



(11) **EP 3 447 162 A1**

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

(43) Date of publication:
27.02.2019 Bulletin 2019/09

(51) Int Cl.:
C22C 38/00 (2006.01) C22C 38/58 (2006.01)

(21) Application number: **17786057.4**

(86) International application number:
PCT/JP2017/016090

(22) Date of filing: **21.04.2017**

(87) International publication number:
WO 2017/183720 (26.10.2017 Gazette 2017/43)

(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:
MA MD

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(30) Priority: **21.04.2016 JP 2016085147**
21.04.2016 JP 2016085148

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(54) **THICK STEEL PLATE**

(57) A thick steel plate is provided that has a chemical composition comprising, by mass%, C: 0.01-0.20%, Si: 0.10-0.25%, Mn: 1.30-2.50%, P: 0.01% or less, S: 0.0010-0.0100%, Ti: 0.005-0.030%, Al: 0.003% or less, O: 0.0010-0.0050%, N: 0.0100% or less, Cu: 0-0.50%, Ni: 0-1.50%, Cr: 0-0.50%, Mo: 0-0.50%, V: 0-0.10%, Nb: 0-0.05%, and the balance: Fe and impurities, and which contains in the steel a composite inclusion in which MnS is present around a Ti oxide. An area fraction of MnS in

a cross-section of the composite inclusion is 10% or more and less than 90%, the proportion which MnS accounts for in the peripheral length of the composite inclusion is 10% or more, and the number density of composite inclusions that have a grain diameter in a range of 0.5-5.0 μm is in a range of 10-100 per mm^2 . The thick steel plate exhibits excellent HAZ low-temperature properties during high heat input welding.

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Description

TECHNICAL FIELD

5 **[0001]** The present invention relates to a thick steel plate. In particular, the present invention relates to a thick steel plate that is excellent in toughness in a weld heat-affected zone (hereinafter, referred to as "HAZ"), that is used in marine structures such as oil and natural gas drilling facilities at sea.

BACKGROUND ART

10 **[0002]** The requirements with respect to the toughness of a thick steel plate to be used in various welded steel structures such as for architecture, bridges, shipbuilding, line pipes, construction machinery, marine structures and tanks are becoming increasingly stricter year by year to increase safety and reliability with respect to weld zones fractures. In particular, securing excellent HAZ toughness is demanded in addition to the toughness of the base metal steel plate.

15 **[0003]** In a HAZ, the heating temperature during welding increases at an area nearer to a fusion line. In particular, in an area near the fusion line which is heated to 1400°C or higher, austenite grains coarsen markedly. Consequently, the HAZ micro-structure after cooling coarsens and the HAZ toughness deteriorates.

[0004] This tendency becomes more prominent as the welding heat input increases. In recent years, high heat input welding operations that use a high-efficiency welding process with an increased welding heat input are performed in order to reduce the number of welding passes and lower the cost of the welding operation. Consequently, since a reduction occurs in the HAZ toughness, various countermeasures are taken to improve the HAZ toughness when performing high heat input welding.

20 **[0005]** The known methods for improving the HAZ toughness include, for example, methods that control the grain diameter in a HAZ. Specifically, the methods that control the grain diameter include a method that inhibits coarsening of austenite grains in the welding heating process by dispersing a large amount of fine pinning particles in the steel, and a method that promotes intragranular transformation in a cooling process of welding by dispersing particles that act as nuclei for ferrite transformation in the steel to thereby break up the interior of the grains.

25 **[0006]** For example, Patent Document 1 discloses a steel material in which oxides composed of Mg, Mn and Al and composite inclusions which are composed of MnS and have a grain diameter of less than 0.6 μm are dispersed and formed in an amount of 1×10^6 per mm³ in steel materials. The steel material inhibits coarsening of prior-austenite grains, and by this means secures excellent toughness even when high heat input welding with input heat of 300 kJ/cm or more is performed.

30 **[0007]** Patent Document 2 discloses a thick steel plate in which a large amount of Mn oxides and Al oxides that are liable to act as precipitation nuclei for MnS particles are finely dispersed in the steel. The thick steel plate has favorable HAZ toughness even when high heat input welding with input heat of 200 kJ/cm is performed.

35 **[0008]** In addition, Patent Document 3 discloses a steel plate having a plate thickness of 10 to 35 mm in which the particle size and number density of TiN particles, MnS particles and composite particles having an equivalent circular diameter of 0.5 to 2.0 μm contained in the steel plate are controlled to within predetermined ranges. The growth of austenite grains in the steel plate is inhibited by a pinning effect when the steel plate is heated by welding. In addition, 40 when the steel plate is cooled after welding, the micro-structure is refined by ferrite transforming to become nuclei. By this means, the HAZ toughness during high heat input welding of the steel plate increases.

LIST OF PRIOR ART DOCUMENTS

45 PATENT DOCUMENT

[0009]

50 Patent Document 1: JP2014-5527A
Patent Document 2: JP5-271864A
Patent Document 3: JP2015-98642A

SUMMARY OF INVENTION

55 TECHNICAL PROBLEM

[0010] In recent years, steel plates to be used in welded structures such as marine structures are required to be thick-walled and have high strength. However, because such thick steel plates are assembled by welding, ensuring the

characteristics of weld zones is a problem. In particular, if a thick steel plate having a plate thickness of 50 mm or more is welded by a single pass or a small number of passes, it is difficult to secure the HAZ toughness because the heat input during welding increases.

[0011] An objective of the present invention is to provide a thick steel plate having excellent HAZ toughness even when high heat input welding is performed.

SOLUTION TO PROBLEM

[0012] The present inventors conducted intensive studies to solve the above described problem, and as a result obtained the findings described hereunder.

[0013] In a HAZ, grains grow by heating to the vicinity of 1400°C, and coarse austenite grains grow. The growth of such coarse austenite grains is one cause of a decline in the HAZ toughness. Therefore, refining the grains and decreasing a fracture unit is effective as means for securing the HAZ toughness. As techniques for refining grains, the known conventional techniques include (i) a technique that utilizes a pinning effect which inhibits the growth of a prior-austenite grain boundary by means of TiN or the like, and (ii) a technique that causes fine intragranular ferrite to grow using inclusions that are present within prior-austenite grains as starting points, to thereby refine the grains.

[0014] The present inventors found that by controlling balance between the contents of Ti, Al, O and N during the steelmaking process, fine TiN particles that were caused to be dispersed in the steel inhibit the growth of austenite grains in HAZs by a pinning effect, and thereby inhibit the growth of coarse austenite grains.

[0015] On the other hand, because TiN particles melt easily in the vicinity of 1400°C, the pinning effect decreases. As a result, coarse austenite grains are liable to grow. Therefore, the present inventors conceived of also utilizing intragranular transformation caused by inclusions in combination therewith.

[0016] Control of inclusions that act as formation nuclei for intragranular ferrite is effective for effectively causing intragranular ferrite to grow within austenite grains during welding. The following matters have been ascertained regarding the growth mechanism of intragranular ferrite.

[1] During welding cooling, a driving force that diffuses Mn from the matrix to the inside of inclusions arises due to the gradient of the Mn concentration that is formed when MnS compositely precipitates around the inclusions.

[2] Mn is absorbed into atomic vacancies that are present inside Ti-based oxides.

[3] An Mn-depleted zone in which the Mn concentration is reduced is formed around the inclusion, and the ferrite growth-initiating temperature at that portion rises.

[4] During cooling, ferrite grows with priority from the inclusions.

[0017] On the premise of the above facts, the present inventors found that the MnS composite amount of an inclusion that serves as a nucleus of intragranular ferrite influences the growth of the intragranular ferrite. In other words, when a large amount of MnS is composited, the driving force that diffuses Mn increases because a larger Mn concentration gradient is formed around the inclusion. As a result, an Mn-depleted zone is formed more easily. On the other hand, when a small amount of MnS is composited, it is difficult for a Mn concentration gradient to be formed around the inclusion. As a result, it is difficult for an Mn-depleted zone to be formed.

[0018] In other words, by controlling the amount and number density of MnS that is composited with inclusions, intragranular ferrite can be precipitated effectively.

[0019] In addition, the present inventors found that to obtain a grain refining effect, it is necessary for the inclusions in the steel to satisfy the following requirements.

