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(54) **STEEL SHEET AND MANUFACTURING METHOD THEREOF**

(57) The present invention relates to a steel sheet and a manufacturing method thereof and, more specifically, to a steel sheet having excellent resistance to the

initiation of ultra-low temperature brittle cracking and a manufacturing method thereof.

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**Description**

## Technical Field

- 5 **[0001]** The present disclosure relates to a steel sheet and a manufacturing method thereof, and more particularly, a steel sheet having excellent resistance to cryogenic brittle crack initiation and a manufacturing method thereof.

## Background Art

- 10 **[0002]** Recently, with the strengthening of environmental regulations, demand for liquefied gas (LNG), an eco-friendly fuel, has increased, and accordingly, the construction of LNG carriers and LNG propulsion vessels using LNG as fuel has increased. In the case of LNG and LNG/ethane, high-Ni steel having a high Ni content may generally be used due to an extremely low liquefaction temperature thereof. To reduce construction costs of vessels transporting LPG, liquefied gases having a liquefaction temperature of -60°C or lower, such as ammonia or CO<sub>2</sub>, carbon steel  
15 having enhanced cryogenic toughness has increasingly been used.

- [0003]** As for an existing LNG carrier tank, a large, non-pressurized Type A tank design may not be primarily used, such that there has been no demand for high-strength steel or a thick material. However, a CO<sub>2</sub> tank and ammonia fuel tanks, which require high pressure, may be designed as Type C and may require high-strength steel and a thick material. Also, when building a Type C tank, due to the mandatory application of post weld heat treatment (PWHT) required by the IGC code, it may be necessary to guarantee the properties of a steel material before and after PWHT.

- 20 **[0004]** Since post-welding heat treatment (PWHT) is a high-temperature heat treatment, strength may degrade after PWHT, and required strength may not be reached. To overcome this, when using precipitation strengthening elements, there may be a problem of reduced impact toughness, such that it may be difficult to simultaneously guarantee strength and toughness before and after PWHT.

- 25 **[0005]** Also, to maximize efficiency when liquefied gas is transported, the size of a tank may need to be enlarged. In this case, an ultra-large heat treatment furnace may need to be constructed to perform PWHT heat treatment after tank construction is complete.

**[0006]** However, in the case above, significant costs may be incurred.

- 30 **[0007]** Meanwhile, instead of a large furnace, PWHT heat treatment may be performed by attaching a heat treatment pad to a welded zone. However, attaching a heat treatment pad to a large tank and performing long-term heat treatment may require significant costs and time. Accordingly, shipbuilders may seek exemptions from PWHT heat treatment when possible.

- [0008]** To be exempt from PWHT heat treatment for a Type C tank, an engineering critical assessment (ECA) may need to be conducted to demonstrate that there are no design issues without stress relief through heat treatment. The welded zone crack tip opening displacement (CTOD) value of a steel material for tank used in determining whether an ECA may be used for assurance may be the most critical factor, and as for a steel material for liquefied CO<sub>2</sub>, the CTOD value in the coarse grained heat-affected zone (CGHAZ) at -55°C, the design temperature, may need to be guaranteed.

- 35 **[0009]** However, since there is almost no history of development of carbon steel which guarantees CTOD properties at such extremely low temperatures, the development of a steel material maximizing toughness through optimization of a microstructure and an alloy composition may be essential.

## Detailed description of present disclosure

- 45 Technical problems to solve

**[0010]** An embodiment of the present disclosure is to provide a steel sheet and a manufacturing method thereof.

**[0011]** An embodiment of the present disclosure is to provide a steel sheet having excellent resistance to cryogenic brittle crack initiation and a manufacturing method thereof.

- 50 **[0012]** The subject matter of the present disclosure is not limited to the above-described content. Those skilled in the art will have no difficulty understanding the additional subject matter of the present disclosure from the overall content of this specification.

## Solution to Problem

- 55 **[0013]** According to an embodiment of the present disclosure, a steel sheet includes by weight%, C: 0.060 to 0.080%, Mn: 1.40 to 1.60%, Si: 0.10 to 0.20%, Al: 0.01 to 0.04%, Ni: 0.30 to 0.50%, Ti: 0.008 to 0.016%, Nb: 0.010 to 0.025%, P: 0.008% or less, S: 0.002% or less, and a balance of Fe and inevitable impurities,

**[0014]** wherein, in a weld heat-affected zone, welded with a heat input of 1.5 kJ/mm, a microstructure in a region of fusion line (FL) to FL+0.2 mm includes an MA phase of 5.0% or less by area%.

