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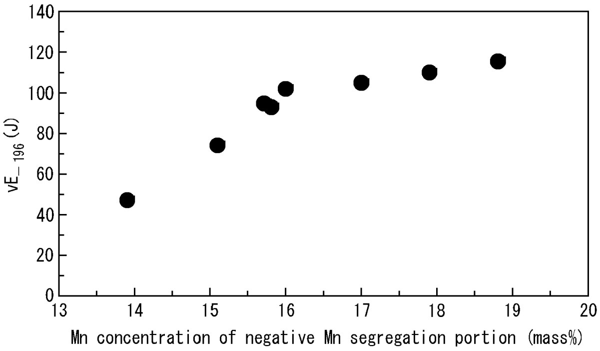
(54) HIGH-MN STEEL AND PRODUCTION METHOD THEREFOR

(57) Provided is high-Mn steel excellent in low-temperature toughness which can suppress costs of materials and production, the steel including: a chemical composition containing, in mass%, C: 0.100% or more and 0.700% or less, Si: 0.05% or more and 1.00% or less, Mn: 20.0% or more and 35.0% or less, P: 0.030% or less, S: 0.0070% or less, Al: 0.01% or more and 0.07% or less, Cr: 0.5% or more and 7.0% or less, N: 0.0050% or more and 0.0500% or less, O: 0.0050% or less, Ti: 0.0050% or less, and Nb: 0.0050% or less with the balance being Fe and inevitable impurities; and a microstructure having austenite as a matrix phase, in which the microstructure has a Mn segregation portion with a Mn concentration of 16% or more and 38% or less, and the high-Mn steel has an average KAM value of 0.3 or more.

FIG. 1



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Description

TECHNICAL FIELD

[0001] This disclosure relates to high-Mn steel that is suitable for structural steel used in an extremely low-temperature environment such as a storage tank of liquefied gas, in particular, high-Mn steel excellent in toughness at low temperature, and a production method therefor.

BACKGROUND

[0002] To use a hot-rolled steel plate in a structure for a storage tank of liquefied gas, the steel plate needs to have high strength and excellent toughness at low temperature because the structure is used at extremely low temperature. For example, when a hot-rolled steel plate is used for a storage tank of liquefied natural gas, excellent toughness needs to be guaranteed at the boiling point of the liquefied natural gas, that is, -164 °C or lower. When a steel material has poor low-temperature toughness, the safety as a structure for an extremely low temperature storage tank may not be maintained. Thus, there is a growing demand for steel materials with improved low-temperature toughness that are applied to such a structure. Hereinafter, an extremely low temperature range including -164 °C is referred to as "low temperature".

[0003] In view of the demand, austenitic stainless steel which has austenite as a microstructure of a steel plate, the austenite having no brittleness at low temperature, 9 % Ni steel, or five thousand series aluminum alloys have been conventionally used. However, the alloy cost and production cost are high, and thus there is a demand for steel materials which are inexpensive and excellent in low-temperature toughness.

[0004] As new steel materials replacing conventional steel for low temperature use, for example, JP 2017-71817 A (PTL 1) proposes using, as structural steel used in a low temperature environment, high-Mn steel added with a large amount of Mn which is a relatively inexpensive austenite-stabilizing element.

[0005] PTL 1 proposes a technique of controlling the Mn segregation ratio to prevent carbides generated in crystal grain boundaries from becoming an origin of fracture.

CITATION LIST

[0006] Patent Literature
PTL1: JP2017-71817A

SUMMARY

(Technical Problem)

[0007] Though it is possible to provide high-Mn steel excellent in low-temperature toughness according to the technique of PTL 1, there has been a demand for material cost reduction since the high-Mn steel needs to contain Ni from the viewpoint of guaranteeing toughness. Further, to reduce the Mn segregation ratio, diffusion heat treatment having a product of heating temperature (°C) and heating time (hr) of 30000 °C·hr or more is required, which incurs a high production cost.

[0008] It could thus be helpful to provide high-Mn steel excellent in low-temperature toughness which can suppress costs of materials and production. Further, it could be helpful to propose an advantageous method for producing such high-Mn steel. As used herein, the phrase "excellent in low-temperature toughness" means that the absorbed energy vE_{-196} in a Charpy impact test at -196 °C is 100 J or more.

(Solution to Problem)

[0009] To achieve the aforementioned objects, the inventors conducted extensive study on high-Mn steel as to various factors determining the chemical composition and microstructure of a steel plate to discover the following:

a. Since high-Mn austenite steel has slow diffusion of Mn, a Mn segregation portion having a low Mn concentration formed during continuous casting remains after hot rolling. When the Mn segregation portion has a Mn concentration of less than 16 %, deformation-induced martensite forms at low temperature, deteriorating low-temperature toughness. Therefore, to improve the low-temperature toughness of high-Mn steel, it is effective to increase the Mn concentration in the Mn segregation portion.

b. Since high-Mn austenite steel has slow diffusion of Mn, a Mn segregation portion having a high Mn concentration

formed during continuous casting remains after hot rolling. The Mn segregation having a Mn concentration of more than 38 % causes intergranular fracture, deteriorating low-temperature toughness. Therefore, to improve the low-temperature toughness of high-Mn steel, it is effective to decrease the Mn concentration in the Mn segregation portion.
c. With hot rolling under suitable conditions, the above a or b can be realized without diffusion heat treatment, and production costs can be suppressed.
d. Performing hot rolling under suitable conditions to provide a high dislocation density is effective for increasing yield stress.

[0010] This disclosure is based on the above discoveries and further investigation conducted by the inventors. The primary features of this disclosure are as follows.

1. High-Mn steel comprising: a chemical composition containing (consisting of), in mass%,

C: 0.100 % or more and 0.700 % or less,
Si: 0.05 % or more and 1.00 % or less,
Mn: 20.0 % or more and 35.0 % or less,
P: 0.030 % or less,
S: 0.0070 % or less,
Al: 0.01 % or more and 0.07 % or less,
Cr: 0.5 % or more and 7.0 % or less,
N: 0.0050 % or more and 0.0500 % or less,
O: 0.0050 % or less,
Ti: 0.0050 % or less, and
Nb: 0.0050 % or less

with the balance being Fe and inevitable impurities; and

a microstructure having austenite as a matrix phase, wherein
the microstructure has a Mn segregation portion with a Mn concentration of 16 % or more and 38 % or less, and the high-Mn steel has an average KAM (Kernel Average Misorientation) value of 0.3 or more, an absorbed energy in a Charpy impact test at -196 °C of 100 J or more, and a yield stress of 400 MPa or more.