(a) A composite inclusion in which MnS is present around a Ti oxide is contained in the steel, with an area fraction of the MnS in a cross-section of the composite inclusion being 10% or more and less than 90%, and the proportion that MnS accounts for in the peripheral length of the composite inclusion being 10% or more.

(b) The number density of the composite inclusions that have a grain diameter in a range of 0.5 to 5.0 μm is in a range of 10 to 100 per mm^2 .

[0020] Based on the mechanism described above, according to the present invention the growth of coarse grains is inhibited by TiN particles, the composite form of Ti-based composite oxides is controlled, and the amount and number density of MnS that is composited with inclusions is controlled to thereby effectively precipitate intragranular ferrite.

[0021] The present invention is based on the foregoing findings and is as enumerated hereunder.

(1) A thick steel plate having a chemical composition comprising, by mass%, C: 0.01 to 0.20%, Si: 0.10 to 0.25%, Mn: 1.30 to 2.50%, P: 0.01% or less, S: 0.0010 to 0.0100%, Ti: 0.005 to 0.030%, Al: 0.003% or less, O: 0.0010 to 0.0050%, N: 0.0100% or less, Cu: 0 to 0.50%, Ni: 0 to 1.50%, Cr: 0 to 0.50%, Mo: 0 to 0.50%, V: 0 to 0.10%, Nb:

0 to 0.05%, and the balance: Fe and impurities, wherein:

a composite inclusion in which MnS is present around a Ti oxide is contained in the steel; an area fraction of the MnS in a cross-section of the composite inclusion is 10% or more and less than 90%; a proportion that the MnS accounts for in a peripheral length of the composite inclusion is 10% or more; and a number density of the composite inclusions which have a grain diameter in a range of 0.5 to 5.0 μm is in a range of 10 to 100 per mm^2 .

(2) The thick steel plate described in item (1) above, containing, by mass%, at least one element selected from Cu: 0.01 to 0.50%, Ni: 0.01 to 1.50%, Cr: 0.01 to 0.50%, Mo: 0.01 to 0.50%, V: 0.01 to 0.10% and Nb: 0.01 to 0.05%.

(3) The thick steel plate described in item (1) or (2) above, wherein a value X obtained by formula (i) hereunder is in a range of 0.04 to 9.70:

$$X = \left[\left(\frac{\text{Ti} - \text{TiO}}{\text{O}} \right) + (\text{Mn} - \text{MnS}) \right] \times \left[(R1 + R2) / 100 \right] \cdots (i)$$

where, the meaning of each symbol in the formula (i) is as follows.

[0022]

Ti_TiO (mass%): Ti amount that becomes a Ti oxide among a total Ti content

O (mass%): O content in the steel

Mn_MnS (mass%): Mn amount that becomes MnS among a total Mn content

R1(%): average value of area fraction of MnS in a cross-section of a composite inclusion

R2(%): average value of proportion that MnS accounts for in a peripheral length of a composite inclusion

ADVANTAGEOUS EFFECTS OF INVENTION

[0023] According to the present invention, a thick steel plate is provided that has excellent HAZ toughness even in a case where high heat input welding is performed.

DESCRIPTION OF EMBODIMENTS

[0024] The thick steel plate according to the present invention will now be described.

A. Chemical Composition

[0025] The operational advantages of each element as well as the reasons for limiting the content of each element will now be described. The symbol "%" as used herein in relation to the chemical composition or concentration means "mass%" unless specifically stated otherwise.

[0026] First, essential elements will be described.

(A1) C: 0.01 to 0.20%

[0027] C has an action that enhances the strength of the base metal and a HAZ. In order to secure strength of 400 to 500 MPa, the C content is 0.01% or more, and in order to secure the strength of the base metal and a HAZ and to ensure the HAZ low-temperature toughness, the C content is preferably 0.02% or more, more preferably is 0.05% or more, and further preferably is 0.06% or more.

[0028] On the other hand, if the C content is more than 0.20%, a HAZ is liable to form a hard micro-structure, and hence the HAZ toughness decreases. Therefore, the C content is 0.20% or less, and in order to ensure the strength of the base metal and the HAZ as well as the HAZ low-temperature toughness, the C content is preferably 0.15% or less and more preferably is 0.08% or less.

(A2) Si: 0.10 to 0.25%

[0029] Si acts as a deoxidizer during production of the steel material, and therefore is effective for controlling the oxygen amount, and also dissolves in the steel and increases the strength. Therefore, the Si content is 0.10% or more, and in order to control the oxygen amount to an appropriate amount and also secure the HAZ low-temperature toughness the Si content is preferably 0.13% or more.

[0030] On the other hand, if the Si content is more than 0.25%, the toughness of the base metal decreases and the HAZ is liable to form a hard micro-structure, and hence the HAZ toughness decreases. Therefore, the Si content is

0.25% or less, and in order to control the oxygen amount to an appropriate amount and also secure the HAZ low-temperature toughness the Si content is preferably 0.18% or less.

(A3) Mn: 1.30 to 2.50%

[0031] Mn acts as an austenite stabilizing element, and inhibits production of coarse ferrite at the grain boundary. Therefore, the Mn content is 1.30% or more, and in order to inhibit production of coarse ferrite and also prevent segregation, the Mn content is preferably 1.40% or more.

[0032] On the other hand, if the Mn content is more than 2.50%, Mn is liable to segregate, and a HAZ is liable to partially form a hard micro-structure. As a result, the HAZ toughness decreases. Therefore, the Mn content is 2.50% or less, and in order to inhibit production of coarse ferrite and also prevent segregation, the Mn content is preferably 2.10% or less, and more preferably is 2.00% or less.

(A4) P: 0.01% or less

[0033] P is an impurity element. A decrease in the grain boundary strength in a HAZ is inhibited by the P content decreasing. Therefore, the P content is 0.01% or less

(A5) S: 0.0010 to 0.0100%

[0034] S causes MnS to compositely precipitate. Therefore, the S content is 0.0010% or more. In order to cause MnS to compositely precipitate and also secure the low-temperature toughness of HAZs, the S content is preferably 0.0020% or more.

[0035] On the other hand, if the S content is more than 0.0100%, coarse singular MnS precipitates, and consequently the HAZ toughness decreases. Therefore, the S content is 0.0100% or less, and in order to cause MnS to compositely precipitate and also secure the low-temperature toughness of HAZs, the S content is preferably 0.0050% or less.

(A6) Ti: 0.005 to 0.030%

[0036] Ti is essential for forming Ti-based oxides. The Ti content is 0.005% or more in order to obtain a sufficient inclusion density, and in order to secure a sufficient inclusion density and also ensure the HAZ toughness the Ti content is preferably 0.009% or more.

[0037] On the other hand, if the Ti content is more than 0.030%, since carbides such as TiC are easily formed, the HAZ toughness decreases. Therefore, the Ti content is 0.030% or less, and in order to secure a sufficient inclusion density and also ensure the HAZ toughness the Ti content is preferably 0.020% or less.

(A7) Al: 0.003% or less

[0038] Al is an impurity element. The formation of Ti-based oxides is inhibited by an increase in the Al content. Therefore, the Al content is 0.003% or less.

(A8) O: 0.0010 to 0.0050%

[0039] O is essential for formation of Ti-based composite oxides. In order to obtain a sufficient inclusion density, the O content is 0.0010% or more.

[0040] On the other hand, if the O content is more than 0.0050%, coarse oxides that can become fracture starting points are easily formed. Therefore, the O content is 0.0050% or less, and the O content is preferably 0.0030% or less in order to inhibit the formation of coarse inclusions.

(A9) N: 0.0100% or less

[0041] N contributes to refining the grains by bonding with Ti to form TiN. However, if the N content is more than 0.0100%, the Ti amount that is necessary for TiN precipitation increases, and it is difficult for Ti oxides to be formed and the TiN also agglomerates and becomes the starting point of fractures. Therefore, the N content is 0.0100% or less, and in order to stably secure a Ti amount for forming Ti oxides the N content is preferably 0.0080% or less, and more preferably is 0.0050% or less.

[0042] Next optional elements will be described.

(A10) Cu: 0 to 0.50%

[0043] Cu may be contained as required in order to increase the strength. However, if the Cu content is more than 0.50%, hot embrittlement occurs and the quality of the slab surface decreases. Therefore, the Cu content is 0.50% or less, and preferably is 0.30% or less.

[0044] To reliably obtain the aforementioned effect, the Cu content is preferably 0.01% or more, and more preferably is 0.25% or more.

