

HIGH-Mn STEEL AND METHOD OF PRODUCING SAME

TECHNICAL FIELD

5 **[0001]** The present disclosure relates to a high-Mn steel having excellent toughness particularly at low temperatures and suitable for structural steel used in very-low-temperature environments such as liquefied gas storage tanks, and a method of producing the same.

BACKGROUND

10 **[0002]** Operating environments of structures such as liquefied gas storage tanks reach very low temperatures, and thus hot-rolled steel plates used for such structures are required to have excellent toughness at very low temperatures as well as excellent strength. For example, a hot-rolled steel plate used for a liquefied natural gas storage needs to have excellent
15 toughness in a temperature range lower than -164 °C which is the boiling point of liquefied natural gas. If the low-temperature toughness of the steel plate used for the very-low-temperature storage structure is insufficient, the safety of the very-low-temperature storage structure is likely to be undermined. There is thus strong need to improve the low-temperature
20 toughness of the steel plate used.

[0003] In response to this need, austenitic stainless steel having, as steel plate microstructure, austenite which is not embrittled at very low temperatures, 9 % Ni steel, and 5000 series aluminum alloys are conventionally used. However, due to high alloy costs or production costs of these materials, there
25 is demand for a steel material that is inexpensive and has excellent low-temperature toughness.

[0004] A structure such as a liquefied gas storage tank needs to be coated in order to prevent the steel plate from rust and corrosion. It is important to achieve aesthetic appearance after the coating, for environmental harmony.
30 Hence, the hot-rolled steel plate used for a liquefied natural gas storage is also required to have excellent characteristics of the steel plate surface as the base of the coating. That is, the roughness of the steel plate surface needs to be low.

[0005] In view of this, for example, JP 2017-507249 A (PTL 1) proposes use

of, as a new steel material to replace conventional steels for very low temperature use, a high-Mn steel containing a large amount of Mn which is a relatively inexpensive austenite-stabilizing element, for structural steel in very-low-temperature environments. The technique proposed in PTL 1 involves controlling stacking fault energy to achieve excellent low-temperature toughness without surface unevenness.

CITATION LIST

Patent Literature

10 [0006] PTL 1: JP 2017-507249 A

SUMMARY

(Technical Problem)

[0007] With the technique described in PTL 1, a high-Mn steel with excellent surface quality can be provided without surface unevenness after working such as tensile working. However, PTL 1 does not mention about the surface roughness of a hot-rolled steel plate produced. The produced hot-rolled steel plate is usually shipped after its surface is made uniform by shot blasting treatment. In the case where the steel plate surface after the shot blasting treatment is rough, local rusting occurs. To prevent this, the surface characteristics need to be adjusted by a grinder or the like. This causes a decrease in productivity.

[0008] It could therefore be helpful to provide a high-Mn steel having excellent low-temperature toughness and excellent surface characteristics. It could also be helpful to provide an advantageous method of producing the high-Mn steel. Herein, “excellent low-temperature toughness” means that the absorbed energy vE_{-196} in the Charpy impact test at $-196\text{ }^{\circ}\text{C}$ is 100 J or more and the percent brittle fracture is less than 10 %, and “excellent surface characteristics” mean that the surface roughness Ra after typical shot blasting treatment is 200 μm or less.

(Solution to Problem)

[0009] We conducted intensive studies on various factors that determine the chemical composition and microstructure of a steel plate for high-Mn steel, and discovered the following a to d:

a. If a Mn-concentrated portion with a Mn concentration of more than 38.0 mass% forms in austenitic steel having high Mn content, the percent brittle fracture reaches 10 % or more at low temperatures, and the low-temperature toughness decreases. Accordingly, an effective way of improving the low-temperature toughness of high-Mn steel is to limit the Mn concentration of the Mn-concentrated portion to 38.0 mass% or less.

[0010] b. If austenitic steel having high Mn content contains Cr in an amount of more than 5.00 mass%, descaling during hot rolling is insufficient. This causes the hot-rolled sheet after shot blasting treatment to have a rough surface with surface roughness Ra of more than 200 μm . Hence, the Cr content needs to be 5.00 mass% or less, for improvement in the surface characteristics of the high-Mn steel.

[0011] c. By performing hot rolling and descaling under appropriate conditions, the foregoing a and b can be achieved without an increase in production costs.

[0012] d. By performing hot rolling under appropriate conditions to provide high dislocation density, yield stress can be effectively increased.

[0013] The present disclosure is based on these discoveries and further studies. We thus provide:

1. A 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: 0.010 % or more and 0.070 % or less, Cr: 0.50 % or more and 5.00 % 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 a balance consisting of Fe and inevitable impurities; and a microstructure having austenite as a matrix, wherein in the microstructure, a Mn concentration of a Mn-concentrated portion is 38.0 mass% or less, and an average of Kernel Average Misorientation (KAM) value is 0.3 or more, yield stress is 400 MPa or more, absorbed energy vE_{-196} in a Charpy impact test at -196 °C is 100 J or more, and percent brittle fracture is less than 10 %.

[0014] 2. The high-Mn steel according to 1., wherein the chemical composition further contains, in mass%, one or more selected from Cu: 0.01 % or more and 0.50 % or less, Mo: 2.00 % or less, V: 2.00 % or less, and W:

2.00 % or less.

[0015] 3. The high-Mn steel according to 1. or 2., wherein the chemical composition further contains, in mass%, one or more selected from 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.

[0016] 4. A method of producing a high-Mn steel, the method comprising: heating a steel raw material having the chemical composition according to any one of 1. to 3. to a temperature range of 1100 °C or more and 1300 °C or less; and thereafter subjecting the steel raw material to hot rolling with a rolling finish temperature of 800 °C or more and a total rolling reduction of 20 % or more, and performing descaling treatment in the hot rolling.

Herein, the temperature range and the temperature are each the surface temperature of the steel raw material or steel plate.

[0017] 5. A method of producing a high-Mn steel, the method comprising: heating a steel raw material having the chemical composition according to any one of 1. to 3. to a temperature range of 1100 °C or more and 1300 °C or less; thereafter subjecting the steel raw material to first hot rolling with a rolling finish temperature of 1100 °C or more and a total rolling reduction of 20 % or more; and thereafter subjecting the hot-rolled steel raw material to second hot rolling with a rolling finish temperature of 700 °C or more and less than 950 °C, and performing descaling treatment in the second hot rolling.

[0018] 6. A method of producing a high-Mn steel, the method comprising: heating a steel raw material having the chemical composition according to any one of 1. to 3. to a temperature range of 1100 °C or more and 1300 °C or less; thereafter subjecting the steel raw material to first hot rolling with a rolling finish temperature of 800 °C or more and less than 1100 °C and a total rolling reduction of 20 % or more; thereafter reheating the hot-rolled steel raw material to 1100 °C or more and 1300 °C or less; and thereafter subjecting the hot-rolled steel raw material to second hot rolling with a rolling finish temperature of 700 °C or more and less than 950 °C, and performing descaling treatment in the second hot rolling.