Further, the KAM value represents an average of orientation difference between each pixel (having a pitch of 0.3 μm) and the adjacent pixel in a crystal grain. For a steel plate after hot rolling, EBSD (Electron Backscatter Diffraction) analysis in a field of 500 μm × 200 μm was performed in arbitrary two fields, and an average of the analysis results for all the measured regions was calculated to determine an average KAM value.
2. The high-Mn steel according to 1., wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of

Mo: 2.0 % or less,
V: 2.0 % or less,
W: 2.0 % or less,
Ca: 0.0005 % or more and 0.0050 % or less,
Mg: 0.0005 % or more and 0.0050 % or less, and
REM: 0.0010 % or more and 0.0200 % or less.

3. A method for producing high-Mn steel, comprising: heating a steel material having the chemical composition according to 1. or 2. to a temperature range of 1100 °C or higher and 1300 °C or lower; and
hot rolling the steel material with a rolling finish temperature of 800 °C or higher and a total rolling reduction of 20 % or more.
4. The method for producing high-Mn steel according to 3., further comprising:

hot rolling the steel material with a rolling finish temperature of 700 °C or higher and lower than 950 °C; and then subjecting the steel material to cooling treatment at an average cooling rate of 1.0 °C/s or more within a range of a temperature at or above (the rolling finish temperature - 100 °C) to a temperature ranging from 300 °C to 650 °C.
As used herein, each temperature range represents a surface temperature of a steel material or a steel plate.

(Advantageous Effect)

[0011] According to this disclosure, it is possible to provide high-Mn steel excellent in low-temperature toughness. Therefore, our high-Mn steel largely contributes to the improvement of the safety and the service life of a steel structure used in a low temperature environment such as a tank for a storage tank of liquefied gas, and has industrially significant effects. Further, our production method does not decrease productivity or increase the production cost, and thus is excellent in economic efficiency.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] In the accompanying drawings:

FIG. 1 is a graph representing a relationship between the Mn concentration of a negative Mn segregation portion and a Charpy absorbed energy (vE_{-196}); and
FIG. 2 is a graph representing a relationship between the Mn concentration of a Mn segregation portion and a Charpy absorbed energy (vE_{-196}).

DETAILED DESCRIPTION

Our high-Mn steel will be described in detail hereinafter.

[Chemical Composition]

[0013] The chemical composition of our high-Mn steel and the reasons for the limitations thereof are described first. In the description of the chemical composition, "%" denotes "mass%" unless otherwise noted.

C: 0.100 % or more and 0.700 % or less

[0014] C is an inexpensive austenite-stabilizing element, and an important element to obtain austenite. To obtain this effect, the C content needs to be 0.100 % or more. On the other hand, a C content beyond 0.700 % generates excessive Cr carbides, deteriorating low-temperature toughness. Therefore, the C content is set to be 0.100 % or more and 0.700 % or less. The C content is preferably 0.200 % or more and 0.600 % or less.

Si: 0.05 % or more and 1.00 % or less

[0015] Si acts as a deoxidizer, is necessary for steelmaking, and is effective at increasing the strength of a steel plate by solid solution strengthening when dissolved in steel. To obtain such an effect, the Si content needs to be 0.05 % or more. On the other hand, a Si content beyond 1.00 % deteriorates weldability. Therefore, the Si content is set to 0.05 % or more and 1.00 % or less, and preferably 0.07 % or more and 0.50 % or less.

Mn: 20.0 % or more and 35.0 % or less

[0016] Mn is a relatively inexpensive austenite-stabilizing element. In this disclosure, Mn is an important element for achieving both strength and low-temperature toughness. To obtain the effects, the Mn content needs to be 20.0 % or more. On the other hand, a Mn content beyond 35.0 % deteriorates low-temperature toughness. Further, such a high Mn content deteriorates weldability and cuttability, and further promotes segregation as well as the occurrence of stress corrosion cracking. Therefore, the Mn content is set to 20.0 % or more and 35.0 % or less, preferably 23.0 % or more and 30.0 % or less, and more preferably 28.0 % or less.

P: 0.030 % or less

[0017] When a P content is beyond 0.030 %, P segregates to grain boundaries and becomes an origin of stress corrosion cracking. Therefore, the upper limit of the P content is 0.030 %, and desirably, the P content is kept as small as possible. Therefore, the P content is set to 0.030 % or less. Excessively reducing P involves high refining cost and is economically disadvantageous. Therefore, the P content is desirably set to 0.002 % or more, preferably 0.005 % or more and 0.028 % or less, and more preferably 0.024 % or less.

S: 0.0070 % or less

[0018] S deteriorates the low-temperature toughness and ductility of the base metal. Therefore, the upper limit of the S content is 0.0070 %, and desirably, the S content is kept as small as possible. Therefore, the S content is set to 0.0070 % or less. Excessively reducing S involves high refining cost and is economically disadvantageous. Therefore, the lower limit of the S content is desirably set to 0.001 % or more. The S content is preferably set to 0.0020 % or more and 0.0060 % or less.

Al: 0.01 % or more and 0.07 % or less

[0019] Al acts as a deoxidizer and is used most commonly in molten steel deoxidizing processes to obtain a steel plate. To obtain such an effect, the Al content needs to be 0.01 % or more. On the other hand, when the Al content is beyond 0.07 %, Al is mixed into a weld metal portion during welding, deteriorating the toughness of the weld metal. Therefore, the Al content is set to 0.07 % or less. Therefore, the Al content is set to 0.01 % or more and 0.07 % or less, and preferably 0.02 % or more and 0.06 % or less.

Cr: 0.5 % or more and 7.0 % or less

[0020] Cr is an element which stabilizes austenite with an appropriate amount of addition and is effective for improving low-temperature toughness and base metal strength. To obtain such effects, the Cr content needs to be 0.5 % or more. On the other hand, a Cr content beyond 7.0 % generates Cr carbides, deteriorating low-temperature toughness and stress corrosion cracking resistance. Therefore, the Cr content is set to 0.5 % or more and 7.0 % or less, preferably 1.0 % or more and 6.7 % or less, and more preferably 1.2 % or more and 6.5 % or less. To further improve stress corrosion cracking resistance, the Cr content is further preferably 2.0 % or more and 6.0 % or less.

N: 0.0050 % or more and 0.0500 % or less

[0021] N is an austenite-stabilizing element and an element which is effective for improving low-temperature toughness. To obtain such an effect, the N content needs to be 0.0050 % or more. On the other hand, the N content beyond 0.0500 % coarsens nitrides or carbonitrides, deteriorating toughness. Therefore, the N content is set to 0.0050 % or more and 0.0500 % or less, and preferably 0.0060 % or more and 0.0400 % or less.

