

DESCRIPTION

TITLE

STEEL SHEET PILE AND PRODUCTION METHOD THEREFOR

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TECHNICAL FIELD

[0001] The present disclosure relates to a steel sheet pile used as a permanent structure or a temporary structure in the civil engineering and construction fields, and a production method therefor.

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BACKGROUND

[0002] Steel sheet piles are subjected to high loads in the case of being used for quay walls or retaining walls, and thus are required to have strength and toughness. For example, steel sheet piles of 290 MPa or more or 390 MPa or more in yield stress (hereafter referred to as YP) are used. In severer environments, steel sheet piles having a strength of 440 MPa or more in YP are often essential.

Typical methods used when producing high-strength and high-toughness steel material products include adding alloying elements and rolling in the non-recrystallization range of austenite. In the production of steel sheet piles having complex shapes, however, rolling and forming at high temperatures with less deformation resistance are desired from the viewpoint of formability, and the addition of alloys that can increase the deformation resistance is sometimes restricted.

[0003] The JIS standard (SYW) for steel sheet piles stipulates the Charpy absorbed energy at 0 °C. However, given that steel sheet piles are also used in environments below 0 °C, such as during the cold season in Japan, steel sheet piles having higher toughness are expected to be in demand in the future.

[0004] Against this background, research and development of high-strength and high-toughness steel sheet piles are underway.

In detail, JP 2018-83963 A (PTL 1) proposes a steel sheet pile having a YP of 440 MPa or more and high toughness, by containing Nb in its chemical composition.

[0005] JP 2018-90845 A (PTL 2) proposes a steel sheet pile having a YP of 440 MPa or more and high toughness, by containing both Nb and V in its chemical composition and controlling the rolling reduction ratio at 1000 °C or

less to adjust the average grain size of ferrite, the area ratio of martensite-austenite constituents, and the number density of precipitates.

[0006] JP 2014-118629 A (PTL 3) proposes a steel sheet pile having a YP of 460 MPa or more and high toughness, by containing both Nb and V in its chemical composition as in PTL 2 and setting the cumulative rolling reduction ratio at 900 °C or less to 90 % or more to adjust the average grain size of ferrite and the number density of precipitates.

[0007] JP 2002-294392 A (PTL 4) proposes a steel sheet pile having a YP of 340 MPa or more and high toughness, by limiting Nb in the inevitable impurities to 0.005 % or less.

[0008] JP 2007-332414 A (PTL 5) and JP 2008-221318 A (PTL 6) each propose a steel sheet pile having a YP of 440 MPa or more and vTrs of -10 °C or less, by water cooling a predetermined part during hot rolling or after rolling.

CITATION LIST

Patent Literature

[0009] PTL 1: JP 2018-83963 A
PTL 2: JP 2018-90845 A
PTL 3: JP 2014-118629 A
PTL 4: JP 2002-294392 A
PTL 5: JP 2007-332414 A
PTL 6: JP 2008-221318 A

SUMMARY

(Technical Problem)

[0010] The techniques described in PTL 1, PTL 2, and PTL 3 each provide a high-strength and high-toughness steel sheet pile by adding Nb to the chemical composition. However, Nb tends to increase the deformation resistance during hot rolling regardless of whether it is in a solid solution state or a precipitated state, so that strict shape control during hot rolling is necessary. Moreover, with the techniques described in PTL 2 and PTL 3, the grain size of ferrite is specified as an average value. However, Nb suppresses the recrystallization of austenite, causing variation in the precipitation state. This may result in mixed ferrite with a large variation in grain size. It is thus necessary to stably obtain high toughness.

[0011] PTL 4 proposes a steel sheet pile having a YP of 340 MPa or more and

high toughness by limiting the rolling temperature and the rolling reduction ratio in the final pass to facilitate complete recrystallization of austenite and also obtaining uniform microstructure. The YP is, however, less than 440 MPa, and further improvement in YP is required.

5 **[0012]** According to PTL 5 or PTL 6, water cooling a predetermined part is essential in order to obtain a steel sheet pile having a YP of 440 MPa or more and vTrs of -10 °C or less. This inevitably causes shape changes such as deflection and camber.

10 **[0013]** It could therefore be helpful to provide a high-strength and high-toughness steel sheet pile stably with high productivity. Herein, “high strength” means that YP is 440 MPa or more, and “high toughness” means that vTrs is -10 °C or less, for example. vTrs is the fracture appearance transition temperature (the temperature at which the percent ductile fracture is 50 %) measured by a Charpy impact test conforming to JIS Z 2242, and is hereafter
15 also referred to as “fracture appearance transition temperature at a percent ductile fracture of 50 %”.