[0019] 7. The method of producing a high-Mn steel according to 5. or 6., wherein descaling treatment is performed in the first hot rolling.

[0020] 8. The method of producing a high-Mn steel according to any one of 4.

to 7., comprising performing cooling treatment, after final hot rolling, at an average cooling rate of 1.0 °C/s or higher in a temperature range from a temperature of or higher than 100 °C below the rolling finish temperature to a temperature of 300 °C or more and 650 °C or less.

5 (Advantageous Effect)

[0021] It is thus possible to provide a high-Mn steel having excellent low-temperature toughness and excellent surface characteristics. The presently disclosed high-Mn steel significantly contributes to improved safety and life of steel structures used in very-low-temperature environments such as liquefied gas storage tanks. This yields significantly advantageous effects in industrial terms. The presently disclosed production method has excellent economic efficiency because it does not cause a decrease in productivity and an increase in production costs.

10

15 BRIEF DESCRIPTION OF THE DRAWINGS

[0022] In the accompanying drawings:

FIG. 1 is a graph illustrating results of measuring the Mn concentration of a Mn-concentrated portion and the absorbed energy in the Charpy impact test at -196 °C.

20

DETAILED DESCRIPTION

[0023] A high-Mn steel according to one of the disclosed embodiments will be described in detail below.

[Chemical composition]

25 First, the chemical composition of the high-Mn steel according to one of the disclosed embodiments and the reasons for limiting the chemical composition will be described below. Herein, “%” used with regard to the chemical composition denotes “mass%” unless otherwise specified.

C: 0.100 % or more and 0.700 % or less

30 C is an inexpensive austenite-stabilizing element, and is important in obtaining austenite. To achieve the effects, the C content needs to be 0.100 % or more. If the C content is more than 0.700 %, Cr carbides form excessively, and the low-temperature toughness decreases. The C content is therefore 0.100 % or more and 0.700 % or less. The C content is preferably

0.200 % or more and 0.600 % or less.

[0024] Si: 0.05 % or more and 1.00 % or less

Si acts as a deoxidizer, and not only is necessary for steelmaking but also has an effect of strengthening the steel plate through solid solution strengthening by dissolving in the steel. To achieve the effects, the Si content needs to be 0.05 % or more. If the Si content is more than 1.00 %, the low-temperature toughness and the weldability decrease. The Si content is therefore 0.05 % or more and 1.00 % or less. The Si content is preferably 0.07 % or more and 0.50 % or less.

[0025] Mn: 20.0 % or more and 35.0 % or less

Mn is a relatively inexpensive austenite-stabilizing element. In the present disclosure, Mn is an important element for achieving both the strength and the low-temperature toughness. To achieve the effects, the Mn content needs to be 20.0 % or more. If the Mn content is more than 35.0 %, the low-temperature toughness decreases. The Mn content is therefore 20.0 % or more and 35.0 % or less. The Mn content is preferably 23.0 % or more and 32.0 % or less.

[0026] P: 0.030 % or less

If the P content is more than 0.030 %, the low-temperature toughness decreases. Moreover, P segregates to grain boundaries and forms a stress corrosion cracking initiation point. It is therefore desirable to reduce the P content as much as possible, with its upper limit being set to 0.030 %. The P content is therefore 0.030 % or less. Excessive reduction of P is economically disadvantageous because the refining costs increase, and accordingly it is desirable to set the P content to 0.002 % or more. The P content is preferably 0.005 % or more and 0.028 % or less, and further preferably 0.024 % or less.

[0027] S: 0.0070 % or less

S decreases the low-temperature toughness and the ductility of the base metal. It is therefore desirable to reduce the S content as much as possible, with its upper limit being set to 0.0070 %. The S content is therefore 0.0070 % or less. Excessive reduction of S is economically disadvantageous because the refining costs increase, and accordingly it is desirable to set the S content to 0.0010 % or more. The S content is

preferably 0.0020 % or more and 0.0060 % or less.

[0028] Al: 0.010 % or more and 0.070 % or less

Al acts as a deoxidizer, and is most generally used in the molten steel deoxidation process for steel plates. To achieve the effects, the Al content
5 needs to be 0.010 % or more. If the Al content is more than 0.070 %, Al is mixed into a weld metal portion during welding and decreases the toughness of the weld metal. The Al content is therefore 0.070 % or less. The Al content is preferably 0.020 % or more and 0.060 % or less.

[0029] Cr: 0.50 % or more and 5.00 % or less

10 Cr is an element that, when added in an appropriate amount, stabilizes austenite and effectively improves the low-temperature toughness and the base metal strength. To achieve the effects, the Cr content needs to be 0.50 % or more. If the Cr content is more than 5.00 %, Cr carbides form, as a result of which the low-temperature toughness and the stress corrosion
15 cracking resistance decrease. In addition, descaling during hot rolling is insufficient, and the surface roughness worsens. The Cr content is therefore 0.50 % or more and 5.00 % or less. The Cr content is preferably 0.60 % or more and 4.00 % or less, and more preferably 0.70 % or more and 3.50 % or less. In particular, to improve the stress corrosion cracking resistance, the
20 Cr content is preferably 2.00 % or more, and further preferably more than 2.70 %.

[0030] N: 0.0050 % or more and 0.0500 % or less

N is an austenite-stabilizing element, and is effective in improving the low-temperature toughness. To achieve the effects, the N content needs to be
25 0.0050 % or more. If the N content is more than 0.0500 %, nitrides or carbonitrides coarsen, and the toughness decreases. The N content is therefore 0.0050 % or more and 0.0500 % or less. The N content is preferably 0.0060 % or more and 0.0400 % or less.

[0031] O: 0.0050 % or less

30 O forms oxides and causes a decrease in low-temperature toughness. The O content is therefore 0.0050 % or less. The O content is preferably 0.0045 % or less. Although no lower limit is placed on the O content, excessive reduction of O is economically disadvantageous because the refining costs increase, and accordingly the O content is preferably 0.0010 %

or more.