O: 0.0050 % or less

[0022] O deteriorates low-temperature toughness because of the formation of oxides. Therefore, the O content is set to 0.0050 % or less, and preferably 0.0045 % or less. Excessively reducing O involves high refining cost and is economically disadvantageous. Therefore, the O content is desirably set to 0.0010 % or more.

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

[0023] Ti and Nb form carbonitrides with a high melting point in steel to prevent coarsening of crystal grains, then becoming an origin of fracture and a propagation path of cracks. In particular, in high-Mn steel, Ti and Nb hinder microstructure control for enhancing low-temperature toughness and improving ductility, and thus, need to be intentionally limited. Specifically, Ti and Nb are components which are inevitably mixed from raw materials and the like into steel, and Ti of more than 0.005 % and 0.010 % or less and Nb of more than 0.005 % and 0.010 % or less are typically mixed. Thus, according to the method described below, it is necessary to avoid inevitable mixing of Ti and Nb and limit the content of each Ti and Nb to 0.005 % or less. By limiting the content of each Ti and Nb to 0.005 % or less, it is possible to eliminate the adverse effect of carbonitrides and guarantee excellent low-temperature toughness and ductility. The content of each Ti and Nb is preferably set to 0.003 % or less. The contents of each Ti and Nb may be 0 %.

[0024] The balance other than the aforementioned components is Fe and inevitable impurities. The inevitable impurities include H, and a total content of 0.01 % or less is allowable.

[Microstructure]

Microstructure having austenite as a matrix phase

[0025] When a steel material has a body centered cubic (bcc) crystal structure, the steel material may cause brittle fracture in a low temperature environment, and thus, is not suitable for use in a low temperature environment. When the steel material is assumed to be used in a low temperature environment, the steel material is required to have, as a matrix phase, an austenite microstructure which has a face centered cubic (fcc) crystal structure. As used herein, the phrase "having austenite as a matrix phase" and similar phrases mean that the area ratio of an austenite phase is 90 % or more. The balance other than the austenite phase is a ferrite or martensite phase. The area ratio of the austenite phase is preferably 95 % or more.

[0026] As stated above, in high-Mn steel containing Mn in an amount of 20.0 % or more and 35.0 % or less, a segregation portion having a low Mn concentration and a segregation portion having a high Mn concentration, compared with the Mn content in the chemical composition are formed. As described below, the inventors found that these portions having different Mn concentrations are a factor behind the deterioration of low-temperature toughness.

[0027] Specifically, the Mn concentration of a Mn segregation portion and an absorbed energy in a Charpy impact test at -196 °C were measured on a steel plate obtained by hot rolling a steel material having the aforementioned chemical composition under various conditions. As used herein, the Mn segregation portion, which is a region having a low or high Mn concentration within a Mn segregation band, is specifically represented by a region having a lowest or highest Mn concentration which is measured by EBSD (Electron Backscatter Diffraction) analysis on a polished surface in a cross section along a rolling direction of a steel plate after hot rolling.

Microstructure having Mn segregation portion with Mn concentration of 16 % or more and 38 % or less

[0028] First, in a Mn segregation portion having a low Mn concentration (negative Mn segregation portion), as FIG. 1 illustrates the result of measuring the Mn concentration and the absorbed energy in the Charpy impact test at -196 °C, it is found that when the Mn concentration in the Mn segregation portion is 16 % or more, an absorbed energy of 100 J or more is achieved. The Mn concentration in the Mn segregation portion is preferably 17 % or more.

[0029] Further, in a Mn segregation portion having a high Mn concentration, as FIG. 2 illustrates a result obtained by measuring the Mn concentration and the absorbed energy in the Charpy impact test at -196 °C, it is found that when the Mn concentration in the Mn segregation portion is 38 % or less, an absorbed energy of 100 J or more is achieved. The Mn concentration in the Mn segregation portion is preferably 37 % or less.

Average KAM (Kernel Average Misorientation) value being 0.3 or more

[0030] As stated above, the KAM value is determined by performing EBSD (Electron Backscatter Diffraction) analysis in a field of 500 μm $\times$ 200 μm in an arbitrary two fields of a steel plate after hot rolling and calculating from the analysis results an average of orientation difference between each pixel (having a pitch of 0.3 μm) and the adjacent pixel in a crystal grain. The KAM value reflects the local crystal orientation change caused by dislocation in the microstructure. A higher KAM value represents a larger orientation difference between a measurement point and the adjacent portion. Specifically, a higher KAM value means a higher local deformation degree in a grain. Therefore, a higher KAM value in a steel plate after rolling means a higher dislocation density. Further, when the average KAM value is 0.3 or more, it means accumulation of a large amount of dislocation, and thus, yield stress increases. The average KAM value is preferably 0.5 or more. On the other hand, when the average KAM value is beyond 1.3, toughness may be deteriorated. Thus, the average KAM value is preferably 1.3 or less.

[0031] A Mn segregation portion having a Mn concentration of 16 % or more and 38 % or less and an average KAM value of 0.3 or more as stated above can be obtained by adjusting the chemical composition as described above and performing hot rolling according to the following conditions.

[0032] In this disclosure, to further improve strength and low-temperature toughness, in addition to the above essential elements, the following elements can be contained as necessary.

At least one of Mo: 2.0 % or less, V: 2.0 % or less, W: 2.0 % or less, Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, and REM: 0.0010 % or more and 0.0200 % or less.

Mo, V, and W: 2.0 % or less

[0033] Mo, V, and W contribute to stabilizing austenite and improving base metal strength. To obtain such an effect, Mo, V, and/or W is preferably contained in an amount of 0.001 % or more. On the other hand, when the content of Mo, V, and/or W is beyond 2.0 %, coarse carbonitrides are generated, which may become an origin of fracture, and additionally increase production cost. Therefore, when Mo, V, and/or W is contained, the content of each added alloying element is 2.0 %, preferably 0.003 % or more and 1.7 % or less, and more preferably 1.5 % or less.

