

HIGH-MN STEEL AND METHOD FOR MANUFACTURING SAME

TECHNICAL FIELD

5 **[0001]** This disclosure relates to a high-Mn steel suitable for a structure used in cryogenic environments, such as a tank for liquefied gas storage, and a method for manufacturing the same.

BACKGROUND

10 **[0002]** A structure for liquefied gas storage is used at cryogenic temperatures. Therefore, a steel sheet used for this type of structure is required to have not only high strength but also excellent toughness at cryogenic temperatures. For example, when a hot rolled steel sheet is used for liquefied natural gas storage, it is necessary to ensure excellent toughness at a temperature of -164
15 °C, which is the boiling point of the liquefied natural gas, or lower. If the low-temperature toughness of the steel material is inferior, the safety as a structure for cryogenic storage may not be maintained. Therefore, there is a strong demand for improving the low-temperature toughness of the applied steel material.

20 **[0003]** In response to this demand, austenitic stainless steel, 9 % Ni steel, and 5000 series aluminum alloy, where austenite, which does not exhibit brittleness at cryogenic temperatures, is the main structure of the steel sheet, have conventionally been used. However, because of the high alloy cost and manufacturing cost, there has been a desire for a steel material that is
25 inexpensive yet has excellent low-temperature toughness.

[0004] JP 2016-84529 A (PTL 1) and JP 2016-196703 A (PTL 2) propose using a high-Mn steel containing a large amount of Mn, which is a relatively inexpensive austenite-stabilizing element, as a structural steel in cryogenic environments, as a new steel material to replace conventional cryogenic
30 steels.

[0005] That is, PTL 1 proposes controlling the carbide coverage of austenite crystal grain boundaries, and PTL 2 proposes controlling the austenite crystal grain size by a carbide coating as well as addition of Mg, Ca, and REM.

CITATION LIST

Patent Literature

[0006] PTL 1: JP 2016-84529 A

PTL 2: JP 2016-196703 A

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SUMMARY

(Technical Problem)

[0007] However, in applications such as tanks for liquefied gas storage, it is required to have excellent fracture resistance under severe fracture conditions in which an initial crack becomes sharper, specifically, excellent CTOD property at low temperatures from the viewpoint of ensuring the safety of the tanks. Although PTL 1 and PTL 2 described above evaluate the low-temperature toughness by a Charpy impact test, they do not guarantee excellent CTOD property.

15 **[0008]** It could thus be helpful to provide a high-Mn steel which not only has high strength and excellent low-temperature toughness but also has excellent CTOD property at low temperatures. As used herein, the “high strength” means that the yield strength is 400 MPa or more, the “excellent low-temperature toughness” means that the absorbed energy vE₋₁₉₆ of a Charpy impact test at -196 °C is 100 J or more, and the “excellent CTOD property at low temperatures” means that the CTOD value at -165 °C is 0.25 mm or more.

(Solution to Problem)

25 **[0009]** We have conducted extensive research on methods for solving the problem with respect to high-Mn steels. As a result, we found the following a to b.

a. High-Mn steels do not develop brittle fractures even at cryogenic temperatures, and, if a fracture occurs, it is generated from crystal grain boundaries. Therefore, in order to improve the fracture resistance of high-Mn steels, it is effective to regulate the size of crystal grains in anticipation of reducing the area of crystal grain boundaries that are the starting point of fractures.

30 b. In addition, realizing homogenization in conjunction with the above regulation of crystal grain size is more effective in improving the fracture

resistance of high-Mn steels.

c. As means for achieving the above a and b, it is appropriate to perform hot rolling and cooling under appropriate manufacturing conditions.

[0010] The present disclosure is based on the aforementioned findings and further studies. We thus provide the following.

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

C: 0.10 % or more and 0.70 % or less,
Si: 0.05 % or more and 0.50 % or less,
10 Mn: 20 % or more and 30 % 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,
15 Ni: 0.01 % or more and less than 0.1 %,
Ca: 0.0005 % or more and 0.0050 % or less,
N: 0.0050 % or more and 0.0500 % or less,
O: 0.0050 % or less,
Ti: less than 0.0050 %, and
20 Nb: less than 0.0050 %,

the balance consisting of Fe and inevitable impurities, and
a microstructure having austenite as a base phase, where the austenite has a grain size of 1 μm or more and a standard deviation of 9 μm or less.