**[0015]** The steel sheet has an R value of 0.38 or less, defined in relational expression 1 below:

$$R = [C] + [Mn]/6 + [Cu]/15 + [Ni]/15 + [Cr]/5 + [Mo]/5 + [V]/5 \quad [\text{Relational expression 1}]$$

where [C], [Mn], [Cu], [Ni], [Cr], [Mo] and [V] are weight% of each element.

**[0016]** In the weld heat-affected zone, an effective grain size at a center of a thickness of fusion line (FL) to FL+0.2 mm region is 100 μm or less.

**[0017]** The steel sheet has a yield strength of 355 MPa or more and an impact toughness of 100 J or more at -80°C.

**[0018]** The steel sheet has a full-thickness crack tip opening displacement (CTOD) value of 0.20 mm or more at -60°C in a coarse grained heat affected zone (CGHAZ).

**[0019]** According to an embodiment of the present disclosure, a method of manufacturing a steel sheet includes heating a steel slab including, by weight%, C: 0.060 to 0.080%, Mn: 1.40 to 1.60%, Si: 0.10 to 0.20%, Al: 0.01 to 0.04%, Ni: 0.30 to 0.50%, Ti: 0.008 to 0.016%, Nb: 0.010 to 0.025%, P: 0.008% or less, S: 0.002% or less, and a balance of Fe and inevitable impurities;

rough-rolling the heated steel slab;

finishing hot-rolling the rough-rolled steel sheet; and

cooling the finishing hot-rolled steel sheet to a temperature range of 400 to 700°C at a cooling rate of 10°C/s or higher with reference to a 1/4 point in a direction of a center of a thickness from a surface.

**[0020]** The steel sheet has an R value of 0.38 or less, defined in relational expression 1 below:

$$R = [C] + [Mn]/6 + [Cu]/15 + [Ni]/15 + [Cr]/5 + [Mo]/5 + [V]/5 \quad [\text{Relational expression 1}]$$

where [C], [Mn], [Cu], [Ni], [Cr], [Mo] and [V] are weight% of each element.

**[0021]** The heating is performed at a temperature range of 1050 to 1160°C,

the rough-rolling is performed at a temperature range of 900°C or higher with a cumulative reduction ratio of 40% or more, and

the finishing hot-rolling is performed at a temperature range of 800°C or higher with a cumulative reduction ratio of 50% or more.

## Advantageous Effects of Invention

**[0022]** According to an embodiment of the present disclosure, a steel sheet and a manufacturing method thereof may be provided.

**[0023]** According to an embodiment of the present disclosure, a steel sheet having excellent resistance to cryogenic brittle crack initiation and a manufacturing method thereof may be provided.

**[0024]** According to an embodiment of the present disclosure, a steel sheet having excellent strength and toughness, and excellent resistance to brittle crack initiation at cryogenic temperature, and thus applicable to various fields such as a liquefied gas tank, a ship hull, and a structure in cryogenic environment, and a manufacturing method thereof may be provided.

**[0025]** The various beneficial advantages and effects of the present disclosure are not limited to the above-described contents, and will be more easily understood in the process of describing the specific embodiments of the present disclosure.

## Best Mode for Invention

**[0026]** Preferred embodiments of the present disclosure will be described below. The embodiments of the present disclosure may be modified in various manners, and the scope of the present disclosure should not be construed as limited to the embodiments described below. The embodiments are provided to further describe the present disclosure to those skilled in the art.

**[0027]** The present disclosure will be described in detail below.

**[0028]** The steel composition of the present disclosure will be described in detail below.

**[0029]** Unless otherwise indicated in the present disclosure, the percentages, %, indicating the content of each element, are based on weight.

**[0030]** The steel sheet according to an embodiment of the present disclosure may include, by weight%, C: 0.060 to 0.080%, Mn: 1.40 to 1.60%, Si: 0.10 to 0.20%, Al: 0.01 to 0.04%, Ni: 0.30 to 0.50%, Ti: 0.008 to 0.016%, Nb: 0.010 to 0.025%, P: 0.008% or less, S: 0.002% or less, and a balance of Fe and inevitable impurities, and in a weld heat-affected zone, welded with a heat input of 1.5 kJ/mm, a microstructure of a region of fusion line (FL) to FL+0.2 mm includes an MA phase of 5.0% or less by area%.

Carbon (C): 0.060 to 0.080%

**[0031]** Carbon (C) may be the most important element for ensuring basic strength of a weld heat-affected zone. Thus, it may be necessary to include carbon (C) in an appropriate range in steel. When the carbon (C) content exceeds 0.080%, martensite-austenite (MA), a coarse secondary phase, may be formed, and toughness may be reduced. When the carbon content is below 0.060%, strength may decrease.