Ca: 0.0005 % or more and 0.0050 % or less, Mg: 0.0005 % or more and 0.0050 % or less, REM: 0.0010 % or more and 0.0200 % or less

[0034] Ca, Mg, and REM are elements useful for morphological control of inclusions and can be contained as necessary. The morphological control of inclusions means granulating elongated sulfide-based inclusions. The morphological control of inclusions improves ductility, toughness, and sulfide stress corrosion cracking resistance. To obtain such effects, Ca and/or Mg is preferably contained in an amount of 0.0005 % or more and REM is preferably contained in an amount of 0.0010 % or more. On the other hand, when these elements are contained in a large amount, not only the amount of nonmetallic inclusions may be increased, ending up deteriorating ductility, toughness, and sulfide stress corrosion cracking resistance, but also an economic disadvantage may be entailed.
[0035] Therefore, when Ca and Mg are contained, the content of each element is set to 0.0005 % or more and 0.0050 % or less. When REM is contained, the content is set to 0.0010 % or more and 0.0200 % or less. Preferably, the Ca content is set to 0.0010 % or more and 0.0040 % or less, the Mg content is set to 0.0010 % or more and 0.0040 % or less, and the REM content is set to 0.0020 % or more and 0.0150 % or less.
[0036] Our high-Mn steel can be obtained from molten steel having the aforementioned chemical composition which is prepared by steelmaking using a publicly-known method such as using a converter and an electric heating furnace. In addition, the high-Mn steel may also be subjected to secondary refinement in a vacuum degassing furnace. During the secondary refinement, to limit the contents of Ti and Nb which hinder suitable microstructure control within the aforementioned range, it is necessary to prevent Ti and Nb from being inevitably mixed from raw materials or the like into steel and decrease the contents of Ti and Nb. For example, by decreasing the basicity of slag in the refining stage such that these alloy elements are concentrated in the slag to be discharged, it is possible to reduce the Ti and Nb concentrations in a final slab product. It is also possible to apply a method in which oxygen is blown into the furnace or the like for oxidation such that an alloy of Ti and Nb can be floated and separated during circulation. Subsequently, it is preferable to make the steel into a steel material such as a slab having a predetermined size by a publicly-known steel making method such as continuous casting.
[0037] The following provides a further definition of production conditions to make the aforementioned steel material into a steel material exhibiting excellent low-temperature toughness.

[Heating temperature of steel material: 1100 °C or higher and 1300 °C or lower]

[0038] To obtain high-Mn steel having the aforementioned features, it is important to perform heating to a temperature range of 1100 °C to 1300 °C and hot rolling with a rolling finish temperature of 800 °C or higher and a total rolling reduction of 20 % or more. The temperature is controlled based on the surface temperature of the steel material.
[0039] Specifically, to promote diffusion of Mn during the hot rolling, the heating temperature before the rolling is set to 1100 °C or higher. On the other hand, a heating temperature beyond 1300 °C may trigger steel melting, and thus, the upper limit of the heating temperature is set to 1300 °C. The heating temperature is preferably 1150 °C or higher and 1250 °C or lower.

[Rolling finish temperature of 800 °C or higher and total rolling reduction of 20 % or more]

[0040] Further, it is important to set the total rolling reduction during the rolling to as high as 20 % or more to thereby decrease the distance between Mn segregation portions such that diffusion of Mn is promoted. Similarly, from the viewpoint of promoting diffusion of Mn during the rolling, the rolling finish temperature is set to 800 °C or higher. This is because Mn is not sufficiently diffused at a temperature of lower than 800 °C, which is well below two thirds of the melting point of Mn. The rolling finish temperature is preferably 950 °C or higher and more preferably 1000 °C or higher and 1050 °C or lower. Further, the total rolling reduction is preferably 30 % or more. No upper limit is placed on the total rolling reduction, but from the viewpoint of improving rolling efficiency, the upper limit is preferably 98 %.
[0041] Further, if necessary, it is advantageous for increasing the KAM value to additionally perform the second hot rolling which satisfies the following conditions after the above hot rolling. Here, when the finish temperature of the above first hot rolling is 1100 °C or higher, the second hot rolling may be continued as it is, whereas when the finish temperature is lower than 1100 °C, re-heating to 1100 °C or higher is performed. Again, a heating temperature beyond 1300 °C may trigger steel melting. Thus, the upper limit of the heating temperature is set to 1300 °C. The temperature is controlled based on the surface temperature of the steel material. The heating temperature is preferably 1150 °C or higher and 1250 °C or lower.

[Rolling finish temperature: 700 °C or higher and lower than 950 °C]

[0042] The second hot rolling requires at least one pass of final finish rolling at 700 °C or higher and lower than 950

°C. Specifically, by performing at least one pass of rolling preferably with a rolling reduction of 10 % or more at lower than 950 °C, dislocations having being introduced during the first rolling are less likely to be recovered and easily remain, and thus, the KAM value can be increased. Further, crystal grains become excessively coarse in a finish temperature range of 950 °C or higher, and thus desired yield stress cannot be obtained. Therefore, it is preferable to perform at least one pass of final finish rolling at lower than 950 °C. The finish temperature is preferably 900 °C or lower and more preferably 850 °C or lower.

[0043] On the other hand, a finish temperature of lower than 700 °C deteriorates toughness, and thus, the finish temperature is set to 700 °C or higher, and preferably 750 °C or higher. The rolling reduction at lower than 950 °C is preferably 20 % or more and more preferably 50 % or more. However, rolling with a rolling reduction of beyond 95 % deteriorates toughness, and thus, a rolling reduction of 95 % or less is preferable.

[Average cooling rate within a range of a temperature at or above (a rolling finish temperature - 100 °C) to a temperature ranging from 300 °C to 650 °C: 1.0 °C/s or more]

[0044] After the hot rolling, cooling is immediately performed. Gentle cooling of the steel plate after the hot rolling promotes formation of precipitates, thus deteriorating low-temperature toughness. Cooling the steel plate at a cooling rate of 1.0 °C/s or more can prevent formation of these precipitates. Further, excessive cooling distorts the steel plate, deteriorating productivity. In particular, for a steel material having a plate thickness of less than 10 mm, air cooling is preferable. Therefore, the upper limit of the cooling start temperature is set to 900 °C. For the aforementioned reasons, in the cooling after the hot rolling, on a surface of the steel plate, the average cooling rate within a range of a temperature at or above (a rolling finish temperature - 100 °C) to a temperature ranging from 300 °C to 650 °C is set to 1.0 °C/s or more. Note that the subsequent heating treatment is unnecessary because the Mn segregation portions in the as-rolled state are maintained within a narrow Mn concentration range.

EXAMPLES

[0045] This disclosure will be described in further detail below by way of examples. Note that this disclosure is not limited to the following examples.

[0046] Steel slabs having the chemical compositions listed in Table 1 were made by a converter-ladle refining-continuous casting process. Next, the obtained steel slabs were subjected to blooming (the first hot rolling) and hot rolling (the second hot rolling) under conditions listed in Table 2 to obtain steel plates having a thickness of 10 mm to 30 mm. Tensile properties, toughness, and microstructure of the obtained steel plates were evaluated as described below.