[0011] 2. The high-Mn steel according to the above 1., wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of

Cu: 1.0 % or less,
Mo: 2.0 % or less,
V: 2.0 % or less,
30 W: 2.0 % or less,
Mg: 0.0005 % or more and 0.0050 % or less, and
REM: 0.0010 % or more and 0.0200 % or less.

[0012] 3. A method of manufacturing a high-Mn steel, comprising heating a steel material having the chemical composition according to the

above 1. or 2. to a temperature range of 1100 °C or higher and 1300 °C or lower, then subjecting the steel material to hot rolling where a rolling finish temperature is 750 °C or higher and lower than 950 °C and an average rolling reduction for one pass is 9 % or more, and then subjecting the hot rolled material to cooling where an average cooling rate from a temperature of (rolling finish temperature – 100 °C) or higher to a temperature range of 300 °C or higher and 650 °C or lower is 1.0 °C/s or more.

(Advantageous Effect)

[0013] According to the present disclosure, it is possible to provide a high-Mn steel having excellent CTOD property and low-temperature toughness especially at cryogenic temperatures. Therefore, by using the high-Mn steel of the present disclosure, it is possible to realize an improvement in safety and product life of a steel structure used in cryogenic environments, such as a tank for liquefied gas storage, which exhibits remarkable industrial effects.

DETAILED DESCRIPTION

[0014] The following describes the high-Mn steel of the present disclosure in detail.

[Chemical composition]

First, the chemical composition of the high-Mn steel of the present disclosure and reasons for limitation will be described. Note that the unit “%” of each component is “mass%” unless otherwise specified.

C: 0.10 % or more and 0.70 % or less

C is an inexpensive austenite-stabilizing element and is an important element in obtaining austenite. To obtain this effect, the C content needs to be 0.10 % or more. On the other hand, when the C content exceeds 0.70 %, Cr carbides are excessively formed, and the low-temperature toughness is deteriorated. Therefore, the C content is 0.10 % or more and 0.70 % or less. The C content is preferably 0.20 % or more. The C content is preferably 0.60 % or less.

[0015] Si: 0.05 % or more and 0.50 % or less

Si is an element that acts as a deoxidizing material. It not only is necessary for steelmaking but also dissolves in steel to increase the strength

of a steel sheet by solid solution strengthening. To obtain these effects, the Si content needs to be 0.05 % or more. On the other hand, when the Si content exceeds 0.50 %, the weldability is deteriorated and the low-temperature toughness, especially the toughness at cryogenic
5 temperatures is lowered. Therefore, the Si content is 0.05 % or more and 0.50 % or less. The Si content is preferably 0.07 % or more and 0.50 % or less.

[0016] Mn: 20 % or more and 30 % or less

Mn is a relatively inexpensive austenite-stabilizing element. Mn is
10 an important element for the present disclosure to achieve both the strength and the toughness at cryogenic temperatures. To obtain this effect, the Mn content needs to be 20 % or more. On the other hand, when the content exceeds 30 %, the effect of improving low-temperature toughness saturates, leading to an increase in alloy cost. In addition, the weldability and the
15 cuttability deteriorate. Further, it promotes segregation and promotes the occurrence of stress corrosion cracking. Therefore, the Mn content is 20 % or more and 30 % or less. The Mn content is preferably 23 % or more. The Mn content is preferably 28 % or less.

[0017] P: 0.030 % or less

When P is contained in excess of 0.030 %, it segregates at grain
20 boundaries and becomes a starting point of stress corrosion cracking. Therefore, the upper limit is set to 0.030 %, and the P content is desirably as low as possible. Thus, the P content is 0.030 % or less. Note that the P content is desirably 0.002 % or more, because excessive reduction of P
25 content increases refining cost and is economically disadvantageous. The P content is preferably 0.005 % or more. The P content is preferably 0.028 % or less. The P content is more preferably 0.024 % or less.

[0018] S: 0.0070 % or less

S is an element that deteriorates low-temperature toughness and base
30 metal ductility. Therefore, the upper limit is set to 0.0070 %, and the S content is desirably as low as possible. Thus, the S content is 0.0070 % or less. Note that the S content is desirably 0.001 % or more, because excessive reduction of S content increases refining cost and is economically disadvantageous. The S content is preferably 0.0020 % or more. The S

content is preferably 0.0060 % or less.

[0019] Al: 0.01 % or more and 0.07 % or less

Al acts as a deoxidizer and is most commonly used in a molten steel deoxidation process of a steel sheet. To obtain this effect, the Al content
5 needs to be 0.01 % or more. On the other hand, when the Al content exceeds 0.07 %, Al is mixed into a weld metal part during welding and deteriorates the toughness of the weld metal. Therefore, the Al content is 0.07 % or less. Thus, the Al content is 0.01 % or more and 0.07 % or less. The Al content is preferably 0.02 % or more. The Al content is preferably 0.06 % or less.