Manganese (Mn): 1.40 to 1.60%

**[0032]** Manganese (Mn) may be a useful element enhancing strength through solid solution strengthening and enhancing hardenability by forming a low-temperature transformation phase. Thus, to ensure the properties targeted in the present disclosure, 1.40% or more of Manganese (Mn) may be included. According to an embodiment of the present disclosure, 1.41% or more may be included. However, when the manganese (Mn) content exceeds 1.60%, hardenability may excessively increase, such that coarse bainite may be formed in a base material, and toughness may be significantly reduced. According to an embodiment of the present disclosure, 1.59% or less of manganese (Mn) may be included.

Silicon (Si): 0.10 to 0.20%

**[0033]** Silicon (Si) may be an essential alloying element for deoxidation by precipitating dissolved oxygen in molten steel in the form of slag during steelmaking and casting processes. When manufacturing a steel material using a converter, 0.10% or more of silicon (Si) may be included. When included in a large amount, Si, Al composite oxides may be coarsely formed, or the large amount of an MA phase, a hard phase, may be formed in the microstructure of the weld heat-affected zone. Thus, an upper limit of the silicon (Si) content may be limited to 0.20%.

Aluminum (Al): 0.01 to 0.04%

**[0034]** Aluminum (Al) may be an essential alloying element for deoxidation by precipitating dissolved oxygen in molten steel in the form of slag during steelmaking and casting processes. When manufacturing a steel material using a converter, 0.01% or more of aluminum (Al) may be included. When the large amount of aluminum (Al) is included, Si, Al composite oxides may be coarsely formed, or the large amount of an MA phase, a hard phase, may be formed in the microstructure of the weld heat-affected zone. Thus, an upper limit for aluminum (Al) content may be limited to 0.04%.

Nickel (Ni): 0.30 to 0.50%

**[0035]** Nickel (Ni) may be an important element facilitating dislocation cross-slip at low temperature, thereby enhancing impact toughness and enhancing hardenability. To improve low-temperature impact toughness of a base material, nickel (Ni) may be included at 0.30% or more. However, when the content exceeds 0.50%, hardenability may be excessively increased, such that the large amount of bainite may be formed, and toughness may be reduced. Manufacturing costs may also increase.

Titanium (Ti): 0.008 to 0.016%

**[0036]** Titanium (Ti) precipitates as TiN during reheating, and may inhibit grain growth in the weld heat-affected zone, thereby significantly improving low-temperature toughness. Thus, to effectively precipitate TiN, titanium (Ti) may be included at 0.008% or more. However, when the content exceeds 0.016%, the issues such as clogging of the playing nozzle or reduction in low-temperature toughness due to central crystallization may occur, and also the Ti/N ratio may be decreased, such that TiN precipitates may become coarse, and resistance to brittle crack initiation may be lowered.

Niobium (Nb): 0.010 to 0.025%

**[0037]** Niobium (Nb) may precipitate as NbC or NbCN, and may enhance strength. Also, dissolved Nb during high-temperature reheating may precipitate relatively finely in the form of NbC during rolling, thereby inhibiting austenite recrystallization. Accordingly, the niobium (Nb) content may be 0.010% or more. When niobium (Nb) is added excessively, brittle cracks may be created at the edges of the steel material, and the large amount of an MA phase, a hard phase, may be formed in the microstructure of the weld heat-affected zone, such that resistance to brittle crack initiation may be reduced. According to an embodiment of the present disclosure, the content may be 0.025% or less.

Phosphorus (P): 0.008% or less

**[0038]** Phosphorus (P) may cause grain boundary embrittlement or may form coarse inclusions, thereby inducing embrittlement. To improve resistance to brittle crack initiation, the content thereof may be controlled to be 0.008% or less.

Sulfur (S): 0.002% or less

**[0039]** Sulfur (S) may cause grain boundary embrittlement or may form coarse inclusions, thereby inducing embrittlement. To improve resistance to brittle crack initiation, the content thereof may be controlled to be 0.002% or less.

**[0040]** The steel material in the present disclosure may include iron (Fe) and inevitable impurities in addition to the composition described above. Inevitable impurities may be unintentionally included during a general manufacturing process and may thus not be excluded. These impurities may be readily apparent to a person skilled in the art of steel manufacturing, and thus, the description thereof is not provided in this specification.