(Solution to Problem)

20 **[0014]** To obtain a steel sheet pile having high strength and improved toughness, we considered using V as an essential component without using Nb, and also looked at and carefully examined not only the temperature control and the management of the cumulative rolling reduction ratio but also the average rolling reduction ratio per pass in the high temperature range during hot rolling. We consequently discovered that a steel sheet pile having high strength of 440 MPa or more in YP and high toughness of -10 °C or less in vTrs is provided by
25 adjusting the rolling conditions to uniformly refine the microstructure and also utilizing precipitation strengthening by V precipitates.

[0015] We thus provide:

1. A steel sheet pile comprising: a chemical composition containing (consisting of), in mass%, C: 0.05 % to 0.18 %, Si: 0.05 % to 0.55 %, Mn: 1.00
30 % to 1.65 %, sol.Al: 0.080 % or less, V: 0.050 % to 0.300 %, and N: 0.0010 % to 0.0060 % with a balance consisting of Fe and inevitable impurities, where contents of P, S, and B as the inevitable impurities are P: 0.025 % or less, S: 0.020 % or less, and B: 0.0003 % or less respectively; a microstructure that is a ferrite-based microstructure and in which an average grain size of ferrite is
35 15 μm or less, a maximum grain size of ferrite is 40 μm or less, and an area ratio of martensite-austenite constituents with respect to the microstructure is

1.0 % or less; a yield stress of 440 MPa or more; and vTrs of -10 °C or less.

[0016] 2. The steel sheet pile according to 1., wherein the chemical composition further contains, in mass%, one or more selected from the group consisting of Cu: 0.50 % or less, Ni: 0.50 % or less, Cr: 0.50 % or less, Mo: 0.30 % or less, Ca: 0.0050 % or less, Nb: 0.005 % or less, Ti: 0.025 % or less, and REM: 0.005 % or less.

[0017] 3. A production method for a steel sheet pile having: a microstructure that is a ferrite-based microstructure and in which an average grain size of ferrite is 15 µm or less, a maximum grain size of ferrite is 40 µm or less, and an area ratio of martensite-austenite constituents with respect to the microstructure is 1.0 % or less; a yield stress of 440 MPa or more; and vTrs of -10 °C or less, the production method comprising: heating a steel material to 1200 °C to 1350 °C, the steel material having a chemical composition containing, in mass%, C: 0.05 % to 0.18 %, Si: 0.05 % to 0.55 %, Mn: 1.00 % to 1.65 %, sol.Al: 0.080 % or less, V: 0.050 % to 0.300 %, and N: 0.0010 % to 0.0060 % with a balance consisting of Fe and inevitable impurities, where contents of P, S, and B as the inevitable impurities are P: 0.025 % or less, S: 0.020 % or less, and B: 0.0003 % or less respectively; and subjecting the steel material to hot rolling in which an average rolling reduction ratio per pass in a range of 900 °C to 1150 °C is 10 % or more, a cumulative rolling reduction ratio in a range of 800 °C to 1150 °C is 60 % or more, and a finish temperature of intermediate rolling is 650 °C to 900 °C.

Herein, the “intermediate rolling” refers to rolling from after rough rolling to before finish rolling, and involves adjusting the thickness by roll-reducing mainly a part corresponding to a web in the thickness direction.

[0018] 4. The production method for a steel sheet pile according to 3., wherein the chemical composition further contains, in mass%, one or more selected from the group consisting of Cu: 0.50 % or less, Ni: 0.50 % or less, Cr: 0.50 % or less, Mo: 0.30 % or less, Ca: 0.0050 % or less, Nb: 0.005 % or less, Ti: 0.025 % or less, and REM: 0.005 % or less.

(Advantageous Effect)

[0019] It is thus possible to provide a high-strength and high-toughness steel sheet pile having a YP of 440 MPa or more and vTrs of -10 °C or less stably with high productivity, which is industrially very useful.

[0020] In the accompanying drawings:

FIG. 1 is a diagram illustrating a cross-sectional shape of a steel sheet pile; and

FIG. 2 is a diagram illustrating typical calibers in a hot rolling process
5 for a hat-shaped steel sheet pile.

DETAILED DESCRIPTION

[0021] [Chemical composition]

First, the reasons for limiting the chemical composition of a steel sheet
10 pile according to an embodiment of the present disclosure will be described below. In the following description, “%” with regard to the content of each element denotes “mass%” unless otherwise specified.