[0032] Each of Ti and Nb: 0.005 % or less

Ti and Nb each form carbonitrides of a high melting point in the steel and suppress coarsening of crystal grains, and as a result form a fracture
5 origin or a crack propagation path. Particularly in high-Mn steel, Ti and Nb hinder microstructure control for enhancing the low-temperature toughness and improving the ductility. Hence, Ti and Nb need to be reduced intentionally. In detail, Ti and Nb are components that are inevitably mixed in from raw material and the like, and usually Ti and Nb are each mixed in
10 within a range of more than 0.005 % and 0.010 % or less. It is necessary to prevent inevitable mixing of Ti and Nb as much as possible by the below-described method or the like, to limit each of the Ti content and the Nb content to 0.005 % or less. As a result of the Ti content and the Nb content each being limited to 0.005 % or less, the foregoing adverse effect of
15 carbonitrides can be avoided and excellent low-temperature toughness and excellent ductility can be ensured. The Ti content and the Nb content are each preferably 0.003 % or less.

[0033] The Ti content and the Nb content may each be reduced to 0 %. This is, however, economically disadvantageous because the load in steelmaking
20 increases. From the viewpoint of economic efficiency, the Ti content and the Nb content are each desirably 0.001 % or more.

[0034] The balance other than the components described above consists of iron and inevitable impurities. The inevitable impurities include, for example, H, B, and the like, and an allowable total amount of inevitable
25 impurities is 0.01 % or less.

[0035] The chemical composition of the high-Mn steel according to one of the disclosed embodiments may optionally contain the following elements in addition to the above-described essential elements, for the purpose of further improving the strength and the low-temperature toughness.

30 One or more selected from Cu: 0.01 % or more and 0.50 % or less, Mo: 2.00 % or less, V: 2.00 % or less, and W: 2.00 % or less

[0036] Cu is an element that not only strengthens the steel plate by solid solution strengthening but also improves the dislocation mobility and improves the low-temperature toughness. To achieve the effects, the Cu

content is preferably 0.01 % or more. If the Cu content is more than 0.50 %, the surface characteristics degrade in rolling. The Cu content is therefore preferably 0.01 % or more and 0.50 % or less. The Cu content is more preferably 0.02 % or more and 0.40 % or less. The Cu content is further
5 preferably less than 0.20 %.

[0037] Mo, V, and W contribute to stabilized austenite, and also contribute to improved base metal strength. To achieve the effects, the Mo content, the V content, and the W content are each preferably 0.001 % or more. If the Mo content, the V content, and the W content are each more than 2.00 %, coarse
10 carbonitrides may form and serve as a fracture origin. In addition, the production costs increase. Accordingly, in the case of containing each of these alloy elements, the content is preferably 2.00 % or less. The content is more preferably 0.003 % or more and 1.70 % or less, and further preferably 1.50 % or less.

[0038] One or more selected from 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
15

Ca, Mg, and REM are each an element useful for morphological control of inclusions, and may be optionally contained. Morphological
20 control of inclusions means turning elongated sulfide-based inclusions into granular inclusions. Through such morphological control of inclusions, the ductility, the toughness, and the sulfide stress corrosion cracking resistance are improved. To achieve the effects, the Ca content and the Mg content are each preferably 0.0005 % or more, and the REM content is preferably 0.0010
25 % or more. If the Ca content, the Mg content, and the REM content are each high, the amount of nonmetallic inclusions increase, which may decrease the ductility, the toughness, and the sulfide stress corrosion cracking resistance. Moreover, high contents of these elements are likely to be economically disadvantageous.

Accordingly, in the case of containing Ca and Mg, the Ca content and the Mg content are each preferably 0.0005 % or more and 0.0050 % or less. In the case of containing REM, the REM content is preferably 0.0010 % or more and 0.0200 % or less. More preferably, the Ca content is 0.0010 % or more and 0.0040 % or less, the Mg content is 0.0010 % or more and 0.0040 %
30

or less, and the REM content is 0.0020 % or more and 0.0150 % or less.

[0039] [Microstructure]

Microstructure having austenite as matrix

In the case where the crystal structure of the steel material is a
5 body-centered cubic structure (bcc), there is a possibility that the steel
material undergoes brittle fracture in a low-temperature environment. Such
steel material is not suitable for use in a low-temperature environment.
Assuming use in a low-temperature environment, it is essential that the crystal
10 structure of the matrix of the steel material is austenite microstructure which
is a face-centered cubic structure (fcc). The expression “having austenite as
a matrix” means that austenite phase is 90 % or more in area ratio. The
remaining phase other than austenite phase is ferrite phase and/or martensite
phase. The area ratio of austenite phase is further preferably 95 % or more.
The area ratio of austenite phase may be 100 %.

15 **[0040]** Mn concentration of Mn-concentrated portion in microstructure: 38.0
mass% or less

A hot-rolled steel plate obtained by hot rolling the steel raw material
having the foregoing chemical composition inevitably has a Mn-concentrated
portion. The “Mn-concentrated portion” is a portion whose Mn
20 concentration is highest in a micro segregation area. When the steel raw
material containing Mn is hot rolled, segregated band of Mn occurs, as a result
of which the Mn-concentrated portion forms inevitably.

[0041] FIG. 1 illustrates results of measuring the Mn concentration of the
Mn-concentrated portion and the absorbed energy in the Charpy impact test at
25 -196 °C for each steel plate obtained by hot rolling the steel raw material
having the foregoing chemical composition under various conditions. As
illustrated in the drawing, as a result of hot rolling the steel raw material
having the foregoing chemical composition under appropriate conditions and
limiting the Mn concentration of the Mn-concentrated portion to 38.0 mass%
30 or less, absorbed energy of 100 J or more can be achieved. The Mn
concentration of the Mn-concentrated portion is preferably 37.0 mass% or
less.

Although no lower limit is placed on the Mn concentration of the
Mn-concentrated portion, the Mn concentration of the Mn-concentrated

portion is preferably 25.0 mass% or more in order to ensure the stability of austenite.

[0042] Average of Kernel Average Misorientation (KAM) value: 0.3 or more

A KAM value is obtained as follows: At each of depth positions of 1/4
5 and 1/2 of the thickness from the surface of the steel plate after hot rolling, electron backscatter diffraction (EBSD) analysis is performed for any two observation fields of 500 μm $\times$ 200 μm . And, from the analysis results, the average value of misorientations (orientation differences) between each pixel and its adjacent pixels within a crystal grain is calculated as the KAM value.
10 The KAM value reflects local crystal orientation changes by dislocations in the microstructure. A higher KAM value indicates greater misorientations between the measurement point and its adjacent parts. That is, a higher KAM value indicates a higher degree of local deformation within the grain. Hence, when the KAM value in the steel plate after the rolling is higher, the
15 dislocation density is higher. If the average KAM value is 0.3 or more, a lot of dislocations are accumulated, so that the yield stress is improved. The average KAM value is preferably 0.5 or more. If the average KAM value is more than 1.3, the toughness is likely to decrease. Accordingly, the average KAM value is preferably 1.3 or less.