**[0041]** The steel sheet according to an embodiment of the present disclosure may contain Cu, Cr, and Ni as impurities, but these elements may not be intentionally added.

**[0042]** The steel sheet according to an embodiment of the present disclosure may have an R value of 0.38 or less, defined by relational expression 1 as below:

$$R = [C] + [Mn]/6 + [Cu]/15 + [Ni]/15 + [Cr]/5 + [Mo]/5 + [V]/5 \quad [\text{Relational expression 1}]$$

(In the relational expression, [C], [Mn], [Cu], [Ni], [Cr], [Mo], and [V] may represent the weight% of each element.)

**[0043]** When the R value defined in the relational expression 1 exceeds 0.38, there may be a concern that the target impact energy may not be sufficiently ensured. According to an embodiment of the present disclosure, the value may be 0.37 or less. According to an embodiment of the present disclosure, the value may be 0.36 or less. Meanwhile, a lower limit of the R value of relational expression 1 is not particularly limited, but to appropriately ensure strength and impact energy, the value may be 0.31 or more according to an embodiment of the present disclosure. According to an embodiment of the present disclosure, the value may be 0.32 or more.

**[0044]** In the description below, the steel microstructure of the present disclosure will be described in detail.

**[0045]** Unless otherwise indicated in the present disclosure, %, percentages, indicating fractions of the microstructure may be based on area.

**[0046]** The microstructure of the steel sheet according to an embodiment of the present disclosure may include one or more of ferrite, acicular ferrite, and pearlite as the main phase. As acicular ferrite and pearlite are not easily distinguishable, a mixture of these phases may be included according to an embodiment of the present disclosure. According to an embodiment of the present disclosure, the main phase may be 70% or more by area%. According to an embodiment of the present disclosure, the main phase may be 80% or more by area%.

**[0047]** In the steel sheet according to an embodiment of the present disclosure, in the weld heat-affected zone, welded with a heat input of 1.5 kJ/mm, the MA phase may be 5.0% or less by area% in the microstructure of the fusion line (FL) to FL+0.2 mm region.

**[0048]** In the present disclosure, to improve resistance to brittle crack initiation, the microstructure fraction in the FL to FL+0.2mm region may be limited to a more stringent range. In other words, the FL to FL+0.2mm region in the weld heat-affected zone may be closest to the FL and may have the weakest CTOD properties, and the MA phase may be formed in the region. The MA phase may act as a brittle crack initiation point, thereby deteriorating resistance to brittle crack initiation.

**[0049]** Meanwhile, during welding, as the heat input decreased, a cooling rate may increase. Accordingly, the MA phase may be easily formed in the weld heat-affected zone, and the CTOD properties of the weld heat-affected zone may be weakened. As the heat input decreases in the weld heat-affected zone, the cooling rate may increase, which may weaken physical properties.

**[0050]** Accordingly, the steel sheet according to an embodiment of the present disclosure may control the MA phase

fraction to a level of 5.0% or less even in the weld heat-affected zone welded with a low heat input of 1.5 kJ/mm, thereby ensuring the targeted CTOD properties.

[0051] Meanwhile, as the remaining structure excluding the MA phase in the weld heat-affected zone, one or more of upper bainite and granular bainite may be included. According to an embodiment of the present disclosure, one or more of upper bainite and granular bainite may be 90.0% or more.

[0052] According to an embodiment of the present disclosure, the microstructure may be measured at a center of a thickness of the steel sheet. According to an embodiment of the present disclosure, the center of the thickness may be a half-point in the thickness direction of the steel sheet.

[0053] According to an embodiment of the present disclosure, in the steel sheet, in the weld heat-affected zone welded with a heat input of 1.5 kJ/mm, an effective grain size at the center of the thickness of the fusion line (FL) to FL+0.2 mm region may be 100  $\mu\text{m}$  or less.

[0054] The effective grain size according to an embodiment of the present disclosure may indicate an average value.

[0055] In the present disclosure, when the effective grain size in the center of the thickness of the FL to FL+0.2mm region is excessively coarse, the formation of low-temperature transformation phases such as bainite may be facilitated due to increased hardenability, such that toughness of the weld heat-affected zone may be degraded and resistance to brittle crack initiation may be reduced. Accordingly, in the present disclosure, the grain size may be limited to 100  $\mu\text{m}$  or less. According to an embodiment of the present disclosure, the size may be 95  $\mu\text{m}$  or less.

[0056] Meanwhile, as described above, according to an embodiment of the present disclosure, by strictly controlling the alloying element content, target properties may be ensured even under stringent welding conditions. That is, according to an embodiment of the present disclosure, the effective grain size in the FL to FL+0.2mm region may be 100  $\mu\text{m}$  or less.