10 **[0020]** Cr: 0.5 % or more and 7.0 % or less

Cr is an element that stabilizes austenite when added in an appropriate amount and is an element effective in improving low-temperature toughness and base metal strength. To obtain these effects, the Cr content needs to be 0.5 % or more. On the other hand, when the content exceeds 7.0 %, the
15 low-temperature toughness and the stress corrosion cracking resistance are deteriorated due to formation of Cr carbides. Therefore, the Cr content is 0.5 % or more and 7.0 % or less. The Cr content is preferably 1.0 % or more. The Cr content is preferably 6.7 % or less. The Cr content is more preferably 1.2 % or more. The Cr content is more preferably 6.5 % or less. In order to
20 further improve the stress corrosion cracking resistance, the content is still more preferably 2.0 % or more and 6.0 % or less.

[0021] Ni: 0.01 % or more and less than 0.1 %

Ni has the effect of improving low-temperature toughness. However, minimizing the necessary alloy cost is an important viewpoint in designing the
25 composition of the present disclosure, and from this viewpoint, the Ni content is 0.01 % or more and less than 0.1 %. Examples of austenitic steels having excellent low-temperature toughness include stainless steels such as SUS304 and SUS316. However, a large amount of Ni is added in these steels to optimize the Ni equivalent and the Cr equivalent as an alloy design for
30 obtaining an austenitic structure. Compared with these steels, the present disclosure is an austenitic material whose price is lowered by minimizing necessary Ni. Note that the minimization of necessary Ni is realized by optimizing the addition amount of Mn. The Ni content is preferably 0.03 % or more. The Ni content is preferably 0.07 % or less.

[0022] Ca: 0.0005 % or more and 0.0050 % or less

Ca improves ductility, toughness and sulfide stress corrosion cracking resistance by controlling the morphology of inclusions described below. In addition, Ca suppresses the deterioration of hot ductility and is effective in
5 reducing the occurrence of cracks in cast steel. To obtain these effects, the Ca content needs to be 0.0005 % or more. On the other hand, when the Ca content exceeds 0.0050 %, the ductility, toughness, and sulfide stress corrosion cracking resistance may be rather deteriorated, and the effect of suppressing the deterioration of hot ductility may saturate. Therefore, the Ca
10 content is 0.0005 % or more and 0.0050 % or less. The Ca content is preferably 0.0010 % or more. The Ca content is preferably 0.0045 % or less.

[0023] N: 0.0050 % or more and 0.0500 % or less

N is an austenite-stabilizing element and is an element effective in improving low-temperature toughness. To obtain these effects, the N content
15 needs to be 0.0050 % or more. On the other hand, when the content exceeds 0.0500 %, nitrides or carbonitrides are coarsened and the toughness is deteriorated. Therefore, the N content is 0.0050 % or more and 0.0500 % or less. The N content is preferably 0.0060 % or more. The N content is preferably 0.0400 % or less.

20 **[0024]** O: 0.0050 % or less

O deteriorates low-temperature toughness due to formation of oxides. Therefore, the O content is in the range of 0.0050 % or less. The O content is preferably 0.0045 % or less. Note that the O content is desirably 0.0003 % or more, because excessive reduction of O content increases refining cost and
25 is economically disadvantageous.

[0025] Ti and Nb contents each suppressed to less than 0.005 %

Ti and Nb form high-melting carbonitrides in steel and suppress the coarsening of crystal grains, and as a result, they become a starting point of fractures and propagation path of cracks. In particular, they hinder the
30 microstructure control for enhancing the low-temperature toughness and improving the ductility in the high-Mn steel. Therefore, the contents of Ti and Nb must be suppressed intentionally. That is, Ti and Nb are components inevitably mixed from raw materials and the like, and they are generally mixed in the ranges of Ti: 0.005 % to 0.010 % and Nb: 0.005 % to 0.010 %.

Therefore, it is necessary to avoid the inevitable mixing of Ti and Nb and to suppress the content of each of Ti and Nb to less than 0.005 % according to a method described below. By suppressing the content of each of Ti and Nb to less than 0.005 %, it is possible to eliminate the above-mentioned adverse effects of carbonitrides and to ensure excellent low-temperature toughness and ductility. The contents of Ti and Nb are preferably 0.003 % or less.