(1) Tensile properties

[0047] JIS NO. 5 tensile test pieces were collected from each steel plate. Then, the test pieces were subjected to a tensile test in conformity with JIS Z 2241 (1998) to investigate tensile properties. In this disclosure, when a test piece had a yield stress of 400 MPa or more and a tensile strength of 800 MPa or more, the corresponding steel plate was determined to have excellent tensile properties. Further, when a test piece had an elongation of 40 % or more, the corresponding steel plate was determined to have excellent ductility.

(2) Low-temperature toughness

[0048] Charpy V-notch test pieces were collected from each steel plate having a plate thickness of more than 20 mm at a 1/4 position of the plate thickness or from each steel plate having a plate thickness of 20 mm or less at a 1/2 position of the plate thickness, in a direction parallel to the rolling direction in conformity with JIS Z 2242 (2005). Then, the test pieces were subjected to Charpy impact test in conformity with JIS Z 2242 (2005), where three test pieces were used for each steel plate, to determine absorbed energy at -196 °C and evaluate base metal toughness. In this disclosure, when the three test pieces had an average absorbed energy (vE_{-196}) of 100 J or more, the corresponding steel plate was determined to have excellent base steel toughness. For steel plates having a plate thickness of less than 10 mm, Charpy V-notch test pieces having a sub-size of 5 mm were collected from each steel plate at a 1/2 position of the plate thickness, in a direction parallel to the rolling direction in conformity with JIS Z 2242 (2005). Then, the test pieces were subjected to Charpy impact test at -196 °C in conformity with JIS Z 2242 (2005), where three test pieces were used for each steel plate. When the three test pieces had an average absorbed energy (vE_{-196}) of 67 J or more, the corresponding steel plate was determined to have excellent base steel toughness.

Percent brittle fracture

[0049] After the Charpy impact test at -196 °C, SEM observation (at 500 magnifications in 10 fields) was performed to measure percent brittle fracture. When the test pieces had a percent brittle fracture of 0 %, the corresponding steel plate was determined to have excellent low-temperature toughness.

(3) Microstructure evaluation

KAM value

[0050] For each steel plate after the hot rolling, EBSD (Electron Backscatter Diffraction) analysis (measurement step: 0.3 μm) in a field of 500 μm × 200 μm was performed in arbitrary two fields (at a 1/4 position of the plate thickness or and 1/2 position of the plate thickness) on a polished surface in a cross section along the rolling direction of the steel plate and an average of the analysis results for all the measured regions was calculated to determine an average KAM value.

Deformation-induced martensite

[0051] After the Charpy impact test, the test piece was polished stepwise for convenience of observation to its notch bottom. In the test piece, five fields with a size of 100 μm × 100 μm were observed by EBSD analysis (measurement step: 0.08 μm) to determine the presence/absence of deformation-induced martensite.

Mn concentration

[0052] Further, at the above-described positions where the KAM values were measured by EBSD, EPMA (Electron Probe Micro Analyzer) analysis was further performed to determine Mn concentrations, and those portions having the lowest Mn concentration and the highest Mn concentration were defined as segregation portions.

[0053] The results of these measurements are listed in Table 3.

Table 1

Steel No.	Chemical compostion (mass%)																	Remarks
	C	Si	Mn	P	S	Al	Cr	O	N	Nb	Ti	V	Mo	W	Ca	Mg	REM	
1	0.150	0.82	29.4	0.025	0.0058	0.034	3.78	0.0034	0.0150	0.002	0.002	-	-	-	-	-	-	Example
2	0.654	0.12	20.8	0.018	0.0042	0.028	2.78	0.0027	0.0132	0.002	0.002	-	-	-	-	-	-	Example
3	0.432	0.26	22.9	0.016	0.0039	0.037	4.81	0.0019	0.0259	0.001	0.002	0.09	-	-	-	-	-	Example
4	0.332	0.78	21.3	0.020	0.0065	0.045	3.12	0.0033	0.0191	0.002	0.003	-	0.48	-	-	-	-	Example
5	0.294	0.77	28.1	0.027	0.0028	0.063	1.87	0.0036	0.0243	0.001	0.002	-	-	0.09	-	-	-	Example
6	0.465	0.63	27.1	0.017	0.0024	0.038	6.19	0.0046	0.0350	0.003	0.003	-	-	-	0.0016	-	-	Example
7	0.327	0.46	22.5	0.018	0.0043	0.056	2.43	0.0032	0.0245	0.002	0.002	-	-	-	-	0.003	-	Example
8	0.364	0.41	20.2	0.028	0.0029	0.029	1.12	0.0042	0.0078	0.004	0.001	-	-	-	-	-	0.0044	Example
9	0.288	0.19	24.3	0.023	0.0057	0.047	5.78	0.0038	0.0334	0.002	0.001	-	-	-	-	-	-	Example
10	0.587	0.32	25.2	0.021	0.0034	0.045	4.24	0.0041	0.0092	0.003	0.001	-	-	-	-	-	-	Example
11	<u>0.912</u>	0.41	27.5	0.020	0.0024	0.038	3.43	0.0022	0.0113	0.002	0.002	-	-	-	-	-	-	Comparative Example
12	0.571	0.03	25.4	0.017	0.0027	0.037	5.11	0.0029	0.0387	0.002	0.002	-	-	-	-	-	-	Comparative Example
13	0.135	0.48	17.6	0.026	0.0019	0.049	2.33	0.0047	0.0471	0.001	0.001	-	-	-	-	-	-	Comparative Example
14	0.172	0.44	26.3	<u>0.042</u>	0.0025	0.039	0.87	0.0039	0.0334	0.001	0.003	-	-	-	-	-	-	Comparative Example
15	0.299	0.25	28.7	0.021	<u>0.0084</u>	0.027	1.86	0.0021	0.0062	0.002	0.001	-	-	-	-	-	-	Comparative Example
16	0.554	0.11	21.4	0.019	0.0034	<u>0.090</u>	3.69	0.0034	0.0224	0.002	0.003	-	-	-	-	-	-	Comparative Example
17	0.291	0.26	27.4	0.013	0.0025	0.061	<u>8.25</u>	0.0042	0.0143	0.003	0.002	-	-	-	-	-	-	Comparative Example
18	0.425	0.13	21.9	0.022	0.0049	0.024	3.77	<u>0.0082</u>	0.0241	0.002	0.002	-	-	-	-	-	-	Comparative Example
19	0.356	0.43	25.7	0.023	0.0036	0.053	6.37	0.0031	<u>0.0589</u>	0.004	0.002	-	-	-	-	-	-	Comparative Example
20	<u>0.095</u>	0.29	28.1	0.025	0.0036	0.042	6.12	0.0023	0.0095	0.002	0.002	-	-	-	-	-	-	Comparative Example
21	0.633	<u>1.04</u>	23.3	0.019	0.0040	0.035	2.53	0.0037	0.0170	0.002	0.002	-	-	-	-	-	-	Comparative Example
22	0.540	0.35	21.6	0.027	0.0033	0.050	<u>0.47</u>	0.0028	0.0210	0.001	0.003	-	-	-	-	-	-	Comparative Example
23	0.451	0.26	20.8	0.029	0.0060	0.035	2.87	0.0038	0.0327	<u>0.006</u>	0.002	-	-	-	-	-	-	Comparative Example
24	0.624	0.51	24.0	0.025	0.0052	0.028	3.18	0.0032	0.0188	0.002	<u>0.006</u>	-	-	-	-	-	-	Comparative Example