(A11) Ni: 0 to 1.50%

[0045] Ni may be contained as required in order to increase the strength without lowering the toughness. However, because Ni is an austenite stabilizing element, if the Ni content is more than 1.50%, it is difficult for intragranular ferrite to be produced. Therefore, the Ni content is 1.50% or less, and in order to promote production of intragranular ferrite the Ni content is preferably 1.00% or less.

[0046] To reliably obtain the aforementioned effect, the Ni content is preferably 0.01% or more, more preferably is 0.50% or more, and further preferably is 0.60% or more.

(A12) Cr: 0 to 0.50%

[0047] Cr may be contained as required in order to increase the strength. However, if the Cr content is more than 0.50%, the HAZ toughness decreases. Therefore, the Cr content is 0.50% or less, and preferably is 0.30% or less.

[0048] To reliably obtain the aforementioned effect, the Cr content is preferably 0.01% or more, and more preferably is 0.10% or more.

(A13) Mo: 0 to 0.50%

[0049] Mo noticeably increases the strength when contained in a small amount, and hence Mo may be contained as required. However, if the Mo content is more than 0.50%, the HAZ toughness markedly decreases. Therefore, the Mo content is 0.50% or less, and preferably is 0.30% or less.

[0050] To reliably obtain the aforementioned effect, the Mo content is preferably 0.01% or more.

(A14) V: 0 to 0.10%

[0051] V is effective for improving the strength and toughness of the base metal, and hence may be contained as required. However, if the V content is more than 0.10%, V forms carbides such as VC, and the toughness decreases. Therefore, the V content is 0.10% or less, and preferably is 0.05% or less.

[0052] To reliably obtain the aforementioned effect, the V content is preferably 0.01% or more, and more preferably is 0.03% or more.

(A15) Nb: 0 to 0.05%

[0053] Nb is effective for improving the strength and toughness of the base metal, and hence may be contained as required. However, if the Nb content is more than 0.05%, carbides such as NbC are easily formed, and the toughness decreases. Therefore, the Nb content is 0.05% or less, and preferably is 0.03% or less.

[0054] To reliably obtain the aforementioned effect, the Nb content is preferably 0.01% or more.

(A16) Balance

[0055] The balance other than the above elements is Fe and impurities. The term "impurities" refers to components which, during industrial production of the steel, are mixed in from raw material such as ore or scrap or due to various factors in the production process, and which are allowed to be contained in an amount that does not adversely affect the present invention.

(B) Composite inclusion

[0056] A composite inclusion in which MnS is present around a Ti oxide is contained in the steel. The area fraction of the MnS in a cross-section of the composite inclusion is 10% or more and less than 90%. The proportion that MnS accounts for in the peripheral length of the composite inclusion is 10% or more, and the number density of the composite

inclusions that have a grain diameter in a range of 0.5 to 5.0 μm is in a range of 10 to 100 per mm^2 .

(B1) Area fraction of MnS in cross-section of composite inclusion in which MnS is present around a Ti oxide: 10% or more and less than 90%

[0057] A composite inclusion which appears at an arbitrary cut section is analyzed. The MnS amount in the composite inclusion is defined by measuring the area fraction of MnS in the cross-sectional area of the composite inclusion. If the area fraction of the MnS in the cross-section of the composite inclusion is less than 10%, the MnS amount in the composite inclusion is small and a sufficient Mn-depleted zone cannot be formed. Therefore, it is difficult to produce intragranular ferrite.

[0058] On the other hand, if the proportion that MnS accounts for in the cross-section of the composite inclusion is 90% or more, the composite inclusion is mainly composed of MnS, and the proportion that a Ti-based oxide accounts for decreases. Therefore, because the Mn absorbability decreases and a sufficient Mn-depleted zone cannot be formed, production of intragranular ferrite is difficult.

(B2) Proportion MnS accounts for in peripheral length of composite inclusion: 10% or more

[0059] The MnS in the composite inclusion is formed around a Ti-based oxide. If the proportion that MnS accounts for in the peripheral length of the composite inclusion is less than 10%, an initial Mn-depleted zone that is formed at the boundary surface between MnS and the matrix will be small. Therefore, since the amount of intragranular ferrite that is produced will be insufficient even if welding is performed, favorable low-temperature HAZ toughness will not be obtained. Therefore, the proportion that MnS accounts for in the peripheral length with respect to the matrix of the composite inclusion is 10% or more.

[0060] The larger the proportion of MnS is, the larger the initial Mn-depleted zone becomes, and the easier it becomes to produce intragranular ferrite. Therefore, although an upper limit of the proportion of MnS is not defined, normally the proportion of MnS is 80% or less.

(B3) Grain diameter of composite inclusion: 0.5 to 5.0 μm If the grain diameter of a composite inclusion is less than 0.5 μm , the Mn

[0061] amount that can be absorbed from the area surrounding the composite inclusion will be small, and as a result it will be difficult to form Mn-depleted zones that are necessary in order to produce intragranular ferrite. On the other hand, if the grain diameter of the composite inclusion is larger than 5.0 μm , the composite inclusion will become a starting point for a fracture. As used herein, the term "grain diameter" refers to a circle-equivalent diameter.

(B4) Number density of composite inclusion: 10 to 100 per mm^2

[0062] To cause stable intragranular ferrite to be produced, it is necessary that at least one composite inclusion is contained within prior-austenite. Therefore, the number density of the composite inclusions is 10 per mm^2 or more. On the other hand, if the number of composite inclusions is excessively large, the composite inclusions are liable to become starting points for fractures. Therefore, the number density of the composite inclusions is 100 per mm^2 or less.

(C) Value X obtained by above formula (i): 0.04 to 9.70

[0063] In formula (i), the first term that is indicated by $(\text{Ti} - \text{TiO}/\text{O})$ represents the balance between the Ti content and the O content that become Ti oxides. The first term is calculated by deducting a Ti amount required for TiN formation that is calculated based on the N content in the steel from the total Ti content. The larger the value of the first term is, the easier it is for Ti oxides to form. When the first term is a negative value, Ti oxides are not formed.

[0064] The second term that is indicated by $(\text{Mn} - \text{MnS})$ in formula (i) represents the Mn amount that becomes MnS. The second term is calculated based on the S content in the steel. The larger the value of the second term is, the easier it is for a large amount of MnS to be composited.

[0065] In the third term that is indicated by $[(\text{R1} + \text{R2})/100]$ in formula (i), the symbol R1 represents the average value of the area fraction of MnS in a cross-section of composite inclusions, and the symbol R2 represents the average value of the proportion that MnS accounts for in the peripheral length of the composite inclusions. The larger the value of the third term is, the greater the amount of inclusions in which a large amount of MnS is composited is.

[0066] The value X obtained by formula (i) indicates the ease with which Ti oxides that composite with MnS are formed, and also the degree of MnS compositing of the composite inclusions that are formed. The larger the value X is, the greater the number of composite inclusions in which a large amount of MnS is composited that are formed is, and the

easier it is for a fine micro-structure to form at a weld zone. Thus, the steel material exhibits excellent toughness.

[0067] When the value X obtained from formula (i) is less than 0.04, the Ti amount required to form Ti oxides, the S amount and Mn amount required for formation of MnS, or the proportion that MnS accounts for is insufficient. In other words, the state is one in which inclusions that are effective for intragranular transformation are not formed. Therefore, in order to form effective Ti oxides, the value X is 0.04 or more, and preferably is 0.50 or more, and more preferably is 1.00 or more.

[0068] On the other hand, when the value X obtained from formula (i) is more than 9.70, agglomeration is liable to occur due to an excess of Ti oxides being formed. As a result, inclusions become starting points for fractures due to coarse inclusions being formed. In addition, since inclusions that are almost singular MnS inclusions are liable to be formed, intragranular transformation is no longer promoted. Consequently, coarse micro-structure increases, and CTOD properties deteriorate. Therefore, the value X is 9.70 or less, more preferably is 5.00 or less, and further preferably is 4.00 or less.

(D) Plate thickness: preferably 50 to 100 mm

[0069] Because the thick steel plate according to the present invention has composite inclusions as described above, even if the plate thickness is 50 mm or more, the HAZ low-temperature toughness is excellent. In other words, in order to weld a thick steel plate having a plate thickness of 50 mm or more with a low number of passes, it is necessary to increase the heat input during welding. However, even when welding is performed with a high heat input, the thick steel plate according to the present invention has excellent HAZ low-temperature toughness.