[0026] The balance other than the above essential components is iron and inevitable impurities. Examples of the inevitable impurities here include H, and a total of 0.01 % or less is acceptable.

[0027] In order to further improve strength and low-temperature toughness, the following elements can be contained as necessary in addition to the above essential components in the present disclosure.

At least one of Cu: 1.0 % or less, Mo: 2.0 % or less, V: 2.0 % or less, W: 2.0 % or less, Mg: 0.0005 % to 0.0050 %, or REM: 0.0010 % to 0.0200 %

Cu: 1.0 % or less, Mo, V, W: each 2.0 % or less

Cu, Mo, V and W contribute to the stabilization of austenite and to the improvement of base metal strength. To obtain these effects, the contents of Cu, Mo, V and W are preferably 0.001 % or more. On the other hand, when the Cu content exceeds 1.0 % and the contents of Mo, V and W each exceed 2.0 %, coarse carbonitrides are formed, which may be a starting point of fractures, and the manufacturing cost also increases. Therefore, when these alloying elements are contained, the contents are 1.0 % or less for Cu and 2.0 % or less for Mo, V and W. The contents are preferably 0.003 % or more. Further, the contents of Mo, V and W are preferably 1.7 % or less. The contents of Mo, V and W are more preferably 1.5 % or less.

[0028] Mg: 0.0005 % to 0.0050 %, and REM: 0.0010 % to 0.0200 %

Mg and REM are useful elements for controlling the morphology of inclusions and can be contained as necessary. Controlling the morphology of inclusions means making expanded sulfide-based inclusions into granular inclusions. By controlling the morphology of inclusions, the ductility, toughness and sulfide stress corrosion cracking resistance are improved. To obtain these effects, the Ca and Mg contents are preferably 0.0005 % or more, and the REM content is preferably 0.0010 % or more. On the other hand, when any of these elements is contained in a large amount, the amount of

nonmetallic inclusions increases, and the ductility, toughness, and sulfide stress corrosion cracking resistance may rather be deteriorated. In addition, it may be economically disadvantageous. Therefore, when Mg is contained, the content is 0.0005 % to 0.0050 %, and when REM is contained, the content is 0.0010 % to 0.0200 %. The Mg content is preferably 0.0010 % or more. The Mg content is preferably 0.0040 % or less. The REM content is preferably 0.0020 % or more. The REM content is preferably 0.0150 % or less.

[0029] [Microstructure]

10 **Microstructure having austenite as a base phase**

When the crystal structure of a steel material is a body-centered cubic structure (bcc), the steel material is not suitable for use in low-temperature environments because it may cause brittle fractures in low-temperature environments. In consideration of the use in low-temperature environments, the base phase of the steel material should be an austenitic structure where the crystal structure is a face-centered cubic structure (fcc). As used here, “austenite as a base phase” means that the austenite phase has an area ratio of 90 % or more. The remainder other than the austenite phase is a ferrite phase or a martensite phase. Of course, the austenite phase may be 100 %.

20 **[0030]** Austenite grain size: 1 μm or more

Because the high-Mn steel has a microstructure having austenite as a base phase, brittle fractures do not occur even at cryogenic temperatures, and, if a fracture occurs, it is generated from crystal grain boundaries. It is advantageous to reduce the area of crystal grain boundaries, which are the starting point of fractures, to improve the fracture resistance of the high-Mn steel. Therefore, it is important that the austenite grain size be 1 μm or more. This is because, when the grain size is less than 1 μm , the increasing amount of grain boundary area increases, which increases the number of locations where fractures occur. It is preferably 2 μm or more.

30 **[0031]** Standard deviation of austenite: 9 μm or less

Realizing homogenization in conjunction with the regulation of crystal grain size is effective in further improving the fracture resistance of the high-Mn steel. That is, in a mixed-grain-size microstructure, a wide grain size distribution from coarse crystal grains to fine crystal grains results in

containing of crystal grains of less than 1 μm , and especially when the standard deviation exceeds 9 μm , the tendency is remarkable. Therefore, it is necessary to avoid a mixed-grain-size microstructure having a standard deviation of more than 9 μm .