(continued)

Steel No.	Chemical compostion (mass%)																	Remarks
	C	Si	Mn	P	S	Al	Cr	O	N	Nb	Ti	V	Mo	W	Ca	Mg	REM	
25	0.236	0.64	34.5	0.022	0.0061	0.042	1.45	0.0031	0.0363	0.002	0.002	-	-	-	-	-	-	Example
26	0.119	0.86	35.7	0.027	0.0063	0.029	0.55	0.0044	0.0466	0.002	0.002	-	-	-	-	-	-	Comparative Example
27	0.671	0.75	21.3	0.020	0.0047	0.008	0.94	0.0095	0.0377	0.001	0.001	-	-	-	-	-	-	Comparative Example
28	0.312	0.32	33.5	0.023	0.0034	0.045	0.50	0.0026	0.0139	0.002	0.002	-	-	-	-	-	-	Example

Table 2

Sample No.	Steel No.	Plate thickness (mm)	First rolling conditions			Second rolling conditions				Remarks
			Slab heating temperature (°C)	Rolling finish temperature (°C)	Total rolling reduction (%)	Re-heating temperature (°C)	Rolling finish temperature (°C)	Cooling start temperature (°C)	Cooling rate within a range of 300 °C to 650 °C (°C/s)	
1	1	22	1130	921	32	1130	810	774	8	Example
2	2	25	1130	918	29	1130	823	787	9	Example
3	3	18	1100	887	36	1100	765	702	9	Example
4	4	20	1100	892	35	1100	796	734	8	Example
5	5	25	1150	939	43	1150	838	805	8	Example
6	6	15	1150	937	46	1150	811	741	12	Example
7	7	10	1180	946	51	1180	805	728	16	Example
8	8	10	1200	953	53	1200	763	671	10	Example
9	9	13	1160	941	30	1160	813	762	7	Example
10	10	28	1250	1034	26	1250	946	915	16	Example
11	1	30	1300	1102	20	-	803	770	14	Example
12	11	20	1250	1011	30	1250	871	836	6	Comparative Example
13	12	15	1250	1019	41	1250	855	817	11	Comparative Example
14	13	20	1120	919	42	1120	789	748	12	Comparative Example
15	14	25	1120	931	29	1120	802	770	7	Comparative Example
16	15	20	1170	955	38	1170	820	774	3	Comparative Example
17	16	10	1170	937	53	1170	786	735	5	Comparative Example

(continued)

Sample No.	Steel No.	Plate thickness (mm)	First rolling conditions			Second rolling conditions				Remarks
			Slab heating temperature (°C)	Rolling finish temperature (°C)	Total rolling reduction (%)	Re-heating temperature (°C)	Rolling finish temperature (°C)	Cooling start temperature (°C)	Cooling rate within a range of 300 °C to 650 °C (°C/s)	
18	17	20	1150	917	43	1150	801	756	13	Comparative Example
19	18	18	1150	926	32	1150	790	746	8	Comparative Example
20	19	13	1130	903	45	1130	767	710	12	Comparative Example
21	20	20	1150	920	38	1150	828	771	10	Comparative Example
22	21	18	1150	914	39	1150	821	760	7	Comparative Example
23	22	25	1170	956	30	1170	837	794	12	Comparative Example
24	23	14	1190	958	48	1190	819	762	8	Comparative Example
25	24	17	1190	966	46	1190	830	788	10	Comparative Example
26	1	17	1130	897	39	1130	682	587	8	Comparative Example
27	2	23	1200	956	16	1200	873	831	12	Comparative Example
28	3	15	1200	961	23	1200	841	780	0.5	Comparative Example
29	4	15	1230	756	37	1230	823	768	7	Comparative Example
30	5	20	1230	975	31	1230	810	653	3	Comparative Example

(continued)

Sample No.	Steel No.	Plate thickness (mm)	First rolling conditions			Second rolling conditions				Remarks
			Slab heating temperature (°C)	Rolling finish temperature (°C)	Total rolling reduction (%)	Re-heating temperature (°C)	Rolling finish temperature (°C)	Cooling start temperature (°C)	Cooling rate within a range of 300 °C to 650 °C (°C/s)	
31	6	15	<u>1050</u>	888	25	1150	876	830	6	Comparative Example
32	7	25	1150	930	36	1050	731	687	10	Comparative Example
33	8	30	1250	1025	55	1300	<u>980</u>	947	9	Comparative Example
34	9	30	1300	<u>704</u>	75	-	-	655	6	Comparative Example
35	25	15	1130	906	35	1130	763	694	7	Example
36	25	15	1130	933	<u>18</u>	1130	707	655	6	Comparative Example
37	<u>26</u>	20	1150	934	42	1150	795	752	8	Comparative Example
38	<u>27</u>	6	1200	920	31	1200	734	air cooling	-	Comparative Example
39	28	6	1250	963	44	1250	860	air cooling	-	Example
40	1	30	1300	808	60	-	-	765	13	Example