20 **[0043]** The hot-rolled sheet that has the foregoing chemical composition and in which the Mn concentration of the Mn-concentrated portion is 38.0 % or less and the average KAM value is 0.3 or more has, as a result of being subjected to descaling at least in final hot rolling, surface roughness Ra of 200 μm or less after shot blasting treatment is performed by a typical method.
25 This is because, as a result of performing descaling, an increase in surface roughness caused by scale biting during rolling is suppressed and cooling unevenness caused by scale during cooling is suppressed, and the material surface hardness is made uniform to thus suppress an increase in surface roughness during shot blasting.

30 If the surface roughness Ra after the shot blasting is more than 200 μm , not only the aesthetic appearance after the coating is impaired, but also local corrosion progresses in recessed parts. Hence, the surface roughness Ra needs to be 200 μm or less. The surface roughness Ra is preferably 150 μm or less, and more preferably 120 μm or less. Although no lower limit is

placed on the surface roughness Ra, the surface roughness Ra is preferably 5 μm or more in order to avoid an increase in mending costs.

Mn forms oxides that diffuse from inside the steel to the steel plate surface to precipitate and concentrate on the steel plate surface. Such oxides
5 are called concentrated substances on surface. Accordingly, by limiting the Mn concentration of the Mn-concentrated portion to 38.0 % or less, surface roughness Ra of 200 μm or less can be achieved.

[0044] For the high-Mn steel according to one of the disclosed embodiments, molten steel having the foregoing chemical composition may be obtained by
10 steelmaking according to a well-known steelmaking method using a converter, an electric heating furnace, or the like. Secondary refining may be performed in a vacuum degassing furnace. In this case, it is necessary to limit Ti and Nb, which hinder suitable microstructure control, to the foregoing range, by preventing Ti and Nb from being inevitably mixed in from raw
15 material and the like and reducing their contents. For example, by decreasing the basicity of slag in the refining stage, alloys of Ti and Nb are concentrated in the slag and discharged, thus reducing the concentrations of Ti and Nb in the final slab product. Alternatively, a method of blowing in oxygen to cause oxidation and, during circulation, inducing floatation
20 separation of alloys of Ti and Nb may be used. Subsequently, a steel raw material such as a slab with predetermined dimensions is preferably obtained by a well-known casting method such as continuous casting.

[0045] Further, to make the steel raw material into a steel material having excellent low-temperature toughness, the steel raw material is heated to a
25 temperature range of 1100 °C or more and 1300 °C or less, and then subjected to hot rolling with a rolling finish temperature of 800 °C or more and a total rolling reduction of 20 % or more and subjected to descaling treatment in the hot rolling. Each of the processes will be described below.

[Steel raw material heating temperature: 1100 °C or more and 1300 °C or less]

30 To obtain the high-Mn steel having the foregoing structure, it is important to heat the steel raw material to a temperature range of 1100 °C or more and 1300 °C or less and subject the steel raw material to hot rolling with a rolling finish temperature of 800 °C or more and a total rolling reduction of 20 % or more. Here, the temperature control is based on the surface

temperature of the steel raw material.

In detail, to facilitate diffusion of Mn in the hot rolling, the heating temperature before the rolling is set to 1100 °C or more. If the heating temperature is more than 1300 °C, there is a possibility that the steel starts to melt. The upper limit of the heating temperature is therefore 1300 °C. The heating temperature is preferably 1150 °C or more and 1250 °C or less.

[0046] [Hot rolling: rolling finish temperature of 800 °C or more and total rolling reduction of 20 % or more]

Next, in the hot rolling, it is important to set a high total rolling reduction of 20 % or more at the end of rolling, to reduce the distance between the Mn-concentrated portion and the Mn-dilute portion and facilitate diffusion of Mn. The total rolling reduction is preferably 30 % or more. Although no upper limit is placed on the total rolling reduction, the total rolling reduction is preferably 98 % or less from the viewpoint of improving the rolling efficiency. The total rolling reduction herein refers to each of the rolling reduction with respect to the thickness of the slab on the entry side of the first hot rolling at the end of the first hot rolling, and the rolling reduction with respect to the thickness of the slab on the entry side of the second hot rolling at the end of the second hot rolling. In the case where hot rolling is performed twice, it is preferable that the total rolling reduction is 20 % or more at the end of the first hot rolling and 50 % or more at the end of the second hot rolling. In the case where hot rolling is performed only once, it is preferable that the total rolling reduction is 60 % or more.

[0047] Likewise, the rolling finish temperature is set to 800 °C or more, from the viewpoint of facilitating diffusion of Mn during the rolling and ensuring the low-temperature toughness. If the rolling finish temperature is less than 800 °C, the rolling finish temperature is well below 2/3 of the melting point (1246 °C) of Mn, so that Mn cannot be diffused sufficiently. We learned from our studies that Mn can be diffused sufficiently if the rolling finish temperature is 800 °C or more. We consider that, because the Mn diffusion coefficient in austenite is low, rolling in a temperature range of 800 °C or more is necessary for sufficient diffusion of Mn. The rolling finish temperature is preferably 950 °C or more, and further preferably 1000 °C or more. The rolling finish temperature is preferably 1050 °C or less, from the

viewpoint of ensuring the strength.

[0048] After the foregoing hot rolling, the second hot rolling satisfying the following conditions may be optionally performed to effectively facilitate diffusion of Mn. In this case, if the finish temperature of the foregoing first
5 hot rolling is 1100 °C or more, the second hot rolling is performed directly after the first hot rolling. If the finish temperature of the first hot rolling is less than 1100 °C, on the other hand, reheating to 1100 °C or more is performed. If the reheating temperature is more than 1300 °C, there is a possibility that the steel starts to melt, as in the foregoing heating. The
10 upper limit of the reheating temperature is therefore 1300 °C. Here, the temperature control is based on the surface temperature of the steel raw material.

[0049] [Second hot rolling: rolling finish temperature: 700 °C or more and less than 950 °C]

15 In the second hot rolling, it is necessary to perform at least one or more passes in a temperature range of 700 °C or more and less than 950 °C. As a result of performing one or more passes of rolling at less than 950 °C with a rolling ratio of preferably 10 % or more per pass, dislocations introduced in the first rolling tend unlikely to recover, thereby likely to
20 remain, with it being possible to further increase the KAM value. If the rolling finish temperature in the second hot rolling is 950 °C or more, crystal grains become excessively coarse, and the desired yield stress cannot be obtained. Hence, finish rolling of one or more passes is performed at less than 950 °C. The rolling finish temperature is preferably 900 °C or less, and
25 more preferably 850 °C or less.

[0050] If the rolling finish temperature is less than 700 °C, the toughness decreases. The rolling finish temperature is therefore 700 °C or more. The rolling finish temperature is preferably 750 °C or more. The total rolling reduction at the end of the second hot rolling is preferably 20 % or more, and
30 more preferably 50 % or more. If the total rolling reduction is more than 95 %, the toughness decreases. Accordingly, the total rolling reduction at the end of the second hot rolling is preferably 95 % or less. Herein, the total rolling reduction at the end of the second hot rolling is a value calculated using the thickness before the second hot rolling and the thickness after the

second hot rolling.