5 **[0032]** [Manufacturing method]

During the manufacture of the high-Mn steel of the present disclosure, first, the steel material may be a molten steel having the above-described chemical composition obtained with a known smelting method such as a converter or an electric furnace. In addition, secondary refinement may be performed in a vacuum degassing furnace. At that time, in order to limit Ti and Nb, which hinder the control of a preferable microstructure, to the above-described ranges, it is necessary to avoid inevitable mixing from raw materials and the like and take measures to reduce the contents thereof. For example, by lowering the basicity of slag in the refining stage, these alloys are concentrated and discharged into the slag, which reduces the concentration of Ti and Nb in a final slab product. Alternatively, a method of blowing oxygen to oxidize the Ti and Nb and floating and separating the alloy of Ti and Nb in reflux may also be used. Subsequently, it is preferable to obtain a steel material such as a slab having a predetermined size with a known casting method such as a continuous casting method or an ingot casting method. It is also acceptable to subject the slab after continuous casting to blooming to obtain a steel material.

25 **[0033]** The following specifies the manufacturing conditions for making the above steel material into a steel material having excellent low-temperature toughness.

Steel material heating temperature: 1100 °C or higher and 1300 °C or lower

The heating temperature before hot rolling is 1100 °C or higher to increase the crystal grain size of the microstructure of the steel material. However, when the temperature exceeds 1300 °C, partial melting may start. Therefore, the upper limit of the heating temperature is set to 1300 °C. The temperature control here is based on the surface temperature of the steel material.

[0034] Rolling finish temperature: 750 °C or higher and lower than 950 °C

The steel material (steel ingot or slab) is subjected to hot rolling after

the heating. In order to obtain coarse crystal grains, it is preferable to increase the cumulative rolling reduction at high temperatures. That is, performing hot rolling at a low temperature makes the microstructure fine and causes excessive working strain. As a result, the low-temperature toughness is deteriorated. Therefore, the lower limit of the rolling finish temperature is set to 750 °C. On the other hand, when the finish temperature is in the range of 950 °C or higher, the crystal grain size becomes excessively coarse, and a desired yield strength cannot be obtained. Therefore, it is necessary to perform the final finish rolling of one or more passes at a temperature of lower than 950 °C. It is preferably 900 °C or lower.

[0035] Average rolling reduction for one pass: 9 % or more

During the hot rolling, in order to realize the homogenization of austenite grain size and control the crystal grain size to 1 μm or more, it is effective to promote the recrystallization of austenite, and it is important to have an average rolling reduction for one pass of 9 % or more during the hot rolling. It is preferably 11 % or more.

[0036] Average cooling rate from a temperature of (rolling finish temperature – 100 °C) or higher to a temperature range of 300 °C or higher and 650 °C or lower: 1.0 °C/s or more

Cooling is immediately performed after the hot rolling. If the steel sheet after hot rolling is cooled slowly, formation of precipitates is promoted and the low-temperature toughness is deteriorated. The formation of these precipitates can be suppressed by cooling the steel sheet at a cooling rate of 1.0 °C/s or more. Excessive cooling distorts the steel sheet and lowers the productivity. Therefore, the upper limit of the cooling start temperature is set to 900 °C. For the above reasons, in the cooling after the hot rolling, the average cooling rate at the steel sheet surface from a temperature of (rolling finish temperature – 100 °C) or higher to a temperature range of 300 °C or higher and 650 °C or lower is 1.0 °C/s or more. On the other hand, from the viewpoint of industrial production, the average cooling rate is preferably 200 °C/s or less.

EXAMPLES

[0037] The following provides a more detailed explanation of the present

disclosure through examples. However, the present disclosure is not limited to the following examples.

Steel slabs having the chemical composition listed in Table 1 were prepared by a process for refining with converter and ladle and continuous casting. Next, the steel slabs thus obtained were subjected to blooming and hot rolling under the conditions listed in Table 2 to obtain steel sheets having a thickness of 10 mm to 30 mm. The steel sheets thus obtained were subjected to tensile property, toughness and microstructure evaluation as described below.

10 **[0038]** (1) Tensile test property

A JIS No. 5 tensile test piece was collected from each steel sheet thus obtained, and the tensile test piece was subjected to a tensile test according to the provisions of JIS Z2241 (1998) to investigate the tensile test property. In the present disclosure, a yield strength of 400 MPa or more and a tensile strength of 800 MPa or more were determined to be excellent in tensile properties. Further, elongation of 40 % or more was determined to be excellent in ductility.