Table 3

Sample No.	Steel No.	Microstructure				Mechanical properties					Remarks
		Average KAM value	Deformation induced martensite	Mn concentration in Mn segregation portion (lowest) (mass%)	Mn concentration in Mn segregation portion (highest) (mass%)	Yield stress (MPa)	Tensile strength (MPa)	Total elongation (%)	Absorbed energy at-196°C ($vE_{-196°C}$) (J)	Brittleness fracture (%)	
1	1	0.9	absent	25.1	33.7	409	845	66	107	0	Example
2	2	0.8	absent	17.0	24.7	506	913	50	105	0	Example
3	3	1.1	absent	20.6	25.0	426	952	65	124	0	Example
4	4	1.0	absent	17.9	24.6	408	821	68	110	0	Example
5	5	0.7	absent	24.5	31.8	418	808	61	117	0	Example
6	6	0.9	absent	23.5	30.7	454	971	65	138	0	Example
7	7	1.2	absent	18.8	25.8	421	943	63	115	0	Example
8	8	0.8	absent	16.0	24.6	438	1012	69	102	0	Example
9	9	0.9	absent	21.3	27.3	413	957	65	131	0	Example
10	10	0.3	absent	22.6	27.4	401	925	67	153	0	Example
11	1	1.0	absent	23.5	35.6	420	855	64	103	0	Example
12	11	0.5	absent	23.3	31.5	614	755	47	61	25	Comparative Example
13	12	0.7	absent	22.2	28.7	385	930	67	124	0	Comparative Example
14	13	1.0	present	13.9	21.8	406	924	71	47	30	Comparative Example
15	14	0.9	absent	21.5	31.1	411	971	62	67	21	Comparative Example
16	15	0.9	absent	25.3	32.5	421	875	53	76	14	Comparative Example
17	16	1.0	absent	18.2	24.6	495	975	61	93	11	Comparative Example

(continued)

Sample No.	Steel No.	Microstructure				Mechanical properties					Remarks
		Average KAM value	Deformation induced martensite	Mn concentration in Mn segregation portion (lowest) (mass%)	Mn concentration in Mn segregation portion (highest) (mass%)	Yield stress (MPa)	Tensile strength (MPa)	Total elongation (%)	Absorbed energy at-196°C ($vE_{-196°C}$) (J)	Brittleness fracture (%)	
18	17	0.9	absent	23.6	31.0	436	850	51	<u>50</u>	<u>38</u>	Comparative Example
19	<u>18</u>	1.0	absent	17.5	26.4	468	891	53	<u>81</u>	<u>13</u>	Comparative Example
20	<u>19</u>	1.1	absent	21.3	30.4	514	840	47	<u>73</u>	<u>14</u>	Comparative Example
21	<u>20</u>	0.8	absent	24.7	31.4	<u>370</u>	785	68	127	0	Comparative Example
22	<u>21</u>	0.8	absent	20.5	26.1	577	775	50	<u>64</u>	<u>23</u>	Comparative Example
23	<u>22</u>	0.7	absent	17.9	25.3	481	893	62	<u>75</u>	<u>15</u>	Comparative Example
24	<u>23</u>	0.9	absent	17.1	24.3	450	936	55	<u>89</u>	<u>12</u>	Comparative Example
25	<u>24</u>	0.7	absent	21.1	27.3	514	940	51	<u>96</u>	<u>11</u>	Comparative Example
26	1	1.5	absent	25.5	33.1	503	865	45	<u>56</u>	<u>28</u>	Comparative Example
27	2	0.5	<u>present</u>	<u>15.7</u>	25.9	536	923	50	<u>95</u>	<u>11</u>	Comparative Example
28	3	0.7	absent	20.8	25.3	415	876	43	<u>61</u>	<u>24</u>	Comparative Example
29	4	0.8	<u>present</u>	<u>15.1</u>	27.5	412	931	53	<u>74</u>	<u>15</u>	Comparative Example

(continued)

Sample No.	Steel No.	Microstructure				Mechanical properties					Remarks
		Average KAM value	Deformation induced martensite	Mn concentration in Mn segregation portion (lowest) (mass%)	Mn concentration in Mn segregation portion (highest) (mass%)	Yield stress (MPa)	Tensile strength (MPa)	Total elongation (%)	Absorbed energy at-196°C ($vE_{-196°C}$) (J)	Brittleness fracture (%)	
30	5	0.8	absent	24.1	31.9	407	770	41	46	40	Comparative Example
31	6	0.4	present	15.8	37.7	440	899	46	93	11	Comparative Example
32	7	1.4	absent	18.6	26.1	468	941	54	73	15	Comparative Example
33	8	0.2	absent	16.5	24.0	365	933	72	116	0	Comparative Example
34	9	1.4	absent	20.7	27.7	553	802	43	41	45	Comparative Example
35	25	1.1	absent	30.8	38.0	427	760	56	102	0	Example
36	25	1.1	absent	30.5	38.6	459	787	52	80	13	Comparative Example
37	26	0.9	absent	31.8	39.4	450	777	50	52	35	Comparative Example
38	27	1.3	absent	17.7	24.9	494	902	52	58*	12	Comparative Example
39	28	0.7	absent	30.8	36.3	449	886	54	73*	0	Example
40	1	1.0	absent	26.1	32.5	418	846	65	104	0	Example

*5 mm sub-size charpy

[0054] Our high-Mn steel samples were all confirmed to satisfy the aforementioned desired performance (a base metal yield stress of 400 MPa or more and an average absorbed energy (vE_{-196}) of 100 J or more for low-temperature toughness). In contrast, the comparative examples out of the scope of this disclosure did not satisfy the aforementioned desired performance in terms of either or both of yield stress and low-temperature toughness.

Claims

1. High-Mn steel comprising:

a chemical composition containing, in mass%,
C: 0.100 % or more and 0.700 % or less,
Si: 0.05 % or more and 1.00 % or less,
Mn: 20.0 % or more and 35.0 % or less,
P: 0.030 % or less,
S: 0.0070 % or less,
Al: 0.01 % or more and 0.07 % or less,
Cr: 0.5 % or more and 7.0 % or less,
N: 0.0050 % or more and 0.0500 % or less,
O: 0.0050 % or less,
Ti: 0.005 % or less, and
Nb: 0.005 % or less

with the balance being Fe and inevitable impurities; and

a microstructure having austenite as a matrix phase, wherein
the microstructure has a Mn segregation portion with a Mn concentration of 16 % or more and 38 % or less, and the high-Mn steel has an average KAM (Kernel Average Misorientation) value of 0.3 or more, an absorbed energy in a Charpy impact test at -196 °C of 100 J or more, and a yield stress of 400 MPa or more.

2. The high-Mn steel according to claim 1, wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of

Mo: 2.0 % or less,
V: 2.0 % or less,
W: 2.0 % or less,
Ca: 0.0005 % or more and 0.0050 % or less,
Mg: 0.0005 % or more and 0.0050 % or less, and
REM: 0.0010 % or more and 0.0200 % or less.

3. A method for producing high-Mn steel, comprising:

heating a steel material having the chemical composition according to claim 1 or 2 to a temperature range of 1100 °C or higher and 1300 °C or lower; and
hot rolling the steel material with a rolling finish temperature of 800 °C or higher and a total rolling reduction of 20 % or more.