[0051] Moreover, by performing descaling treatment once or more in the hot rolling, a steel plate having excellent surface characteristics can be produced. The descaling treatment is preferably performed twice or more, and more
5 preferably performed three times or more. Although no upper limit is placed on the number of times the descaling treatment is performed, the number of times the descaling treatment is performed is preferably 20 or less from the operational viewpoint. The descaling treatment is preferably performed before the first pass of the hot rolling. In the case where the hot rolling is
10 performed once, the descaling treatment is performed in the hot rolling. In the case where the hot rolling is performed twice, the descaling treatment is performed at least in the second hot rolling. In the case where the hot rolling is performed twice, it is more preferable to perform the descaling treatment both in the first hot rolling and in the second hot rolling.

[0052] Next, cooling treatment according to the following conditions is preferably performed. In the case where the hot rolling is performed twice, the cooling treatment is performed after the hot rolling. In the case where the hot rolling is performed twice, the cooling treatment is performed after the
15 second hot rolling.

[Cooling rate in temperature range from temperature not less than (rolling finish temperature - 100 °C) to temperature of 300 °C or more and 650 °C or less: 1.0 °C/s or higher]
20

After the hot rolling ends, it is preferable to perform cooling rapidly. If the steel plate after the hot rolling is cooled slowly, the formation of
25 precipitates is promoted, which is likely to cause a decrease in low-temperature toughness. Such precipitate formation can be suppressed by cooling at a cooling rate of 1.0 °C/s or higher in a temperature range from a temperature not less than (rolling finish temperature - 100 °C) to a temperature of 300 °C or more and 650 °C or less (in other words, to a
30 temperature between 300 to 650 °C). The reason for limiting the cooling rate in the temperature range from a temperature not less than (rolling finish temperature - 100 °C) to a temperature of 300 °C or more and 650 °C or less is because this temperature range corresponds to the carbide precipitation temperature range. Excessive cooling strains the steel plate, and causes a

decrease in productivity. Particularly in the case where the thickness of the steel material is 10 mm or less, air cooling is preferable. Accordingly, the upper limit of the cooling start temperature is preferably 900 °C.

5 [0053] If the average cooling rate in the foregoing temperature range is less than 1.0 °C/s, precipitate formation is likely to be promoted. The average cooling rate is therefore preferably 1.0 °C/s or more. From the viewpoint of preventing strain of the steel plate due to excessive cooling, the average cooling rate is preferably 15.0 °C/s or less. Particularly in the case where the thickness of the steel material is 10 mm or less, the average cooling rate is
10 preferably 5.0 °C/s or less, and further preferably 3.0 °C/s or less.

[0054] The hot-rolled steel plate produced as a result of the processes described above has a Mn-concentrated portion of low Mn concentration as hot rolled, and thus need not be heat-treated subsequently.

15 EXAMPLES

[0055] The presently disclosed techniques will be described in more detail below by way of examples. The presently disclosed techniques are not limited to the examples described below.

20 Steel slabs having the chemical compositions indicated in Table 1 were produced in a process for refining with converter and ladle and continuous casting. Each obtained steel slab was then subjected to hot rolling under the conditions indicated in Table 2, to obtain a steel plate of 6 mm to 30 mm in thickness. For each obtained steel plate, the tensile property, the toughness, and the microstructure were evaluated as follows.

25 [0056] (1) Tensile test property

A JIS No. 5 tensile test piece was collected from each obtained steel plate, and a tensile test was performed in accordance with JIS Z 2241 (1998) to examine the tensile test property. In the case where the yield stress was 400 MPa or more and the tensile strength was 800 MPa or more, the sample
30 was determined to have excellent tensile property. In the case where the elongation was 40 % or more, the sample was determined to have excellent ductility.

[0057] (2) Low-temperature toughness

At a position of 1/4 of the thickness from the surface of each steel

plate of more than 20 mm in thickness and at a position of 1/2 of the thickness from the surface of each steel plate of 10 mm or more and 20 mm or less in thickness, three V-notch Charpy test pieces were collected in the rolling direction in accordance with JIS Z 2202 (1998) and subjected to the Charpy impact test in accordance with JIS Z 2242 (1998) to determine the absorbed energy at -196 °C and evaluate the base metal toughness. For each steel plate of less than 10 mm in thickness, three 5 mm subsize V-notch Charpy test pieces were collected and subjected to the Charpy impact test in accordance with the foregoing JIS standards, to determine the absorbed energy at -196 °C. The determined value was then multiplied by 1.5 to evaluate the base metal toughness. In the case where the average value of the absorbed energies (vE_{-196}) of the three test pieces was 100 J or more, the sample was determined to have excellent base metal toughness. This is because brittle fracture may be included if the average absorbed energy is less than 100 J.

[0058] (3) Microstructure evaluation

KAM value

At each of positions of 1/4 and 1/2 of the thickness on a polished surface of a cross-section in the rolling direction of each steel plate after the hot rolling, electron backscatter diffraction (EBSD) analysis (measurement step: 0.3 μm) was performed for any two observation fields of 500 $\mu\text{m} \times 200 \mu\text{m}$ using scanning electron microscope (SEM) JSM-7001F produced by JEOL Ltd. From the analysis results, the average value of misorientations (orientation differences) between each pixel and its adjacent pixels within a crystal grain was calculated, and the average value of the calculated average values over the whole measurement region was taken to be the average KAM value.

[0059] Mn concentration of Mn-concentrated portion

Further, electron probe micro analyzer (EPMA) analysis was performed at each EBSD measurement position for the KAM value to determine the Mn concentration, and a portion having the highest Mn concentration was taken to be the concentrated portion.

[0060] Austenite area ratio

EBSD analysis (measurement step: 0.3 μm) was performed at each EBSD measurement position, and the austenite area ratio was measured from

the resultant phase map.

[0061] Percent brittle fracture

After performing the Charpy impact test at -196 °C, SEM observation (for 10 observation fields with 500 magnification) was performed, and the
5 percent brittle fracture was measured.

[0062] Surface roughness Ra

Each steel plate after the hot rolling was subjected to shot blasting treatment using a blast material having a Vickers hardness (HV) of 400 or more and a granularity of not less than ASTM E11 sieve No.12. For the
10 resultant steel plate surface, the reference length and the evaluation length were determined and the surface roughness Ra was measured in accordance with JIS B 0633. In the case where the surface roughness Ra was 200 μm or less, the sample was determined to have excellent surface characteristics.

These results are indicated in Table 3.