[0039] (2) Low-temperature toughness

A Charpy V-notch test piece was collected from a direction parallel to the rolling direction at a position at a depth of one-fourth of the sheet thickness from the surface of each steel sheet having a thickness of more than 20 mm (hereinafter referred to as “position of sheet thickness $\times$ 1/4”), or a position at a depth of half of the sheet thickness of each steel sheet having a thickness of 20 mm or less (hereinafter referred to as “position of sheet thickness $\times$ 1/2”) according to the provisions of JIS Z2202 (1998). Three Charpy impact tests were performed on each steel sheet according to the provisions of JIS Z2242 (1998) to determine the absorbed energy at $-196\text{ }^{\circ}\text{C}$, thereby evaluating the base metal toughness. In the present disclosure, when the average of three absorbed energy (vE -196) values was 100 J or more, it was determined to be excellent in base metal toughness.

[0040] (3) CTOD value evaluation

A CTOD test piece was collected from a direction parallel to the rolling direction at the position of sheet thickness $\times$ 1/2 of the steel sheet, and two or three tests were conducted at $-165\text{ }^{\circ}\text{C}$ to evaluate the average value.

In the present disclosure, a CTOD value of 0.25 mm or more was determined to be excellent in fracture resistance.

[0041] (4) Microstructure

Electron backscatter diffraction (EBSD) analysis was performed on a
5 L cross section at the position of sheet thickness $\times$ 1/4 of the steel sheet.
Two or three visual fields of $200\ \mu\text{m} \times 200\ \mu\text{m}$ were selected arbitrarily and
observed, and the minimum value of austenite crystal grain size in each visual
field was measured. In addition, the standard deviation of the austenite grain
size was evaluated from the distribution of the area ratio of each crystal grain
10 size using the results of the EBSP analysis. All the crystal grain sizes thus
obtained were taken as a population, a variance that is a sum of squares of the
difference between each individual value and the average value was obtained,
and a square root of the variance was obtained to determine the standard
deviation.

15 The evaluation results thus obtained are listed in Table 3.

[0042] It has been confirmed that the high-Mn steel of the present disclosure
satisfies the above-mentioned desired performance (the yield strength of base
metal is 400 MPa or more, the average value of absorbed energy (vE-196) is
100 J or more with respect to the low-temperature toughness, and the average
20 value of CTOD value is 0.25 mm or more). On the other hand, Comparative
Examples, which are outside the scope of the present disclosure, do not satisfy
at least one of the above-mentioned desired performance of yield strength,
low-temperature toughness, and CTOD value.

[0043]

Table 1

Steel No.	Chemical composition (mass%)																			Remarks
	C	Si	Mn	P	S	Al	Cr	O	N	Nb	Ti	V	Cu	Ni	Mo	W	Ca	Mg	REM	
A	0.162	0.22	29.6	0.019	0.0049	0.055	4.52	0.0019	0.0176	0.001	0.001	-	-	0.05	-	-	0.0011	-	-	Example
B	0.664	0.09	21.9	0.013	0.0051	0.031	2.66	0.0047	0.0385	0.002	0.001	-	-	0.08	-	-	0.0023	-	-	Example
C	0.420	0.41	23.5	0.021	0.0035	0.029	4.46	0.0021	0.0233	0.003	0.002	-	-	0.02	-	-	0.0005	-	-	Example
D	0.343	0.49	20.8	0.021	0.0066	0.041	3.24	0.0035	0.0189	0.001	0.003	0.07	-	0.03	0.46	-	0.0034	-	-	Example
E	0.291	0.37	28.5	0.026	0.0025	0.064	1.78	0.0024	0.0237	0.002	0.001	-	-	0.01	-	0.08	0.0042	-	-	Example
F	0.459	0.28	26.7	0.016	0.0052	0.040	6.21	0.0047	0.0355	0.002	0.002	-	-	0.05	-	-	0.0021	-	-	Example
G	0.332	0.43	23.4	0.019	0.0050	0.052	2.44	0.0029	0.0194	0.003	0.001	-	-	0.04	-	-	0.0018	0.0016	-	Example
H	0.402	0.22	20.6	0.021	0.0044	0.032	1.25	0.0039	0.0065	0.003	0.002	-	-	0.09	-	-	0.0011	-	0.0031	Example
I	0.312	0.15	25.5	0.019	0.0030	0.044	5.42	0.0023	0.0145	0.004	0.001	-	-	0.06	-	-	0.0024	-	-	Example
J	0.415	0.35	24.0	0.018	0.0032	0.031	4.13	0.0019	0.0206	0.001	0.002	-	0.58	0.05	-	-	0.0028	-	-	Example
K	0.590	0.35	26.4	0.014	0.0033	0.036	4.34	0.0016	0.0088	0.002	0.002	-	-	0.07	-	-	0.0031	-	-	Example
L	<u>0.929</u>	0.40	20.1	0.028	0.0055	0.032	4.11	0.0042	0.0304	0.004	0.003	-	-	0.03	-	-	-	-	-	Comparative Example
M	0.105	0.03	24.4	0.022	0.0029	0.041	5.07	0.0031	0.0298	0.001	0.002	-	-	-	-	-	0.0002	-	-	Comparative Example
N	0.128	0.44	<u>16.9</u>	0.025	0.0049	0.038	2.10	0.0040	0.0463	0.002	0.002	-	-	0.04	-	-	-	-	-	Comparative Example
O	0.220	0.50	23.5	0.049	0.0067	0.042	0.93	0.0044	0.0321	0.001	0.001	-	-	0.01	-	-	-	-	-	Comparative Example
P	0.315	0.32	27.7	0.030	<u>0.0091</u>	0.025	1.35	0.0028	0.0059	0.001	0.003	-	-	0.02	-	-	-	-	-	Comparative Example
Q	0.498	0.29	23.9	0.018	0.0055	<u>0.094</u>	3.49	0.0029	0.0250	0.003	0.002	-	-	<u>0.15</u>	-	-	-	-	-	Comparative Example
R	0.287	0.44	26.5	0.015	0.0042	0.063	<u>7.97</u>	0.0037	0.0187	0.002	0.001	-	-	0.02	-	-	-	-	-	Comparative Example
S	0.433	0.43	26.1	0.025	0.0035	0.052	6.22	<u>0.0079</u>	0.0224	0.004	0.003	-	-	0.03	-	-	<u>0.0061</u>	-	-	Comparative Example
T	0.367	0.09	24.6	0.029	0.0048	0.024	3.27	0.0029	<u>0.0755</u>	0.002	0.001	-	-	0.05	-	-	-	-	-	Comparative Example