[0057] In particular, in the weld heat-affected zone, as the distance to the fusion line (FL) reduces, the effective grain size may become coarse. Thus, by limiting the effective grain size in the FL to FL+0.2mm region, which is closest to the FL, target properties may be effectively ensured.

[0058] Also, as described above, as the heat input decreases, the cooling rate may increase, which may degrade the properties of the weld heat-affected zone. However, according to an embodiment of the present disclosure, even in a weld heat-affected zone welded with a low heat input of 1.5 kJ/mm, the effective grain size may be 100  $\mu\text{m}$  or less.

[0059] The steel sheet according to an embodiment of the present disclosure may have a yield strength of 355 MPa or more, an impact toughness of 100 J or more at -80°C, and a full-thickness crack tip opening displacement (CTOD) of 0.20 mm or more at -60°C in accordance with ISO 12135.

[0060] In the description below, a method of manufacturing steel according to the present disclosure will be described in detail.

[0061] The steel sheet according to an embodiment of the present disclosure may be manufactured by heating, rough-rolling, finishing, hot-rolling, and cooling a steel slab satisfying the alloy composition described above.

[Heating]

[0062] The steel slab satisfying the alloy composition described in the present disclosure may be heated at a temperature ranging from 1050 to 1160°C.

[0063] The heating temperature may be 1050°C or higher such that carbonitrides of Ti and/or Nb formed during casting may be dissolved and may be finely precipitated during subsequent rolling or PWHT. According to an embodiment of the present disclosure, to sufficiently dissolve carbonitrides of Ti and/or Nb, heating to 1100°C or higher may be performed. However, heating to an excessively high temperature may cause coarsening of austenite, and thus, the heating temperature may be limited to 1160°C or lower.

[Rough-rolling]

[0064] The heated steel slab may be rough-rolled at a temperature range of 900°C or higher.

[0065] Rough-rolling according to an embodiment of the present disclosure may be performed to adjust the shape of the reheated steel slab.

[0066] During the rough-rolling process, the temperature may be determined to be the temperature at which austenite recrystallization ceases, ( $T_{nr}$ ) or higher. According to an embodiment of the present disclosure, the temperature may be 900°C or higher. By the rough-rolling process, the effect of reducing the grain size may be obtained through recrystallization of coarse austenite along with destruction of cast structures, such as dendrites formed during casting.

[0067] According to an embodiment of the present disclosure, to induce sufficient recrystallization and refine the structure, the total cumulative reduction ratio may be controlled to be 40% or more during rough-rolling.

[Finishing hot-rolling]

**[0068]** The rough-rolled steel sheet may be finished hot-rolled at a temperature of 800°C or higher.

**[0069]** Finishing hot-rolling according to an embodiment of the present disclosure may be performed to introduce a nonuniform microstructure into the austenitic structure of the rough-rolled steel sheet. To maximize the strain in the structure, finishing hot-rolling may be performed at a temperature of 800°C or higher. When the finishing hot-rolling temperature is lower than 800°C, the ferrite grain size may not be uniform due to abnormal rolling, and coarse ferrite may be formed.

**[0070]** According to an embodiment of the present disclosure, to maximize the formation of a finer structure, the cumulative reduction ratio may be controlled to be 50% or more during finishing rolling.

[Cooling]

**[0071]** The hot-rolled steel sheet may be cooled from the surface toward the center of the thickness to a temperature range of 400 to 700°C at a cooling rate of 10°C/s or higher.

**[0072]** When the cooling rate is less than 10°C/s, it may be difficult to ensure the properties targeted in the present disclosure. An upper limit of the cooling rate is not specifically defined, but according to an embodiment of the present disclosure, the upper limit of the cooling rate may be 100°C/s.

**[0073]** When the cooling end temperature is lower than 400°C, a large amount of hard phase may be generated, which may reduce impact toughness of the base material. When the temperature exceeds 700°C, a microstructure based on coarse ferrite and pearlite may be formed, which may reduce strength. Mode for Invention

**[0074]** The present disclosure is described in greater detail below through embodiments. However, it should be noted that the embodiments below are intended only to illustrate and describe the present disclosure in greater detail and are not intended to limit the scope of the present disclosure.