Steel No.	Chemical composition (mass%)															Remarks		
	C	Si	Mn	P	S	Al	Cr	O	N	Nb	Ti	Cu	V	Mo	W		Ca	Mg
1	0.230	0.66	32.2	0.020	0.0064	0.029	3.42	0.0040	0.0141	0.002	0.002	0.35	-	-	-	-	-	Example
2	0.423	0.45	33.3	0.022	0.0035	0.048	0.74	0.0035	0.0095	0.002	0.002	0.24	-	-	-	-	-	Example
3	0.531	0.12	24.3	0.018	0.0043	0.035	5.00	0.0027	0.0268	0.002	0.001	0.50	0.10	-	-	-	-	Example
4	0.334	0.55	33.5	0.026	0.0042	0.051	0.63	0.0033	0.0319	0.001	0.003	0.28	-	0.51	-	-	-	Example
5	0.456	0.30	31.5	0.025	0.0036	0.056	3.85	0.0016	0.0088	0.002	0.002	0.41	-	-	0.07	-	-	Example
6	0.185	0.96	35.0	0.014	0.0016	0.040	0.50	0.0023	0.0152	0.001	0.001	-	-	-	-	0.0021	-	Example
7	0.610	0.08	23.6	0.016	0.0024	0.047	3.56	0.0034	0.0156	0.003	0.003	0.13	-	-	-	-	0.0050	Example
8	0.411	0.35	28.9	0.026	0.0036	0.029	2.71	0.0041	0.0427	0.002	0.002	0.27	-	-	-	-	-	Example
9	0.513	0.31	32.4	0.019	0.0062	0.043	1.20	0.0025	0.0140	0.003	0.003	0.42	-	-	-	-	-	Example
10	0.612	0.45	20.0	0.024	0.0045	0.039	4.56	0.0021	0.0102	0.002	0.001	0.05	-	-	-	-	-	Example
11	0.704	0.85	34.1	0.023	0.0019	0.041	2.39	0.0022	0.0125	0.002	0.002	0.37	-	-	-	-	-	Comparative Example
12	0.165	0.04	21.6	0.020	0.0038	0.047	3.77	0.0027	0.0310	0.002	0.002	0.24	-	-	-	-	-	Comparative Example
13	0.184	0.45	35.4	0.024	0.0041	0.050	1.02	0.0044	0.0412	0.001	0.002	0.45	-	-	-	-	-	Comparative Example
14	0.346	0.60	27.0	0.033	0.0065	0.053	0.89	0.0040	0.0238	0.003	0.002	0.08	-	-	-	-	-	Comparative Example
15	0.378	0.36	22.6	0.018	0.0073	0.036	4.74	0.0025	0.0089	0.001	0.002	0.31	-	-	-	-	-	Comparative Example
16	0.353	0.35	33.1	0.014	0.0055	0.049	3.55	0.0029	0.0184	0.001	0.002	0.58	-	-	-	-	-	Comparative Example
17	0.634	0.62	20.7	0.025	0.0036	0.072	3.50	0.0037	0.0275	0.001	0.003	0.18	-	-	-	-	-	Comparative Example
18	0.175	0.71	32.3	0.016	0.0035	0.042	5.08	0.0028	0.0189	0.002	0.002	0.29	-	-	-	-	-	Comparative Example
19	0.610	0.48	30.1	0.022	0.0060	0.026	1.16	0.0052	0.0198	0.002	0.002	0.36	-	-	-	-	-	Comparative Example
20	0.554	0.75	24.9	0.020	0.0021	0.043	0.97	0.0030	0.0541	0.002	0.004	0.27	-	-	-	-	-	Comparative Example
21	0.096	0.31	21.5	0.022	0.0035	0.046	2.31	0.0019	0.0087	0.002	0.002	0.15	-	-	-	-	-	Comparative Example
22	0.574	1.04	34.7	0.029	0.0037	0.030	4.63	0.0035	0.0157	0.002	0.003	0.41	-	-	-	-	-	Comparative Example
23	0.733	0.64	21.8	0.019	0.0040	0.028	0.46	0.0033	0.0221	0.003	0.001	0.20	-	-	-	-	-	Comparative Example
24	0.650	0.25	22.8	0.025	0.0062	0.047	3.42	0.0018	0.0413	0.006	0.002	0.16	-	-	-	-	-	Comparative Example
25	0.106	0.47	23.4	0.013														

[0064]

[Table 2]

Sample No.	Steel No.	Thickness (mm)	First rolling conditions			Second rolling conditions			Cooling conditions		Number of times descaling is performed	Remarks
			Slab heating temperature (°C)	Rolling finish temperature (°C)	Total rolling reduction (%)	Reheating temperature (°C)	Rolling finish temperature (°C)	Total rolling reduction (%)	Cooling start temperature (°C)	Cooling rate from cooling start to 650°C (°C/s)		
1	1	20	1100	890	31	1100	773	69	737	7.0	1	Example
2	2	20	1100	903	35	1100	764	67	718	9.0	2	Example
3	3	25	1150	934	40	1150	805	58	763	10.0	1	Example
4	4	25	1150	882	42	1150	794	57	738	9.0	1	Example
5	5	30	1200	951	39	1200	855	53	827	11.0	3	Example
6	6	30	1200	947	43	1200	834	50	815	10.0	1	Example
7	7	15	1170	912	55	1170	803	70	750	13.0	2	Example
8	8	15	1170	919	51	1170	784	73	721	10.0	3	Example
9	9	6	1250	1020	53	1250	921	95	921	2.0	2	Example
10	10	10	1250	1012	43	1250	746	84	697	8.0	1	Example
11	1	30	1300	1104	20	-	806	57	775	15.0	2	Example
12	2	30	1300	805	60	-	-	-	759	14.0	2	Example
13	11	13	1160	870	47	1160	780	80	741	7.0	3	Comparative Example
14	12	13	1160	883	44	1160	800	82	746	11.0	2	Comparative Example
15	13	17	1210	962	39	1210	851	69	813	10.0	1	Comparative Example
16	14	17	1210	951	35	1210	832	71	795	12.0	3	Comparative Example
17	15	23	1130	939	23	1130	736	65	671	5.0	1	Comparative Example
18	16	15	1200	977	36	1200	864	77	830	15.0	1	Comparative Example
19	17	23	1130	907	38	1130	745	63	683	3.0	2	Comparative Example
20	18	25	1170	903	48	1170	790	56	761	7.0	1	Comparative Example
21	19	27	1150	920	26	1150	796	59	752	6.0	1	Comparative Example
22	20	27	1150	932	23	1150	787	60	737	11.0	3	Comparative Example
23	21	20	1200	948	40	1200	833	65	786	5.0	3	Comparative Example
24	22	20	1200	934	36	1200	840	66	802	13.0	1	Comparative Example
25	23	25	1170	908	46	1170	776	57	734	8.0	1	Comparative Example