[0070] However, when the plate thickness is too large, it is difficult to control the composite inclusions, and producing a thick steel plate satisfying the aforementioned conditions regarding composite inclusions that are defined by the present invention is difficult. Therefore, the plate thickness of the thick steel plate is preferably 100 mm or less.

[0071] Note that, the yield stress of the thick steel plate according to the present invention is 400 to 500 MPa.

(E) Production Method

[0072] A method for producing the thick steel plate according to the present invention is not particularly limited. For example, the thick steel plate can be produced by heating a slab having the chemical composition described above, and thereafter subjecting the slab to hot rolling, and finally performing cooling.

[0073] In the hot rolling process, the ausform rolling reduction, that is, the rolling reduction at 950°C or less before accelerated cooling is preferably 20% or more. If the rolling reduction at 950°C or less before accelerated cooling is less than 20%, depending on the rolling the majority of dislocations introduced immediately after rolling may disappear due to recrystallization, and therefore not function as nuclei for transformation. As a result, the micro-structure after transformation coarsens, and in many cases embrittlement caused by dissolved nitrogen is a problem. Therefore, the rolling reduction at 950°C or less before accelerated cooling is preferably 20% or more.

EXAMPLE 1

[0074] The present invention will now be described more specifically by way of examples.

<Production of rolled base metal>

[0075] Steels having the chemical compositions of test number examples 1 to 28 and comparative examples 1 to 18 shown in Table 1 were melted by an actual production process. In the production process, Ar gas was blown into the molten steel from an upper portion before a RH vacuum degassing process to cause a reaction between the slag on the surface of the molten steel and the molten steel and thereby adjust the total Fe amount in the slag.

[0076] The flow rate of the Ar gas was regulated within the range of 100 to 200 L/min, and the blowing time period was regulated within the range of 5 to 15 min.

[0077] Thereafter, the respective elements were added in an RH vacuum degassing apparatus for component adjustment, and a 300 mm slab was cast by continuous casting. After casting, the slab was heated within a range of 1000 to 1100°C in a heating furnace. After heating, hot rolling at 760°C or higher was performed until becoming a thickness of 2t (t: final finishing plate thickness), and thereafter the slab was subjected to hot rolling in a temperature range of 730 to 750°C until becoming the final finishing plate thickness t. After hot rolling, the water cooling was performed at -2 to -3°C/sec until the temperature became 200°C or less, and a specimen was prepared.

<Calculation of MnS area fraction in cross-section of composite inclusion, and proportion MnS accounts for in peripheral length of composite inclusion>

[0078] The test specimen used for composite inclusion analysis was taken from a portion that, when the plate thickness of the specimen is taken as "t", was at a plate thickness of $1/4t$. The MnS area fraction and the proportion that MnS accounted for in the peripheral length of the composite inclusions were measured from a mapping image obtained by performing area analysis of composite inclusions using an electron probe microanalyzer (EPMA).

[0079] Specifically, the MnS area fraction was calculated by measuring the cross-sectional area of the entire composite inclusion and the cross-sectional area that an MnS portion accounted for in the entire composite inclusion from an image. The proportion that an MnS portion accounted for in the peripheral length of the composite inclusion was calculated by measuring the peripheral length of the Ti oxide in the composite inclusion and the length of an MnS boundary surface that contacted the Ti oxide from an image. To reduce variations in the measurements, the MnS area fraction and the proportion that MnS accounted for in the peripheral length of the composite inclusions was determined by performing analysis by EPMA for twenty composite inclusions per specimen, and calculating the average values. The results are shown in Table 1.

<Calculation of number density of composite inclusions>

[0080] The number density of the composite inclusions was calculated by calculating the number of composite inclusions whose grain diameter was in the range of 0.5 to 5.0 μm by means of an automatic inclusion analyzer combined with SEM-EDX, and from shape measurement data of the detected composite inclusions. The results are shown in Table 1.

[Table 1]

[0081]

Table 1

Test No.	Chemical Composition (mass%, balance: Fe and impurities)													MnS Area Fraction (%) In Composite Inclusion Cross- Section	Proportion (%) MnS Accounts for In Peripheral Length of Composite Inclusion	Number Density of Composite Inclusions (per mm ²)	Remarks
	C	Si	Mn	P	S	Ti	Al	O	N	Cu	Ni	Cr	Mo	V	Nb		
Example 1	0.07	0.16	1.87	0.0060	0.0026	0.013	0.001	0.0018	0.0030	-	-	-	-	-	-	25	Example Embodiment of Present Invention
Example 2	0.08	0.23	1.83	0.0041	0.0038	0.020	0.001	0.0020	0.0040	-	-	-	-	-	-	34	
Example 3	0.13	0.21	1.83	0.0022	0.0021	0.020	0.001	0.0013	0.0050	-	-	-	-	-	-	21	
Example 4	0.13	0.23	1.55	0.0022	0.0038	0.014	0.001	0.0026	0.0040	-	-	-	-	-	-	15	
Example 5	0.08	0.23	1.96	0.0041	0.0044	0.012	0.001	0.0034	0.0030	-	-	-	-	-	-	39	
Example 6	0.15	0.17	1.55	0.0041	0.0032	0.020	0.001	0.0011	0.0040	0.01	0.01	0.02	0.01	0.02	0.03	18	
Example 7	0.15	0.19	1.69	0.0052	0.0021	0.014	0.002	0.0026	0.0050	0.01	0.30	0.03	0.01	0.01	0.02	15	
Example 8	0.10	0.21	1.69	0.0081	0.0028	0.016	0.001	0.0042	0.0050	0.01	0.02	0.01	0.02	0.01	0.02	16	
Example 9	0.05	0.19	1.69	0.0062	0.0032	0.020	0.001	0.0019	0.0021	-	0.03	0.02	-	0.02	-	24	
Example 10	0.13	0.10	1.83	0.0022	0.0021	0.014	0.001	0.0026	0.0040	0.02	-	-	0.02	-	-	23	
Example 11	0.11	0.15	1.40	0.0022	0.0026	0.012	0.001	0.0034	0.0021	-	0.03	-	-	0.02	-	12	
Example 12	0.11	0.23	1.69	0.0010	0.0038	0.020	0.001	0.0034	0.0030	-	-	-	-	0.02	-	23	
Example 13	0.11	0.15	1.83	0.0015	0.0010	0.014	0.001	0.0019	0.0021	-	-	-	0.02	0.02	0.02	11	
Example 14	0.11	0.15	1.83	0.0035	0.0044	0.005	0.001	0.0019	0.0030	-	-	-	-	0.02	-	37	
Example 15	0.20	0.19	2.10	0.0002	0.0036	0.010	0.001	0.0042	0.0030	-	-	-	-	0.02	0.02	49	
Example 16	0.08	0.19	2.50	0.0010	0.0026	0.010	0.002	0.0026	0.0021	-	0.02	-	0.02	-	-	55	
Example 17	0.11	0.19	1.85	0.0100	0.0028	0.010	0.002	0.0011	0.0040	-	-	-	-	-	-	14	
Example 18	0.06	0.15	1.83	0.0085	0.0030	0.014	0.001	0.0011	0.0030	0.03	-	0.02	-	-	-	31	
Example 19	0.11	0.15	1.83	0.0022	0.0028	0.030	0.002	0.0026	0.0041	-	-	-	-	0.02	-	63	
Example 20	0.15	0.25	1.84	0.0022	0.0032	0.014	0.003	0.0042	0.0021	-	-	-	-	-	0.02	25	
Example 21	0.15	0.15	1.88	0.0041	0.0050	0.020	0.003	0.0042	0.0050	-	-	-	-	-	-	29	
Example 22	0.06	0.22	1.88	0.0055	0.0030	0.011	0.001	0.0022	0.0020	0.35	-	-	-	-	-	39	
Example 23	0.07	0.15	1.86	0.0061	0.0030	0.015	0.001	0.0026	0.0030	-	0.49	-	-	-	-	28	
Example 24	0.06	0.19	1.78	0.0063	0.0020	0.022	0.001	0.0015	0.0030	-	-	0.40	-	-	-	53	
Example 25	0.06	0.18	1.85	0.0044	0.0030	0.019	0.001	0.0023	0.0030	-	-	-	0.31	-	-	24	
Example 26	0.08	0.24	1.68	0.0040	0.0020	0.025	0.001	0.0024	0.0050	-	-	-	-	0.07	-	25	
Example 27	0.07	0.12	1.87	0.0062	0.0025	0.021	0.001	0.0030	0.0040	-	-	-	-	-	0.04	20	
Comp. Ex. 1	0.23	0.21	1.96	0.0060	0.0032	0.020	0.002	0.0018	0.0020	-	0.02	-	-	-	-	23	Comparative Example
Comp. Ex. 2	0.10	0.35	1.54	0.0011	0.0050	0.020	0.002	0.0017	0.0010	-	-	-	-	-	-	40	
Comp. Ex. 3	0.13	0.15	3.25	0.0040	0.0038	0.012	0.001	0.0019	0.0020	0.01	-	-	0.02	-	-	18	
Comp. Ex. 4	0.13	0.15	1.82	0.0040	0.0028	0.032	0.001	0.0020	0.0040	-	-	-	-	-	-	63	
Comp. Ex. 5	0.11	0.21	1.82	0.0040	0.0026	0.018	0.005	0.0016	0.0010	-	-	-	-	-	0.01	36	
Comp. Ex. 6	0.11	0.23	1.68	0.0013	0.0056	0.016	0.002	0.0055	0.0040	-	-	-	-	-	-	64	
Comp. Ex. 7	0.15	0.15	1.10	0.0023	0.0010	0.009	0.002	0.0020	0.0040	-	-	-	-	-	-	53	
Comp. Ex. 8	0.06	0.11	2.65	0.0012	0.0110	0.010	0.001	0.0023	0.0035	-	-	-	-	-	-	8	
Comp. Ex. 9	0.16	0.13	1.20	0.0010	0.0005	0.010	0.001	0.0022	0.0030	-	-	0.02	-	0.01	-	91	
Comp. Ex. 10	0.15	0.11	1.70	0.0011	0.0031	0.005	0.003	0.0015	0.0042	-	-	-	-	-	-	10	
Comp. Ex. 11	0.07	0.16	1.88	0.0060	0.0024	0.013	0.001	0.0018	0.0030	0.60	-	-	-	-	-	9	
Comp. Ex. 12	0.07	0.13	1.82	0.0055	0.0040	0.012	0.001	0.0030	0.0040	-	-	0.60	-	-	-	52	
Comp. Ex. 13	0.08	0.19	1.88	0.0049	0.0030	0.011	0.001	0.0030	0.0030	-	-	-	-	-	-	24	
Comp. Ex. 14	0.06	0.20	1.64	0.0026	0.0040	0.017	0.001	0.0022	0.0040	-	-	-	-	-	-	25	
Comp. Ex. 15	0.07	0.22	1.59	0.0050	0.0030	0.030	0.001	0.0026	0.0020	-	-	-	-	-	0.07	51	