[0044]

Table 2

Sample No.	Steel No.	Plate thickness (mm)	Hot rolling method					Remarks
			Slab heating temperature (°C)	Rolling finish temperature (°C)	Average rolling reduction for one pass (%)	Cooling start temperature (°C)	Cooling rate until the range of 300 °C or higher and 650 °C or lower (°C/s)	
1	A	31	1180	857	11	830	9	Example
2	B	25	1150	830	12	800	10	Example
3	C	11	1160	785	14	730	12	Example
4	D	20	1100	796	12	764	10	Example
5	E	25	1130	855	12	825	10	Example
6	F	14	1130	842	14	787	11	Example
7	G	9	1250	883	15	819	16	Example
8	H	10	1220	766	14	707	13	Example
9	I	15	1150	826	13	770	3	Example
10	J	30	1150	848	10	821	2	Example
11	C	10	1100	758	14	708	12	Example
12	J	12	1150	775	13	723	11	Example
12	L	20	1250	779	10	747	9	Comparative Example
13	M	30	1250	890	11	863	8	Comparative Example
14	N	14	1120	825	13	770	12	Comparative Example
15	O	25	1120	858	11	828	10	Comparative Example
16	P	20	1180	807	11	764	5	Comparative Example
17	Q	10	1180	773	12	714	11	Comparative Example
18	R	20	1150	801	11	764	9	Comparative Example
19	S	15	1150	810	12	754	10	Comparative Example
20	T	30	1130	845	9	821	2	Comparative Example
21	C	12	1180	<u>673</u>	10	618	11	Comparative Example
22	D	19	1200	804	11	772	<u>0.4</u>	Comparative Example
23	A	31	1200	759	<u>7</u>	732	9	Comparative Example
24	E	25	<u>1030</u>	848	12	818	10	Comparative Example
25	D	10	1100	763	<u>6</u>	716	11	Comparative Example
26	B	25	1130	<u>993</u>	10	955	10	Comparative Example

[0045]