*Total rolling reduction = rolling reduction calculated from thicknesses at entry and delivery of each of first and second hot rollings

[Table 2](cont'd)

Sample No.	Steel No.	Thickness (mm)	First rolling conditions			Second rolling conditions				Cooling conditions		Number of times descaling is performed	Remarks
			Slab heating temperature (°C)	Rolling finish temperature (°C)	Total rolling reduction (%)	Reheating temperature (°C)	Rolling finish temperature (°C)	Total rolling reduction (%)	Cooling start temperature (°C)	Cooling rate from cooling start to 650°C (°C/s)			
26	<u>24</u>	10	1270	1035	26	1270	738	87	655	4.0	2	Comparative Example	
27	<u>25</u>	10	1270	1046	24	1270	742	90	665	10.0	2	Comparative Example	
28	1	30	1100	841	30	1100	<u>693</u>	60	657	7.0	1	Comparative Example	
29	2	15	1100	886	<u>18</u>	1100	741	55	714	14.0	1	Comparative Example	
30	3	30	1200	924	<u>10</u>	1200	776	51	685	<u>0.5</u>	2	Comparative Example	
31	4	30	1150	<u>757</u>	31	1150	751	55	674	7.0	1	Comparative Example	
32	5	25	<u>1080</u>	915	21	1150	786	57	<u>677</u>	3.0	3	Comparative Example	
33	6	25	<u>1090</u>	830	25	1150	832	63	795	5.0	1	Comparative Example	
34	7	30	1250	1036	21	<u>1050</u>	735	53	662	12.0	2	Comparative Example	
35	8	20	1250	995	38	1300	<u>957</u>	66	928	6.0	2	Comparative Example	
36	9	30	1300	<u>706</u>	78	-	-	-	655	15.0	2	Comparative Example	
37	1	30	1200	951	<u>18</u>	1200	844	51	801	12.0	0	Comparative Example	
38	2	15	<u>1080</u>	931	22	1200	836	45	783	10.0	1	Comparative Example	
39	<u>26</u>	30	1100	850	33	1100	741	51	713	5.0	2	Comparative Example	
40	<u>27</u>	17	1100	903	25	1100	750	83	709	10.0	2	Comparative Example	
41	7	15	1120	938	41	1120	763	70	<u>660</u>	7.0	1	Comparative Example	
42	10	13	1140	956	37	1140	781	77	725	<u>0.5</u>	1	Comparative Example	
43	28	30	1150	954	39	1150	840	56	803	7.0	1	Example	
44	29	25	1200	931	41	1200	828	60	781	9.0	2	Example	
45	30	20	1250	915	45	1250	885	63	839	11.0	3	Example	
46	<u>31</u>	15	1200	906	37	1200	794	72	737	12.0	1	Comparative Example	
47	<u>32</u>	6	1100	870	54	1100	780	92	780	1.0	2	Comparative Example	
48	<u>33</u>	15	1170	902	25	1170	801	77	742	8.0	3	Comparative Example	
49	<u>34</u>	12	1100	894	49	1100	773	81	697	10.0	2	Comparative Example	
50	<u>35</u>	6	1120	887	51	1120	764	90	764	1.0	1	Comparative Example	

*Total rolling reduction = rolling reduction calculated from thicknesses at entry and delivery of each of first and second hot rollings

[0065]

[Table 3]

Sample No.	Steel No.	Microstructure				Mechanical properties					Remarks
		Austenite phase area ratio (%)	Average KAM value	Mn concentration of Mn-concentrated portion (mass %)	Surface roughness Ra (μm)	Yield stress (MPa)	Tensile strength (MPa)	Total elongation (%)	Absorbed energy at -196°C (vE _{-196°C}) (J)	Percent brittle fracture (%)	
1	1	100	1.1	35.4	117	430	838	65	127	0	Example
2	2	100	1.1	36.1	69	461	813	62	119	0	Example
3	3	100	0.9	28.6	160	443	878	61	120	0	Example
4	4	100	1.0	36.1	61	428	806	62	112	0	Example
5	5	100	0.7	34.7	99	425	828	63	136	0	Example
6	6	100	0.8	38.0	200	435	767	59	105	0	Example
7	7	100	0.9	27.1	109	463	934	56	109	0	Example
8	8	100	1.0	31.2	101	422	841	63	116	0	Example
9	9	100	0.3	35.5	151	453	836	64	117*	0	Example
10	10	100	1.3	25.6	146	429	976	56	103	0	Example
11	1	100	0.9	35.8	112	421	846	67	125	0	Example
12	2	100	0.7	36.3	156	444	797	63	125	0	Example
13	<u>11</u>	100	1.1	36.9	123	506	807	54	<u>90</u>	<u>11</u>	Comparative Example
14	<u>12</u>	100	0.9	24.5	121	<u>374</u>	802	68	109	0	Comparative Example
15	<u>13</u>	100	0.7	<u>38.2</u>	205	407	774	56	<u>63</u>	<u>32</u>	Comparative Example
16	<u>14</u>	100	0.8	29.8	70	435	884	53	<u>86</u>	<u>14</u>	Comparative Example
17	<u>15</u>	100	1.4	25.4	143	423	880	53	<u>89</u>	<u>13</u>	Comparative Example
18	<u>16</u>	100	0.7	37.1	212	450	868	60	114	0	Comparative Example
19	<u>17</u>	100	1.3	24.0	98	474	950	51	<u>90</u>	<u>12</u>	Comparative Example
20	<u>18</u>	100	1.0	35.7	208	405	802	48	105	0	Comparative Example
21	<u>19</u>	100	1.0	32.5	99	455	839	50	<u>83</u>	<u>13</u>	Comparative Example
22	<u>20</u>	100	1.1	28.3	64	525	767	44	<u>74</u>	<u>15</u>	Comparative Example
23	<u>21</u>	95	0.7	25.1	45	<u>366</u>	783	66	113	0	Comparative Example
24	<u>22</u>	100	0.6	37.3	190	518	794	47	<u>87</u>	<u>13</u>	Comparative Example
25	<u>23</u>	100	1.1	25.1	81	436	813	52	<u>91</u>	<u>11</u>	Comparative Example

* value obtained by multiplying absorbed energy in 5mm subsize test piece by 1.5

[Table 3](cont'd)