(Embodiment)

**[0075]** A steel slab having a thickness of 300 mm and the composition as in Table 1 below was heated to a temperature of 1128 to 1145°C, went through rough rolling continuously at a cumulative reduction ratio of 40% or more, and the rough rolling was finished at 950°C or higher. Thereafter, finishing hot-rolling was performed at 820 to 835°C with a cumulative reduction ratio of 50% or more, a steel sheet having a thickness of 50 mm was manufactured, and cooling was performed from the surface to 522 to 543°C at a cooling rate of 10 to 12°C/s, with reference to a 1/4 point in the direction of the center of the thickness.

[Table 1]

| Steel type         | Alloy composition (wt%) |      |      |      |      |       |       |    |    | Relational expression1 |
|--------------------|-------------------------|------|------|------|------|-------|-------|----|----|------------------------|
|                    | C                       | Mn   | Si   | Al   | Ni   | Nb    | Ti    | P* | S* | R                      |
| A                  | 0.071                   | 1.47 | 0.15 | 0.02 | 0.46 | 0.018 | 0.014 | 38 | 10 | 0.35                   |
| B                  | 0.064                   | 1.51 | 0.17 | 0.03 | 0.37 | 0.022 | 0.016 | 41 | 12 | 0.34                   |
| C                  | 0.076                   | 1.42 | 0.12 | 0.03 | 0.42 | 0.017 | 0.013 | 51 | 8  | 0.34                   |
| D                  | 0.069                   | 1.53 | 0.11 | 0.02 | 0.49 | 0.019 | 0.012 | 48 | 12 | 0.36                   |
| E                  | 0.093                   | 1.56 | 0.18 | 0.03 | 0.32 | 0.024 | 0.013 | 44 | 11 | 0.37                   |
| F                  | 0.079                   | 1.69 | 0.17 | 0.02 | 0.35 | 0.028 | 0.012 | 46 | 9  | 0.38                   |
| G                  | 0.068                   | 1.46 | 0.16 | 0.02 | 0.37 | 0.038 | 0.006 | 51 | 12 | 0.34                   |
| H                  | 0.067                   | 1.48 | 0.11 | 0.02 | 0.18 | 0.021 | 0.014 | 58 | 8  | 0.33                   |
| * Unit may be ppm. |                         |      |      |      |      |       |       |    |    |                        |

$$R = [C] + [Mn]/6 + [Cu]/15 + [Ni]/15 + [Cr]/5 + [Mo]/5 + [V]/5$$

[Relational expression 1]

(In the relational expression, [C], [Mn], [Cu], [Ni], [Cr], [Mo], and [V] may represent weight% of each element.)

**[0076]** Table 2 below lists the strength and impact toughness with respect to the manufactured steel material. Also, the manufactured steel material was multi-layer welded with a heat input of 1.5 kJ/cm, and the microstructural properties and CTOD values of the weld heat-affected zone (FL) to FL+0.2 mm region were measured.

**[0077]** Yield strength was measured by a room-temperature tensile test according to JIS-5. Also, the impact absorption energy was measured by a Charpy impact test at -80°C at the center of the steel sheet (at 1/2 point in the thickness direction), and the results were listed.

**[0078]** The microstructure fraction of the weld heat-affected zone was measured by observing the center position of each sample using an optical microscope after nital etching. In this case, as the remaining structure, excluding the MA phase, one or more of upper bainite and granular bainite were observed.

**[0079]** The effective grain size of the weld heat-affected zone was measured by measuring grains having a boundary angle of 15° or higher five times at the center of the thickness of the steel sheet using electron backscatter diffraction (EBSD), and the average value was presented.

**[0080]** The CTOD value was evaluated by conducting a full-thickness CTOD test at -60°C in the CGHAZ section in accordance with the ISO 15653 standard, resistance to brittle crack initiation was assessed, and the results were listed in Table 2.

[Table 2]

| Sample No. | Steel type | Base material        |                                   | Weld heat-affected zone   |                            |                                              | Notes                 |
|------------|------------|----------------------|-----------------------------------|---------------------------|----------------------------|----------------------------------------------|-----------------------|
|            |            | Yield strength (MPa) | Impact energy at center (-80°C,J) | FL to FL+0.2mm region     |                            | CGHAZ section full thickness CTOD (-60°C,mm) |                       |
|            |            |                      |                                   | MA phase fraction (area%) | Effective grain size ( μm) |                                              |                       |
| 1          | A          | 415                  | 287                               | 3.6                       | 89                         | 0.36                                         | Inventive example 1   |
| 2          | B          | 437                  | 243                               | 2.8                       | 78                         | 0.51                                         | Inventive example 2   |
| 3          | C          | 441                  | 296                               | 4.1                       | 93                         | 0.36                                         | Inventive example 3   |
| 4          | D          | 463                  | 265                               | 3.8                       | 81                         | 0.29                                         | Inventive example 4   |
| 5          | E          | 492                  | 89                                | 6.2                       | 79                         | 0.14                                         | Comparative example 1 |
| 6          | F          | 524                  | 94                                | 4.3                       | 105                        | 0.16                                         | Comparative example 2 |
| 7          | G          | 487                  | 207                               | 5.9                       | 132                        | 0.09                                         | Comparative example 3 |
| 8          | H          | 436                  | 198                               | 2.7                       | 87                         | 0.18                                         | Comparative example 4 |