Table 3

Sample No.	Steel No.	Minimum value of γ grain size (μm)	Standard deviation of γ grain size (μm)	Yield strength (MPa)	Tensile strength (MPa)	Total elongation (%)	Absorbed energy at $-196\text{ }^{\circ}\text{C}$ ($\text{vE}_{-196^{\circ}\text{C}}$) (J)	CTOD value (mm)	Remarks
1	A	5.2	7.6	418	850	69	133	0.41	Example
2	B	3.4	7.4	554	941	58	118	0.39	Example
3	C	2.6	5.7	566	969	62	123	0.36	Example
4	D	2.9	7.1	559	952	55	115	0.36	Example
5	E	5.5	7.3	489	886	64	138	0.42	Example
6	F	6.1	6.2	453	854	67	139	0.44	Example
7	G	5.9	4.9	418	936	62	126	0.44	Example
8	H	3.1	5.5	512	968	61	104	0.37	Example
9	I	5.7	6.6	447	849	66	131	0.43	Example
10	J	4.8	7.8	407	847	69	136	0.40	Example
11	C	1.9	5.4	575	978	58	115	0.36	Example
12	J	2.8	5.8	557	952	63	124	0.37	Example
12	<u>L</u>	2.3	7.9	622	970	51	<u>58</u>	<u>0.21</u>	Comparative Example
13	<u>M</u>	4.9	7.4	<u>363</u>	818	70	127	0.40	Comparative Example
14	<u>N</u>	5.5	6.8	443	868	68	<u>36</u>	<u>0.17</u>	Comparative Example
15	<u>Q</u>	4.7	7.3	447	878	64	<u>72</u>	0.33	Comparative Example
16	<u>P</u>	4.8	7.5	529	940	59	<u>79</u>	0.36	Comparative Example
17	<u>Q</u>	2.9	6.1	502	957	61	<u>89</u>	0.37	Comparative Example
18	<u>R</u>	4.5	7.3	518	935	60	<u>48</u>	0.34	Comparative Example
19	<u>S</u>	5.2	6.8	455	850	67	<u>83</u>	0.40	Comparative Example
20	<u>T</u>	4.3	7.9	417	853	68	<u>75</u>	0.40	Comparative Example
21	C	1.7	6.5	667	1057	49	<u>42</u>	0.29	Comparative Example
22	D	2.5	7.3	547	943	56	<u>67</u>	0.34	Comparative Example
23	A	<u>0.7</u>	<u>9.8</u>	534	964	59	103	<u>0.15</u>	Comparative Example
24	E	3.5	7.4	476	875	63	<u>69</u>	0.36	Comparative Example
25	D	<u>0.4</u>	<u>10.5</u>	569	970	60	119	<u>0.12</u>	Comparative Example
26	B	4.9	7.5	<u>375</u>	<u>795</u>	70	112	0.37	Comparative Example

CLAIMS

1. A high-Mn steel comprising
a chemical composition containing, in mass%,
5 C: 0.10 % or more and 0.70 % or less,
Si: 0.05 % or more and 0.50 % or less,
Mn: 20 % or more and 30 % or less,
P: 0.030 % or less,
S: 0.0070 % or less,
10 Al: 0.01 % or more and 0.07 % or less,
Cr: 0.5 % or more and 7.0 % or less,
Ni: 0.01 % or more and less than 0.1 %,
Ca: 0.0005 % or more and 0.0050 % or less,
N: 0.0050 % or more and 0.0500 % or less,
15 O: 0.0050 % or less,
Ti: less than 0.0050 %, and
Nb: less than 0.0050 %,
the balance consisting of Fe and inevitable impurities, and
a microstructure having austenite as a base phase, where the austenite
20 has a grain size of 1 μm or more and a standard deviation of 9 μm or less,
and, a yield strength of 400 MPa or more and a tensile strength of 800
MPa or more, absorbed energy value (vE-196) at -196 °C determined by
Charpy impact tests is 100 J or more, and a CTOD value at -165 °C is 0.25
mm or more.
25
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
Cu: 1.0 % or less,
30 Mo: 2.0 % or less,
V: 2.0 % or less,
W: 2.0 % 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 of manufacturing a high-Mn steel, comprising heating a steel material having the chemical composition according to claim 1
5 or 2 to a temperature range of 1100 °C or higher and 1300 °C or lower, then
subjecting the steel material to hot rolling where a rolling finish temperature
is 750 °C or higher and lower than 950 °C and an average rolling reduction for
one pass is 9 % or more, and then subjecting the hot rolled material to cooling
where an average cooling rate from a temperature of (rolling finish
10 temperature – 100 °C) or higher to a temperature range of 300 °C or higher
and 650 °C or lower is 1.0 °C/s or more,
and a microstructure having austenite as a base phase, where the
austenite has a grain size of 1 µm or more and a standard deviation of 9 µm or
less,
15 and, a yield strength of 400 MPa or more and a tensile strength of 800
MPa or more, absorbed energy value (vE–196) at –196 °C determined by
Charpy impact tests is 100 J or more, and a CTOD value at –165 °C is 0.25
mm or more.