Sample No.	Steel No.	Microstructure				Mechanical properties					Remarks
		Austenite phase area ratio (%)	Average KAM value	Mn concentration of Mn-concentrated portion (mass%)	Surface roughness Ra (μm)	Yield stress (MPa)	Tensile strength (MPa)	Total elongation (%)	Absorbed energy at -196°C (√E _{-196°C}) (J)	Percent brittle fracture (%)	
26	<u>24</u>	100	1.5	26.4	113	458	752	54	<u>96</u>	<u>11</u>	Comparative Example
27	<u>25</u>	100	1.4	27.8	106	418	764	52	<u>90</u>	<u>11</u>	Comparative Example
28	1	100	1.6	36.1	163	483	808	49	<u>87</u>	<u>13</u>	Comparative Example
29	2	100	1.5	<u>38.4</u>	207	475	776	51	<u>60</u>	<u>35</u>	Comparative Example
30	3	100	1.5	<u>38.1</u>	181	434	800	42	<u>86</u>	<u>13</u>	Comparative Example
31	4	100	1.5	<u>38.7</u>	210	440	741	43	<u>55</u>	<u>40</u>	Comparative Example
32	5	100	1.0	<u>38.3</u>	150	465	772	45	<u>73</u>	<u>17</u>	Comparative Example
33	6	100	0.7	<u>39.2</u>	209	451	753	48	<u>53</u>	<u>49</u>	Comparative Example
34	7	100	1.5	27.4	121	480	905	52	<u>93</u>	<u>11</u>	Comparative Example
35	8	100	<u>0.2</u>	31.4	106	<u>376</u>	793	65	121	0	Comparative Example
36	9	100	1.7	36.3	103	558	795	43	<u>80</u>	<u>14</u>	Comparative Example
37	1	100	0.8	<u>38.5</u>	224	424	981	58	<u>76</u>	<u>15</u>	Comparative Example
38	2	100	0.5	<u>38.4</u>	207	456	819	55	<u>79</u>	<u>14</u>	Comparative Example
39	<u>26</u>	90	0.8	22.3	65	422	936	63	<u>78</u>	<u>15</u>	Comparative Example
40	<u>27</u>	95	1.3	23.0	108	404	946	57	<u>95</u>	<u>11</u>	Comparative Example
41	7	100	1.1	26.8	150	471	928	55	<u>89</u>	<u>12</u>	Comparative Example
42	10	100	1.2	25.3	73	435	970	55	<u>85</u>	<u>13</u>	Comparative Example
43	28	100	0.7	27.5	178	444	870	65	125	0	Example
44	29	100	0.9	37.7	136	458	833	61	135	0	Example
45	30	100	0.5	30.5	111	432	856	63	116	0	Example
46	<u>31</u>	100	1.3	25.3	175	510	931	52	<u>88</u>	<u>13</u>	Comparative Example
47	<u>32</u>	100	1.5	23.9	101	483	906	54	<u>95*</u>	<u>11</u>	Comparative Example
48	<u>33</u>	90	1.3	23.1	75	451	854	57	<u>81</u>	<u>14</u>	Comparative Example
49	<u>34</u>	100	1.4	35.4	87	505	891	55	<u>92</u>	<u>12</u>	Comparative Example
50	<u>35</u>	100	1.5	24.0	180	478	879	56	<u>98*</u>	<u>11</u>	Comparative Example

* value obtained by multiplying absorbed energy in 5mm subsize test piece by 1.5

[0066] Each high-Mn steel according to the present disclosure satisfied the foregoing target performance (i.e. the yield stress of base metal is 400 MPa or more, the low-temperature toughness is 100 J or more in average absorbed energy (vE₁₉₆), the percent brittle fracture is less than 10 %, and the surface roughness Ra is 200 μm or less). Each Comparative Example outside the range according to the present disclosure failed to satisfy the target performance in at least one of the yield stress, the low-temperature toughness, and the surface roughness.

CLAIMS

1. A high-Mn steel comprising:
a chemical composition containing, in mass%,
5 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,
10 Al: 0.010 % or more and 0.070 % or less,
Cr: 0.50 % or more and 5.00 % or less,
N: 0.0050 % or more and 0.0500 % or less,
O: 0.0050 % or less,
Ti: 0.005 % or less, and
15 Nb: 0.005 % or less,
with a balance consisting of Fe and inevitable impurities; and
a microstructure having austenite as a matrix,
wherein in the microstructure, a Mn concentration of a
Mn-concentrated portion is 38.0 % or less, and an average of Kernel Average
20 Misorientation value is 0.3 or more,
yield stress is 400 MPa or more,
absorbed energy vE_{-196} in a Charpy impact test at -196 °C is 100 J or
more, and
percent brittle fracture is less than 10 %.

25

2. The high-Mn steel according to claim 1, wherein the chemical
composition further contains, in mass%, one or more selected from

Cu: 0.01 % or more and 0.50 % or less,
Mo: 2.00 % or less,
30 V: 2.00 % or less, and
W: 2.00 % or less.

3. The high-Mn steel according to claim 1 or 2, wherein the
chemical composition further contains, in mass%, one or more selected from

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.

5 4. A method of producing a high-Mn steel, the method comprising:

 heating a steel raw material having the chemical composition according to any one of claims 1 to 3 to a temperature range of 1100 °C or more and 1300 °C or less; and

10 thereafter subjecting the steel raw material to hot rolling with a rolling finish temperature of 800 °C or more and a total rolling reduction of 20 % or more, and performing descaling treatment in the hot rolling.

 5. A method of producing a high-Mn steel, the method
15 comprising:

 heating a steel raw material having the chemical composition according to any one of claims 1 to 3 to a temperature range of 1100 °C or more and 1300 °C or less;

 thereafter subjecting the steel raw material to first hot rolling with a
20 rolling finish temperature of 1100 °C or more and a total rolling reduction of 20 % or more; and

 thereafter subjecting to second hot rolling with a rolling finish temperature of 700 °C or more and less than 950 °C, and performing descaling treatment in the second hot rolling.

25

 6. A method of producing a high-Mn steel, the method comprising:

 heating a steel raw material having the chemical composition according to any one of claims 1 to 3 to a temperature range of 1100 °C or
30 more and 1300 °C or less;

 thereafter subjecting the steel raw material to first hot rolling with a rolling finish temperature of 800 °C or more and less than 1100 °C and a total rolling reduction of 20 % or more;

 thereafter reheating to 1100 °C or more and 1300 °C or less; and

thereafter subjecting to second hot rolling with a rolling finish temperature of 700 °C or more and less than 950 °C, and performing descaling treatment in the second hot rolling.

5 7. The method of producing a high-Mn steel according to claim 5 or 6, wherein descaling treatment is performed in the first hot rolling.

8. The method of producing a high-Mn steel according to any one of claims 4 to 7, comprising

10 performing cooling treatment, after final hot rolling, at an average cooling rate of 1.0 °C/s or higher in a temperature range from a temperature of or higher than 100 °C below the rolling finish temperature to a temperature of 300 °C or more and 650 °C or less.