**[0081]** As indicated in Table 3, the inventive example, which satisfied the alloy composition and manufacturing conditions of the present disclosure, satisfied the microstructural properties suggested in the present disclosure and also the material properties targeted in the present disclosure was ensured.

**[0082]** On the other hand, comparative example 1 may be an example in which the carbon content suggested in the present disclosure was exceeded. Due to high hardenability, a large amount of low-temperature transformation phases were formed in the microstructure, and accordingly, the base material had excessively high yield strength and impact energy was deteriorated. Also, due to the high carbon content, the MA phase was excessively formed in the weld heat-affected zone, and the target CTOD value was not ensured.

**[0083]** Comparative example 2 may be an example in which the manganese content suggested in the present disclosure was exceeded. Due to high hardenability, a large amount of the low-temperature transformation phase were formed in the microstructure, and accordingly, the base material had excessively high yield strength and impact energy was also deteriorated. Also, due to the high manganese content, coarse bainite was formed in the weld heat-affected zone, such that the effective grain size exceeded the target level, and the target CTOD value was not ensured.

**[0084]** Comparative example 3 may be an example in which the Nb content exceeded the Nb content suggested in the present disclosure, and the Ti content was insufficient. Due to the addition of the large amount of Nb, the MA phase was excessively formed in the weld heat-affected zone, and TiN precipitates was not sufficiently formed, such that the microstructure in the FL to FL+0.2 mm region was coarsened, and the target CTOD value was not ensured.

**[0085]** Comparative example 4 may be an example in which the Ni content did not satisfy the Nb content suggested in the present disclosure. Accordingly, toughness was deteriorated, such that the target CTOD value was not ensured.

**[0086]** While the present disclosure has been described in detail through embodiments, other embodiments may be made. Thus, the technical spirit and scope of the claims set forth below are not limited to the embodiments.

## Claims

## 1. A steel sheet, comprising:

by weight%, C: 0.060 to 0.080%, Mn: 1.40 to 1.60%, Si: 0.10 to 0.20%, Al: 0.01 to 0.04%, Ni: 0.30 to 0.50%, Ti: 0.008 to 0.016%, Nb: 0.010 to 0.025%, P: 0.008% or less, S: 0.002% or less, and a balance of Fe and inevitable impurities, wherein, in a weld heat-affected zone, welded with a heat input of 1.5 kJ/mm, a microstructure in a region of fusion line (FL) to FL+0.2 mm includes an MA phase of 5.0% or less by area%.

## 2. The steel sheet of claim 1, wherein the steel sheet has an R value of 0.38 or less, defined in relational expression 1 below:

$$R = [C] + [Mn]/6 + [Cu]/15 + [Ni]/15 + [Cr]/5 + [Mo]/5 + [V]/5 \quad [\text{Relational expression 1}]$$

where [C], [Mn], [Cu], [Ni], [Cr], [Mo] and [V] are weight% of each element.

3. The steel sheet of claim 1, wherein, in the weld heat-affected zone, an effective grain size at a center of a thickness of fusion line (FL) to FL+0.2 mm region is 100  $\mu$ m or less.

## 4. The steel sheet of claim 1, wherein the steel sheet has a yield strength of 355 MPa or more and an impact toughness of 100 J or more at -80°C.

## 5. The steel sheet of claim 1, wherein the steel sheet has a full-thickness crack tip opening displacement (CTOD) value of 0.20 mm or more at -60°C in a coarse grained heat affected zone (CGHAZ).

## 6. A method of manufacturing a steel sheet, the method comprising:

heating a steel slab comprising, by weight%, C: 0.060 to 0.080%, Mn: 1.40 to 1.60%, Si: 0.10 to 0.20%, Al: 0.01 to 0.04%, Ni: 0.30 to 0.50%, Ti: 0.008 to 0.016%, Nb: 0.010 to 0.025%, P: 0.008% or less, S: 0.002% or less, and a balance of Fe and inevitable impurities;  
rough-rolling the heated steel slab;  
finishing hot-rolling the rough-rolled steel sheet; and  
cooling the finishing hot-rolled steel sheet to a temperature range of 400 to 700°C at a cooling rate of 10°C/s or higher with reference to a 1/4 point in a direction of a center of a thickness from a surface.