Mark*** indicates value is outside range defined by the present invention.

<Tension test>

[0082] A JIS No. 4 tensile test specimens was taken from a 1/4 t position when taking the plate thickness of the prepared specimen as "t", and a tension test was performed at room temperature, and the yield stress (YP) and tensile strength (TS) of the rolled base metal were measured.

<CTOD test>

[0083] Test specimens for a CTOD test of a number $n = 3$ were taken from each of the prepared specimens. Each test specimen was subjected to the preparation of a weld groove, and multi-layer welding was performed with heat input of 5.0 kJ/mm by submerged arc welding (SAW). The HAZ of the prepared welded joint was subjected to notching, and a CTOD test was performed in conformity with the BS 7448 standard at a test temperature of -20°C . A decision regarding whether the test result was a pass or fail was made based on the criteria described below. Among the criteria described below, a test specimen for which the decision was $\odot$ or $\circ$ was regarded as having passed the test. The results are shown in Table 2.

[0084]

- $\odot$: All of the three test specimens were over the gauge
- $\circ$: Among the three test specimens, 0 to 2 of the test specimens were over the gauge, and all of the test specimens that were not over the gauge had a CTOD value of 0.4 mm or more
- $\times$: Among the three test specimens, the CTOD value of at least one test specimens was less than 0.4 mm

[0085] Note that, the term "over the gauge" means that an attached grip gauge could be fully opened to the limit. Further, since the CTOD property of a joint at a typically required temperature of -20°C is a CTOD value of 0.4 mm or more, the standard for the CTOD value was made 0.4 mm.

[0086] The test results are shown in Table 2.

[Table 2]

[0087]

Table 2

Test No.	Strength (MPa)		CTOD Test Result			
	YP	TS	n=1	n=2	n=3	Decision
Example 1	430	620	>1.4	>1.4	>1.4	$\odot$
Example 2	438	631	>1.4	>1.4	>1.4	$\odot$
Example 3	442	635	>1.4	>1.4	>1.4	$\odot$
Example 4	422	611	>1.4	>1.4	>1.4	$\odot$
Example 5	436	624	>1.4	>1.4	>1.4	$\odot$
Example 6	434	639	>1.4	>1.4	>1.4	$\odot$
Example 7	440	645	>1.4	>1.4	>1.4	$\odot$
Example 8	426	614	>1.4	>1.4	>1.4	$\odot$
Example 9	421	605	>1.4	>1.4	>1.4	$\odot$
Example 10	421	607	>1.4	>1.4	>1.4	$\odot$
Example 11	420	603	>1.4	>1.4	>1.4	$\odot$
Example 12	431	621	>1.4	>1.4	>1.4	$\odot$
Example 13	440	635	>1.4	>1.4	1.256	$\circ$
Example 14	438	629	>1.4	>1.4	1.113	$\circ$
Example 15	461	670	>1.4	0.681	1.052	$\circ$
Example 16	463	671	>1.4	0.658	0.956	$\circ$
Example 17	462	668	>1.4	0.551	0.638	$\circ$
Example 18	431	622	>1.4	0.692	0.63	$\circ$
Example 19	435	622	>1.4	1.029	0.79	$\circ$
Example 20	440	632	>1.4	0.657	0.482	$\circ$

(continued)

Test No.	Strength (MPa)		CTOD Test Result			
	YP	TS	n=1	n=2	n=3	Decision
Example 21	441	635	>1.4	0.784	0.821	○
Example 22	442	635	0.893	0.742	0.691	○
Example 23	441	630	0.998	0.851	0.744	○
Example 24	445	640	0.759	0.846	0.951	○
Example 25	451	681	0.567	0.513	0.612	○
Example 26	440	635	0.511	0.419	0.425	○
Example 27	435	661	0.564	0.558	0.981	○
Comp. Ex. 1	469	681	>1.4	0.201	0.159	×
Comp. Ex. 2	470	680	0.156	0.264	0.258	×
Comp. Ex. 3	491	701	>1.4	0.269	0.357	×
Comp. Ex. 4	483	696	0.246	0.331	0.249	×
Comp. Ex. 5	461	668	0.229	0.344	0.094	×
Comp. Ex. 6	431	623	>1.4	0.321	0.249	×
Comp. Ex. 7	430	620	>1.4	0.194	0.106	×
Comp. Ex. 8	451	665	>1.4	0.173	0.167	×
Comp. Ex. 9	421	613	>1.4	0.153	0.154	×
Comp. Ex. 10	432	611	>1.4	0.142	0.268	×
Comp. Ex. 11	462	685	0.23	0.154	0.65	×
Comp. Ex. 12	469	700	0.124	0.223	0.315	×
Comp. Ex. 13	470	701	0.11	0.112	0.223	×
Comp. Ex. 14	471	703	0.134	0.168	0.226	×
Comp. Ex. 15	469	681	0.162	0.187	0.364	×
">1.4" in the table indicates that the relevant result is over the gauge.						

[0088] The test specimens of examples 1 to 27 satisfied all conditions with respect to the ranges of the present invention, and hence the result of the CTOD test for these examples was "pass".

[0089] In example 9, although the CTOD test result was "pass", the YP and TS were low because the C content was close to the lower limit value of the range of the present invention.

[0090] In example 10, although the CTOD test result was "pass", the YP and TS were low because the Si content was close to the lower limit value of the range of the present invention.

[0091] In example 11, although the CTOD test result was "pass", the YP and TS were low because the Mn content was close to the lower limit value of the range of the present invention.

[0092] In example 12, although the P content was small, the small P content did not influence the result of the CTOD test.

