048], [0070]-[0076], [0110], tables 1, 3, 5	3
Y	WO 2019/058424 A1 (NIPPON STEEL & SUMITOMO METAL	2
A	CORP.) 28 March 2019, paragraphs [0069]-[0092], [0140], [0143], tables 1-9, fig. 4, 5	1, 3
Y	JP 2019-502018 A (POSCO) 24 January 2019,	2
A	paragraphs [0039]-[0077], tables 1-4	1, 3
Y	WO 2011/096456 A1 (NIPPON STEEL CORP.) 11 August	1-2
	2011, table 2	

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search
17.06.2020

Date of mailing of the international search report
30.06.2020

Name and mailing address of the ISA/
Japan Patent Office
3-4-3, Kasumigaseki, Chiyoda-ku,
Tokyo 100-8915, Japan

Authorized officer

Telephone No.

INTERNATIONAL SEARCH REPORT

International application No. PCT/JP2020/014612
--

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2011-179042 A (JFE STEEL CORP.) 15 September 2011	1-3

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

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/JP2020/014612

Patent Documents referred to in the Report	Publication Date	Patent Family	Publication Date
JP 2013-204145 A	07.10.2013	KR 10-2013-0111394 A CN 103361554 A KR 10-2016-0014087 A (Family: none)	
WO 2019/058424 A1	28.03.2019	US 2018/0363081 A1	
JP 2019-502018 A	24.01.2019	paragraphs [0045]- [0146], tables 1-4 WO 2017/095175 A1 EP 3385401 A1 CN 108368587 A KR 10-1726082 B1 CN 102666884 A BR 112012019769 A2 (Family: none)	
WO 2011/096456 A1	11.08.2011		
JP 2011-179042 A	15.09.2011		

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

REFERENCES CITED IN THE DESCRIPTION

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

Patent documents cited in the description

- JP 8158006 A [0007]
- JP 2009127065 A [0007]
- JP 2008025014 A [0007]
- JP 2007270194 A [0007]
- JP 2019081271 A [0084]
- JP 2020007626 A [0084]