4. The method for producing high-Mn steel according to claim 3, further comprising:

hot rolling the steel material with a rolling finish temperature of 700 °C or higher and lower than 950 °C; and then subjecting the steel material to cooling treatment at an average cooling rate of 1.0 °C/s or more within a range of a temperature at or above (the rolling finish temperature - 100 °C) to a temperature ranging from 300 °C to 650 °C.

FIG. 1

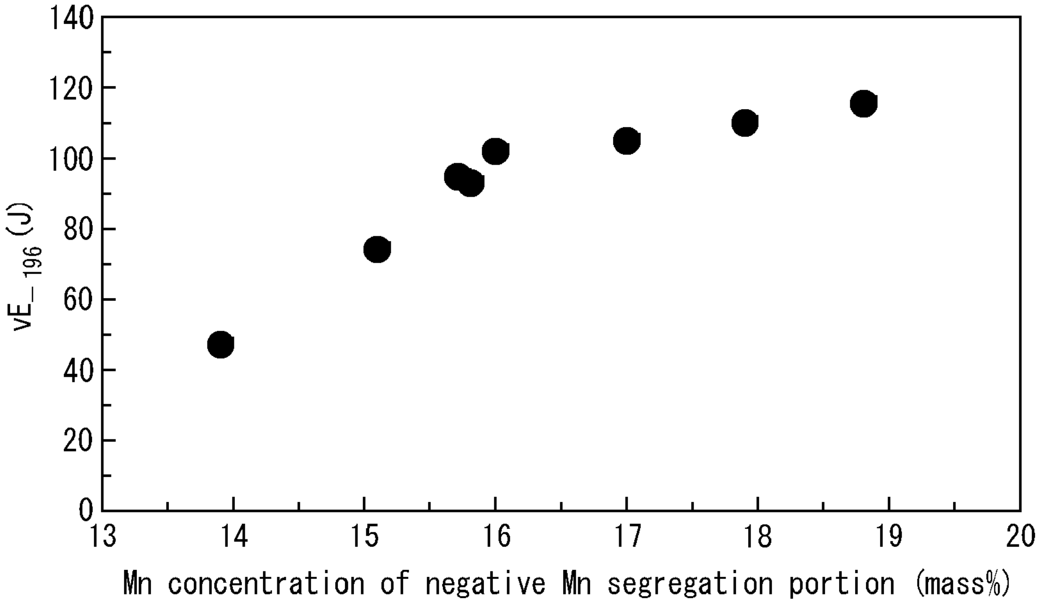
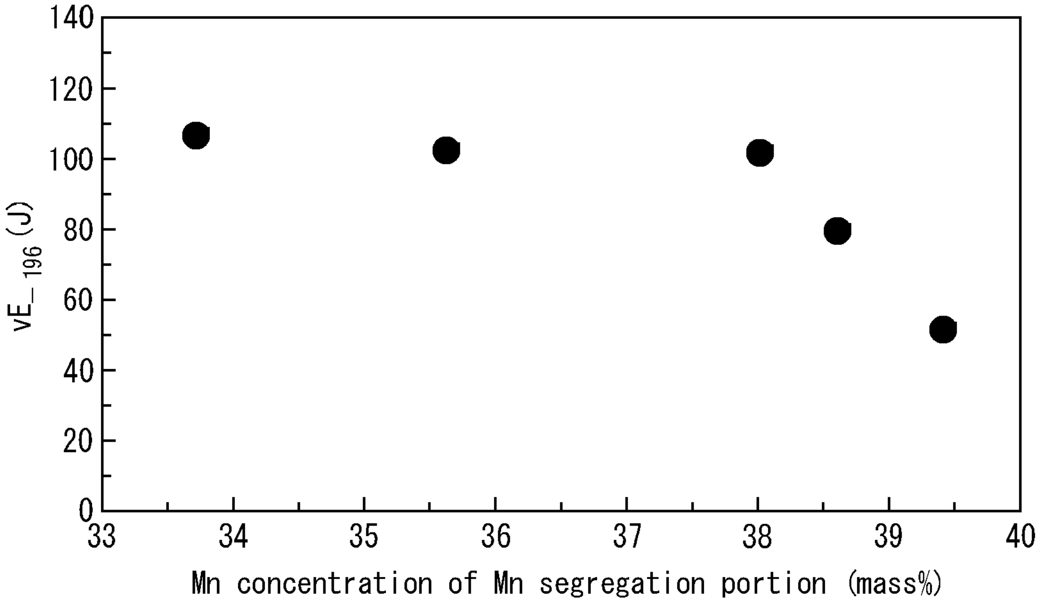

140
120
100
80
60
40
20
0
vE_196 (J)
13
14
15
16
17
18
19
20
Mn concentration of negative Mn segregation portion (mass%)

FIG. 2


140
120
100
80
60
40
20
0
vE_196 (J)
33
34
35
36
37
38
39
40
Mn concentration of Mn segregation portion (mass%)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2018/032022

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl. C22C38/00(2006.01)i, C21D8/02(2006.01)i, C22C38/38(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)
Int.Cl. C22C38/00-38/60, C21D8/02

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	1971-2018
Registered utility model specifications of Japan	1996-2018
Published registered utility model applications of Japan	1994-2018

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	JP 2007-126715 A (SUMITOMO METAL INDUSTRIES, LTD.) 24 May 2007, claims, paragraphs [0001], [0029], [0036]-[0062] (Family: none)	1-3 4
A	JP 2017-71817 A (NIPPON STEEL & SUMITOMO METAL CORPORATION) 13 April 2017, claims, paragraphs [0039]-[0046] (Family: none)	1-4

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 October 2018 (26.10.2018)	06 November 2018 (06.11.2018)

Name and mailing address of the ISA/	Authorized officer
Japan Patent Office 3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan	Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2018/032022

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 2016-196703 A (NIPPON STEEL & SUMITOMO METAL CORPORATION) 24 November 2016 (Family: none)	1-4
A	JP 58-67824 A (KAWASAKI STEEL CORP.) 22 April 1983 (Family: none)	1-4
A	JP 60-204864 A (SANYO SPECIAL STEEL CO., LTD.) 16 October 1985 (Family: none)	1-4
A	JP 57-200543 A (KAWASAKI STEEL CORP.) 08 December 1982 (Family: none)	1-4
A	JP 56-258 A (SUMITOMO METAL INDUSTRIES, LTD.) 06 January 1981 (Family: none)	1-4
A	US 5833919 A (KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY) 10 November 1998 (Family: none)	1-4

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Patent documents cited in the description

- JP 2017071817 A **[0004] [0006]**