[0093] In example 13, because the S content was close to the lower limit value of the range of the present invention, the MnS composite amount decreased, and the MnS area fraction in a cross-section of the composite inclusions as well as the proportion that MnS accounted for in the peripheral length of the composite inclusions decreased. As a result, in the CTOD test, only one test specimen was not over the gauge.

[0094] In example 14, because the Ti content was close to the lower limit value of the range of the present invention, the number density of the composite inclusions was low. As a result, in the CTOD test, only one test specimen was not over the gauge.

[0095] In example 15, because the C content was close to the upper limit value of the range of the present invention, the amount of hard micro-structure increased. Consequently, in the CTOD test, although two test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0096] In example 16, because the Mn content was close to the upper limit value of the range of the present invention, segregation occurred. As a result, in the CTOD test, although two test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0097] In example 17, because the P content was close to the upper limit value of the range of the present invention, the toughness decreased. As a result, in the CTOD test, although two test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0098] In example 18, because the S content was close to the upper limit value of the range of the present invention, the toughness decreased. As a result, in the CTOD test, although two test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0099] In example 19, because the Ti content was close to the upper limit value of the range of the present invention, the toughness decreased due to an increase in carbides such as TiC. As a result, in the CTOD test, although two test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0100] In example 20, because the Al content was close to the upper limit value of the range of the present invention, inclusions that act as intragranular ferrite formation nuclei decreased, and as a result the toughness decreased. Consequently, in the CTOD test, although two test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0101] In example 21, because the N content was close to the upper limit value of the range of the present invention, TiN increased and, as a result, the toughness decreased. Consequently, in the CTOD test, although two test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0102] In example 22, because the Cu content was within the range of the present invention, the result of the CTOD test was "pass". Note that, because the Cu content was more than 0.3%, the surface quality of the slab decreased, and it was necessary to repair the surface during production.

[0103] In example 23, although the Ni content was within the range of the present invention, because the Ni content was more than 0.4%, even though the result of the CTOD test was "pass", there was little intragranular ferrite in the micro-structure and the toughness was comparatively low.

[0104] In example 24, although the Cr content was within the range of the present invention, because the Cr content was more than 0.3%, even though the result of the CTOD test was "pass", the toughness was comparatively low.

[0105] In example 25, although the Mo content was within the range of the present invention, because the Mo content was more than 0.30%, even though the result of the CTOD test was "pass", the toughness was comparatively low.

[0106] In example 26, although the V content was within the range of the present invention, because the V content was more than 0.05%, even though the result of the CTOD test was "pass", a relatively large amount of VC precipitated and the toughness was comparatively low.

[0107] In example 27, although the Nb content was within the range of the present invention, because the Nb content was more than 0.03%, a relatively large amount of NbC precipitated and, consequently, the toughness was comparatively low.

[0108] In comparative example 1, because the C content was outside the range of the present invention, the amount of hard micro-structure increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0109] In comparative example 2, because the Si content was outside the range of the present invention, the amount of hard micro-structure increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0110] In comparative example 3, because the Mn content was outside the range of the present invention, segregation increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0111] In comparative example 4, because the Ti content was outside the range of the present invention, the toughness decreased due to an increase in coarse TiC. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0112] In comparative example 5, because the Al content was outside the range of the present invention, the toughness decreased due to an increase in coarse Al_2O_3 . Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0113] In comparative example 6, because the O content was outside the range of the present invention, coarse oxides increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0114] In comparative example 7, because the Mn content was outside the range of the present invention, the MnS area fraction in a cross-section of the composite inclusions was lower than the range defined in the present invention. Consequently, intragranular ferrite did not grow sufficiently and the toughness decreased. Therefore, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0115] In comparative example 8, because the Mn content was outside the range of the present invention, the MnS area fraction in a cross-section of the composite inclusions was more than the range of the present invention. Conse-

quently, intragranular ferrite did not grow sufficiently and the toughness decreased. Therefore, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0116] In comparative example 9, because the Mn content was outside the range of the present invention, the MnS proportion at a boundary surface of the composite inclusions was less than the range of the present invention. Consequently, intragranular ferrite did not grow sufficiently and the toughness decreased. As a result, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0117] In comparative example 10, the Ti content was small and the number density of the composite inclusions was less than the range of the present invention. Consequently, intragranular ferrite did not grow sufficiently and the toughness decreased. Therefore, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0118] In comparative example 11, because the Cu content was outside the range of the present invention, the strength increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0119] In comparative example 12, because the Cr content was outside the range of the present invention, the strength increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0120] In comparative example 13, because the Mo content was outside the range of the present invention, the strength increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0121] In comparative example 14, because the V content was outside the range of the present invention, in addition to the strength increasing, a large amount of VC was precipitated. As a result, the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0122] In comparative example 15, because the Nb content was outside the range defined by the present invention, a large amount of NbC precipitated, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

EXAMPLE 2

[0123] Similarly to Example 1, steels having the chemical compositions of test number examples 31 to 61 and comparative examples 21 to 32 shown in Table 3 were melted by an actual production process, and specimens were prepared. Further, in a similar manner to Example 1, calculation of the MnS area fraction at a cross-section of composite inclusions as well as the proportion that MnS accounted for in the peripheral length of the composite inclusions, and calculation of the number density of the composite inclusions was performed. The results are shown in Table 3.

[Table 3]

[0124]