## 7. The method of claim 6, wherein the steel sheet has an R value of 0.38 or less, defined in relational expression 1 below:

$$R = [C] + [Mn]/6 + [Cu]/15 + [Ni]/15 + [Cr]/5 + [Mo]/5 + [V]/5 \quad [\text{Relational expression 1}]$$

where [C], [Mn], [Cu], [Ni], [Cr], [Mo] and [V] are weight% of each element.

## 8. The method of claim 6,

wherein the heating is performed at a temperature range of 1050 to 1160°C,  
wherein the rough-rolling is performed at a temperature range of 900°C or higher with a cumulative reduction ratio of 40% or more, and  
wherein the finishing hot-rolling is performed at a temperature range of 800°C or higher with a cumulative reduction ratio of 50% or more.

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/KR2024/015912

**A. CLASSIFICATION OF SUBJECT MATTER**

**C22C 38/04**(2006.01)i; **C22C 38/02**(2006.01)i; **C22C 38/08**(2006.01)i; **C22C 38/14**(2006.01)i; **C22C 38/12**(2006.01)i;  
**C21D 8/02**(2006.01)i; **C21D 9/46**(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)

C22C 38/04(2006.01); B21B 3/00(2006.01); C21D 8/00(2006.01); C21D 8/02(2006.01); C21D 9/46(2006.01);  
C22C 38/00(2006.01); C22C 38/14(2006.01); C22C 38/16(2006.01)

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

Korean utility models and applications for utility models: IPC as above

Japanese utility models and applications for utility models: IPC as above

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

eKOMPASS (KIPO internal) & keywords: 용-용선(fusion line), 용-접열영향부(heat affected zone), 도상 마르텐사이트상  
(martensite-austenite phase, MA), 용-접후열처리(PWHT)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages  | Relevant to claim No. |
|-----------|-------------------------------------------------------------------------------------|-----------------------|
| Y         | JP 08-060239 A (NIPPON STEEL CORP.) 05 March 1996 (1996-03-05)<br>See claims 1-3.   | 1-8                   |
| Y         | KR 10-2023-0078073 A (POSCO) 02 June 2023 (2023-06-02)<br>See claims 5-7.           | 1-8                   |
| A         | KR 10-1786258 B1 (POSCO) 18 October 2017 (2017-10-18)<br>See claims 1, 3, 5 and 6.  | 1-8                   |
| A         | KR 10-2012-0070657 A (POSCO) 02 July 2012 (2012-07-02)<br>See claims 1-5.           | 1-8                   |
| A         | JP 2003-313629 A (NIPPON STEEL CORP.) 06 November 2003 (2003-11-06)<br>See claim 1. | 1-8                   |

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

\* Special categories of cited documents:

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

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

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

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

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

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

“&” document member of the same patent family

|                                                                                                                                                                                                               |                                                                              |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Date of the actual completion of the international search<br><b>20 January 2025</b>                                                                                                                           | Date of mailing of the international search report<br><b>21 January 2025</b> |
| Name and mailing address of the ISA/KR<br><b>Korean Intellectual Property Office<br/>Government Complex-Daejeon Building 4, 189 Cheongsaro, Seo-gu, Daejeon 35208</b><br>Facsimile No. <b>+82-42-481-8578</b> | Authorized officer<br><br>Telephone No.                                      |

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## INTERNATIONAL SEARCH REPORT

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### C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                          | Relevant to claim No. |
|-----------|-------------------------------------------------------------------------------------------------------------|-----------------------|
| PX        | KR 10-2024-0091614 A (POSCO) 21 June 2024 (2024-06-21)<br>See paragraphs [0102]-[0103] and claims 8 and 10. | 6,8                   |

## INTERNATIONAL SEARCH REPORT

### Information on patent family members

International application No.

**PCT/KR2024/015912**

| Patent document cited in search report |                 |    | Publication date (day/month/year) | Patent family member(s) |                   | Publication date (day/month/year) |
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| KR                                     | 10-2023-0078073 | A  | 02 June 2023                      | CN                      | 117795115 A       | 29 March 2024                     |
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| JP                                     | 2003-313629     | A  | 06 November 2003                  | JP                      | 3616609 B2        | 02 February 2005                  |
| KR                                     | 10-2024-0091614 | A  | 21 June 2024                      | None                    |                   |                                   |