Table 3

Test No.	Chemical Composition (mass%; balance: Fe and impurities)															MnS Area Fraction Rt (%) in Composite Inclusion Cross- Section	Proportion Pz (%) MnS Accounts for in Peripheral Length of Composite Inclusion	Number Density of Composite Inclusions (per mm²)	X Given by Formula (I)	Remarks
	C	Si	Mn	P	S	Ti	Al	N	O	N	Cr	Mo	V	Nb						
Example 31	0.07	0.16	1.87	0.0060	0.0026	0.013	0.001	0.64	0.0018	0.0030	-	-	-	-	55	25	26	1.22	Example Embodiment of Present Invention	
Example 32	0.08	0.13	1.78	0.0030	0.0032	0.016	0.001	0.68	0.0018	0.0033	-	-	-	-	73	70	35	3.48		
Example 33	0.09	0.18	1.53	0.0050	0.0021	0.009	0.001	0.86	0.0014	0.0025	-	-	-	-	55	61	11	0.55		
Example 34	0.07	0.15	1.53	0.0021	0.0044	0.019	0.001	0.64	0.0010	0.0050	-	-	-	-	54	57	30	2.05		
Example 35	0.10	0.12	1.69	0.0030	0.0050	0.016	0.001	0.65	0.0014	0.0033	-	-	-	0.01	67	61	32	3.97		
Example 36	0.08	0.15	1.84	0.0040	0.0044	0.016	0.001	0.63	0.0030	0.0043	-	-	-	0.02	83	80	59	0.18		
Example 37	0.07	0.12	1.78	0.0011	0.0021	0.015	0.001	0.65	0.0026	0.0020	-	-	-	0.01	78	76	52	4.83		
Example 38	0.05	0.18	1.53	0.0021	0.0010	0.010	0.001	0.81	0.0010	0.0002	-	-	-	-	53	30	12	7.55		
Example 39	0.01	0.18	1.53	0.0011	0.0026	0.020	0.001	0.62	0.0010	0.0033	-	-	-	-	47	44	49	7.65		
Example 40	0.08	0.10	1.37	0.0021	0.0026	0.020	0.001	0.60	0.0018	0.0049	-	-	-	-	32	35	67	1.24		
Example 41	0.04	0.12	1.00	0.0011	0.0044	0.016	0.001	0.65	0.0014	0.0032	-	-	-	-	11	12	32	0.77		
Example 42	0.04	0.15	2.00	0.0020	0.0032	0.020	0.001	0.61	0.0026	0.0033	-	-	-	0.02	86	88	69	5.84		
Example 43	0.07	0.15	2.00	0.0030	0.0010	0.011	0.001	0.82	0.0026	0.0021	-	-	-	0.01	15	13	15	0.45		
Example 44	0.08	0.18	2.00	0.0040	0.0038	0.019	0.001	0.80	0.0018	0.0025	-	-	-	0.03	86	82	91	9.64		
Example 45	0.07	0.10	1.95	0.0050	0.0044	0.006	0.001	0.85	0.0048	0.0015	-	-	-	-	41	37	10	0.15		
Example 46	0.08	0.15	2.00	0.0001	0.0026	0.011	0.001	0.88	0.0010	0.0017	-	-	-	-	87	81	13	9.20		
Example 47	0.10	0.10	1.84	0.0050	0.0032	0.020	0.001	0.64	0.0026	0.0017	-	-	-	-	76	69	55	7.64		
Example 48	0.08	0.25	1.84	0.0021	0.0032	0.015	0.001	0.55	0.0026	0.0002	-	-	-	-	71	65	60	7.54		
Example 49	0.08	0.13	2.50	0.0050	0.0026	0.019	0.001	0.64	0.0014	0.0050	-	-	-	0.02	87	81	59	2.25		
Example 50	0.07	0.12	1.84	0.0100	0.0050	0.020	0.001	0.55	0.0018	0.0049	-	-	-	-	71	77	69	2.75		
Example 51	0.09	0.18	1.84	0.0030	0.0100	0.016	0.001	0.53	0.0030	0.0022	-	-	-	0.02	82	78	73	4.38		
Example 52	0.08	0.12	1.76	0.0021	0.0032	0.011	0.001	1.50	0.0018	0.0020	-	-	-	0.02	64	60	11	2.84		
Example 53	0.08	0.18	1.84	0.0011	0.0038	0.030	0.001	0.51	0.0030	0.0036	-	-	-	69	77	93	9.62			
Example 54	0.07	0.12	1.89	0.0001	0.0038	0.010	0.003	0.89	0.0018	0.0028	-	-	-	-	55	58	11	0.27		
Example 55	0.06	0.18	1.96	0.0011	0.0032	0.030	0.001	0.88	0.0018	0.0087	-	-	-	0.02	83	86	18	0.26		
Example 56	0.07	0.12	1.53	0.0021	0.0044	0.020	0.001	0.51	0.0050	0.0022	-	-	-	0.03	48	41	92	2.25		
Example 57	0.06	0.22	1.88	0.0055	0.0030	0.011	0.001	0.61	0.0022	0.0020	0.35	-	-	-	53	28	15	1.29		
Example 58	0.06	0.19	1.78	0.0063	0.0020	0.022	0.001	0.67	0.0015	0.0030	-	0.40	-	-	53	25	36	8.78		
Example 59	0.06	0.18	1.85	0.0044	0.0030	0.019	0.001	0.63	0.0023	0.0030	-	-	-	-	52	20	50	3.49		
Example 60	0.08	0.24	1.88	0.0040	0.0020	0.025	0.001	0.64	0.0024	0.0050	-	-	0.07	-	52	23	88	5.25		
Example 61	0.07	0.12	1.87	0.0062	0.0025	0.021	0.001	0.65	0.0030	0.0040	-	-	-	0.04	54	27	91	2.91		
Comp. Ex. 21	0.11	0.12	1.52	0.0030	0.0050	0.020	0.001	0.82	0.0010	0.0030	-	-	-	-	47	48	15	9.27		
Comp. Ex. 22	0.07	0.30	1.51	0.0040	0.0038	0.020	0.001	0.81	0.0030	0.0032	-	-	-	-	89	81	69	5.15		
Comp. Ex. 23	0.06	0.18	3.00	0.0040	0.0090	0.009	0.001	0.88	0.0014	0.0016	-	-	-	0.02	96	99	11	5.22		
Comp. Ex. 24	0.09	0.16	1.69	0.0010	0.0026	0.032	0.001	0.50	0.0018	0.0064	-	-	-	-	13	16	107	1.71		
Comp. Ex. 25	0.06	0.18	2.00	0.0050	0.0020	0.020	0.005	0.55	0.0030	0.0053	-	-	-	0.02	86	87	73	1.09		
Comp. Ex. 26	0.08	0.18	1.88	0.0010	0.0026	0.009	0.001	0.87	0.0022	0.0110	-	-	-	0.02	41	44	12	-11.04		
Comp. Ex. 27	0.07	0.15	1.84	0.0000	0.0044	0.009	0.001	0.80	0.0055	0.0018	-	-	-	0.01	76	74	11	0.97		
Comp. Ex. 28	0.07	0.16	1.88	0.0060	0.0024	0.013	0.001	0.66	0.0015	0.0030	0.60	-	-	-	55	25	26	3.05		
Comp. Ex. 29	0.07	0.13	1.82	0.0055	0.0040	0.012	0.001	0.63	0.0030	0.0040	-	0.60	-	-	51	23	30	0.44		
Comp. Ex. 30	0.08	0.19	1.88	0.0049	0.0030	0.011	0.001	0.64	0.0020	0.0030	-	-	-	0.55	55	21	13	1.59		
Comp. Ex. 31	0.06	0.20	1.84	0.0028	0.0040	0.017	0.001	0.64	0.0022	0.0040	-	-	-	-	54	22	41	3.28		
Comp. Ex. 32	0.07	0.22	1.89	0.0050	0.0030	0.030	0.001	0.66	0.0028	0.0020	-	-	-	0.07	58	28	95	6.83		

Mark "" indicates value is outside range defined by the present invention.

[0125] Further, a tension test and a CTOD test were performed similarly to Example 1. The test results are shown in Table 4.

[Table 4]

[0126]

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Table 4

Test No.	Strength (MPa)		CTOD test result			
	YP	TS	n=1	n=2	n=3	Decision
Example 31	420	630	>1.4	>1.4	>1.4	○
Example 32	412	621	>1.4	>1.4	>1.4	○
Example 33	431	642	>1.4	>1.4	>1.4	○
Example 34	412	620	>1.4	>1.4	>1.4	○
Example 35	425	621	>1.4	>1.4	>1.4	○
Example 36	435	644	>1.4	>1.4	>1.4	○
Example 37	431	641	>1.4	>1.4	>1.4	○
Example 38	430	627	>1.4	>1.4	>1.4	○
Example 39	400	600	>1.4	>1.4	>1.4	○
Example 40	402	603	>1.4	>1.4	>1.4	○
Example 41	403	606	>1.4	>1.4	1.28	○
Example 42	446	652	>1.4	>1.4	>1.4	○
Example 43	441	655	>1.4	>1.4	1.13	○
Example 44	443	651	>1.4	>1.4	1.16	○
Example 45	437	649	>1.4	>1.4	1.19	○
Example 46	445	654	>1.4	>1.4	1.11	○
Example 47	432	651	0.84	0.94	1.23	○
Example 48	431	647	0.71	0.88	1.03	○
Example 49	452	661	0.56	0.61	0.84	○
Example 50	441	641	0.66	0.88	0.91	○
Example 51	438	635	0.55	0.58	0.62	○
Example 52	436	637	0.86	0.88	0.98	○
Example 53	435	641	0.67	0.77	0.98	○
Example 54	425	635	0.51	0.72	0.82	○
Example 55	439	647	0.56	0.63	0.71	○
Example 56	416	625	0.55	0.63	0.74	○
Example 57	442	635	0.97	1.36	>1.4	○
Example 58	445	640	0.43	0.46	0.58	○
Example 59	451	681	0.41	0.43	0.52	○
Example 60	440	635	0.74	0.88	0.91	○
Example 61	435	661	0.47	0.66	0.67	○
Comp. Ex. 21	418	628	0.29	0.36	0.41	×
Comp. Ex. 22	413	615	0.21	0.23	0.36	×
Comp. Ex. 23	490	664	0.16	0.22	0.26	×
Comp. Ex. 24	419	617	0.25	0.34	0.41	×
Comp. Ex. 25	443	642	0.21	0.22	0.34	×

(continued)

Test No.	Strength (MPa)		CTOD test result			
	YP	TS	n=1	n=2	n=3	Decision
Comp. Ex. 26	424	634	0.31	0.36	0.37	×
Comp. Ex. 27	425	621	0.22	0.36	0.39	×
Comp. Ex. 28	462	685	0.28	0.61	0.99	×
Comp. Ex. 29	469	700	0.31	0.62	0.87	×
Comp. Ex. 30	470	701	0.09	0.22	0.34	×
Comp. Ex. 31	471	703	0.24	0.35	0.97	×
Comp. Ex. 32	469	681	0.22	0.31	0.91	×
">1.4" in the table indicates that the relevant result is over the gauge.						

[0127] Examples 31 to 61 satisfied all conditions with respect to the ranges of the present invention, and hence the result of the CTOD test for these examples was "pass".

[0128] In example 39, although the CTOD test result was "pass", the YP and TS were low because the C content was close to the lower limit value of the range of the present invention.

[0129] In example 40, although the CTOD test result was "pass", the YP and TS were low because the Si content was close to the lower limit value of the range of the present invention.

[0130] In example 41, although the CTOD test result was "pass", the YP and TS were low because the Mn content was close to the lower limit value of the range of the present invention.

[0131] In example 43, because the S content was close to the lower limit value of the range of the present invention, the MnS composite amount decreased, and the MnS area fraction in a cross-section of the composite inclusions as well as the proportion that MnS accounted for in the peripheral length of the composite inclusions decreased. As a result, in the CTOD test, only one test specimen was not over the gauge.

[0132] In example 44, because the Ni content was close to the lower limit value of the range of the present invention, the toughness decreased. As a result, in the CTOD test, only one test specimen was not over the gauge.

[0133] In example 45, because the Ti content was close to the lower limit value of the range of the present invention, the number density of the composite inclusions was low. As a result, in the CTOD test, only one test specimen was not over the gauge.

[0134] In example 46, because the O content was close to the lower limit value of the range of the present invention, the number density of the composite inclusions was low. As a result, in the CTOD test, only one test specimen was not over the gauge.

[0135] In example 47, because the C content was close to the upper limit value of the range of the present invention, the amount of hard micro-structure increased. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0136] In example 48, because the Si content was close to the upper limit value of the range of the present invention, the amount of hard micro-structure increased. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0137] In example 49, because the Mn content was close to the upper limit value of the range of the present invention, segregation occurred. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0138] In example 50, because the P content was close to the upper limit value of the range of the present invention, the toughness decreased due to segregation. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0139] In example 51, because the S content was close to the upper limit value of the range of the present invention, the toughness decreased due to segregation. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0140] In example 52, because the Ni content was close to the upper limit value of the range of the present invention, the toughness decreased due to formation of intragranular transformation ferrite being inhibited. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0141] In example 53, because the Ti content was close to the upper limit value of the range of the present invention, the toughness decreased due to an increase in carbides such as TiC. Consequently, in the CTOD test, although all of

the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0142] In example 54, because the Al content was close to the upper limit value of the range of the present invention, inclusions that act as intragranular ferrite formation nuclei decreased, and as a result the toughness decreased. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0143] In example 55, because the N content was close to the upper limit value of the range of the present invention, TiN increased and, as a result, the toughness decreased. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0144] In example 56, because the O content was close to the upper limit value of the range of the present invention, the toughness decreased due to an increase in coarse oxides. Consequently, in the CTOD test, although all of the test specimens were not over the gauge, the CTOD values were 0.4 mm or more.

[0145] In example 57, although the result of the CTOD test was "pass" because the Cu content was within the range of the present invention, the toughness was comparatively low.

[0146] In example 58, although the result of the CTOD test was "pass" because the Cr content was within the range of the present invention, the toughness was comparatively low.

[0147] In example 59, although the result of the CTOD test was "pass" because the Mo content was within the range of the present invention, the toughness was comparatively low.

[0148] In example 60, although the result of the CTOD test was "pass" because the V content was within the range of the present invention, the toughness was comparatively low.

[0149] In example 61, although the result of the CTOD test was "pass" because the Nb content was within the range of the present invention, the toughness was comparatively low.

[0150] In comparative example 21, because the C content was outside the range of the present invention, the amount of hard micro-structure increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0151] In comparative example 22, because the Si content was outside the range of the present invention, the amount of hard micro-structure increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0152] In comparative example 23, because the Mn content was outside the range of the present invention, segregation increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0153] In comparative example 24, because the Ti content was outside the range of the present invention, the toughness decreased due to an increase in coarse TiC. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0154] In comparative example 25, because the Al content was outside the range of the present invention, the toughness decreased due to an increase in coarse Al_2O_3 . Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0155] In comparative example 26, because the N content was outside the range of the present invention, agglomeration of coarse TiN occurred, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0156] In comparative example 27, because the O content was outside the range of the present invention, coarse oxides increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0157] In comparative example 28, because the Cu content was outside the range of the present invention, the strength increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0158] In comparative example 29, because the Cr content was outside the range of the present invention, the strength increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0159] In comparative example 30, because the Mo content was outside the range of the present invention, the strength increased, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0160] In comparative example 31, because the V content was outside the range of the present invention, in addition to the strength increasing, a large amount of VC was precipitated. As a result, the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

[0161] In comparative example 32, because the Nb content was outside the range of the present invention, a large amount of NbC precipitated, and as a result the toughness decreased. Consequently, in the CTOD test, there was a test specimen for which the CTOD value was less than 0.4 mm.

INDUSTRIAL APPLICABILITY

[0162] According to the present invention, a thick steel plate can be provided that is excellent in low-temperature toughness for a HAZ when high heat input welding is performed. Therefore, the thick steel plate of the present invention can be favorably used for welded structures such as marine structures, and particularly for thick steel plates that have a plate thickness of 50 mm or more.

Claims

1. A thick steel plate having a chemical composition comprising, by mass%,

C: 0.01 to 0.20%,
 Si: 0.10 to 0.25%,
 Mn: 1.30 to 2.50%,
 P: 0.01% or less,
 S: 0.0010 to 0.0100%,
 Ti: 0.005 to 0.030%,
 Al: 0.003% or less,
 O: 0.0010 to 0.0050%,
 N: 0.0100% or less,
 Cu: 0 to 0.50%,
 Ni: 0 to 1.50%,
 Cr: 0 to 0.50%,
 Mo: 0 to 0.50%,
 V: 0 to 0.10%,
 Nb: 0 to 0.05%, and
 the balance: Fe and impurities;
 wherein:

a composite inclusion in which MnS is present around a Ti oxide is contained in the steel;
 an area fraction of the MnS in a cross-section of the composite inclusion is 10% or more and less than 90%;
 a proportion that the MnS accounts for in a peripheral length of the composite inclusion is 10% or more; and
 a number density of the composite inclusions which have a grain diameter in a range of 0.5 to 5.0 μm is in a range of 10 to 100 per mm^2 .

2. The thick steel plate according to claim 1, containing, by mass%, at least one element selected from:

Cu: 0.01 to 0.50%,
 Ni: 0.01 to 1.50%,
 Cr: 0.01 to 0.50%,
 Mo: 0.01 to 0.50%,
 V: 0.01 to 0.10%, and
 Nb: 0.01 to 0.05%

3. The thick steel plate according to claim 1 or 2, wherein a value X obtained by formula (i) below is in a range of 0.04 to 9.70:

$$X = \left[\left(\frac{\text{Ti} - \text{TiO}}{\text{O}} \right) + (\text{Mn} - \text{MnS}) \right] \times \left[(\text{R1} + \text{R2}) / 100 \right] \cdots (i)$$

where, the meaning of each symbol in the formula (i) is as follows:

Ti_TiO (mass%): Ti amount that becomes a Ti oxide among a total Ti content
 O (mass%): O content in the steel
 Mn_MnS (mass%): Mn amount that becomes MnS among a total Mn content
 R1(%): average value of area fraction of MnS in a cross-section of a composite inclusion

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R2(%): average value of proportion that MnS accounts for in a peripheral length of a composite inclusion.

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2017/016090

A. CLASSIFICATION OF SUBJECT MATTER

C22C38/00(2006.01)i, C22C38/58(2006.01)i

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, C22C38/58

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2017
 Kokai Jitsuyo Shinan Koho 1971-2017 Toroku Jitsuyo Shinan Koho 1994-2017

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 6-136439 A (Kobe Steel, Ltd.), 17 May 1994 (17.05.1994), (Family: none)	1-3
A	JP 1-191765 A (Nippon Steel Corp.), 01 August 1989 (01.08.1989), (Family: none)	1-3
A	WO 2014/199488 A1 (Nippon Steel & Sumitomo Metal Corp.), 18 December 2014 (18.12.2014), & EP 2843073 A1 & CN 104364405 A & KR 10-2015-0020181 A	1-3

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

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Date of the actual completion of the international search
05 July 2017 (05.07.17)Date of mailing of the international search report
18 July 2017 (18.07.17)Name and mailing address of the ISA/
Japan Patent Office
3-4-3, Kasumigaseki, Chiyoda-ku,
Tokyo 100-8915, Japan

Authorized officer

Telephone No.

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

REFERENCES CITED IN THE DESCRIPTION

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