[0022] C: 0.05 % to 0.18 %

C is an essential element that combines with V and N in the steel to
15 stably ensure the strength of the base metal as V(C, N). The C content needs to be 0.05 % or more. If the C content is more than 0.18 %, bainite including martensite-austenite constituents forms, and the increase of the martensite-austenite constituents causes a significant decrease in toughness. Moreover, precipitates form excessively, causing a further decrease in toughness. The C
20 content is therefore 0.05 % to 0.18 %. The C content is preferably 0.10 % or more. The C content is preferably 0.16 % or less.

[0023] Si: 0.05 % to 0.55 %

Si is an element that increases the strength of the base metal by solid
solution strengthening. The Si content needs to be 0.05 % or more. If the Si
25 content is excessive, the formation of martensite-austenite constituents which decrease the toughness is promoted. The Si content is therefore 0.55 % or less. That is, the Si content is 0.05 % to 0.55 %. The Si content is preferably 0.10 % or more. The Si content is preferably 0.50 % or less.

[0024] Mn: 1.00 % to 1.65 %

Mn is a relatively inexpensive element that has the effect of increasing
30 the strength of the steel, and is necessary for higher strength, as with Si. If the Mn content is less than 1.00 %, its effect is insufficient. If the Mn content is more than 1.65 %, the formation of upper bainite including martensite-austenite constituents is promoted, which greatly impairs the toughness. The
35 Mn content is therefore 1.00 % to 1.65 %. The Mn content is preferably 1.10 % or more. The Mn content is preferably 1.60 % or less.

[0025] sol. Al: 0.080 % or less

Al is an element added as a deoxidizer. The effect of Al as a deoxidizer is saturated when the sol.Al content is more than 0.080 %. The sol.Al content is therefore 0.080 % or less. The sol.Al content is preferably 0.060 % or less. Although no lower limit is placed on the sol.Al content, the sol.Al content is preferably 0.001 % or more for deoxidation. The sol.Al content is more preferably 0.003 % or more.

[0026] V: 0.050 % to 0.300 %

V is an important element that has the effect of refining crystal grains by precipitating into austenite as V(C, N) during rolling or cooling and contributing as a ferrite nucleation site. V also acts to increase the strength of the base metal by precipitation strengthening as precipitates, and thus is essential for ensuring the strength and the toughness. To enhance these effects, the V content needs to be 0.050 % or more. If the V content is more than 0.300 %, precipitation embrittlement is promoted, and the toughness of the base metal is greatly impaired. The V content is therefore 0.050 % to 0.300 %. The V content is preferably 0.075 % or more. The V content is further preferably more than 0.080 %. The V content is preferably 0.200 % or less.

[0027] N: 0.0010 % to 0.0060 %

N is a useful element that combines with V and C in the steel to improve the strength of the base metal as V(C, N). The N content needs to be 0.0010 % or more. If the N content is more than 0.0060 %, the carbonitrides formed coarsen, and the toughness of the base metal is greatly impaired. The N content is therefore 0.0010 % to 0.0060 %. The N content is preferably 0.0015 % or more. The N content is preferably 0.0055 % or less.

[0028] The basic chemical composition of the steel sheet pile according to an embodiment of the present disclosure has been described above. The chemical composition may optionally further contain one or more of the following elements:

[0029] Cu: 0.50 % or less

Cu is an element that can further increase the strength of the steel by solid solution strengthening. To achieve this effect, the Cu content is preferably 0.01 % or more. If the Cu content is more than 0.50 %, Cu cracking tends to occur. Accordingly, in the case where the chemical composition of the steel contains Cu, the Cu content is preferably 0.50 % or less.

[0029] Ni: 0.50 % or less

Ni is an element that dissolves in the steel and increases the strength of the steel without degrading the ductility and the toughness, as with Cu. To achieve this effect, the Ni content is preferably 0.01 % or more. In particular, adding Ni together with Cu suppresses Cu cracking. Hence, it is preferable to
5 add Ni together with Cu. If the Ni content is excessive, the formation of martensite-austenite constituents is promoted. Moreover, Ni is an expensive element. The Ni content is therefore preferably 0.50 % or less.

[0030] Cr: 0.50 % or less

Cr is an element that can further increase the strength of the steel by
10 solid solution strengthening. To achieve this effect, the Cr content is preferably 0.01 % or more. If the Cr content is excessive, the formation of martensite-austenite constituents is promoted. The Cr content is therefore preferably 0.50 % or less.

[0031] Mo: 0.30 % or less

15 Mo is an element that can further increase the strength of the steel by solid solution strengthening. To achieve this effect, the Mo content is preferably 0.01 % or more. If the Mo content is excessive, the formation of martensite-austenite constituents is promoted. The Mo content is therefore preferably 0.30 % or less.

20 **[0032]** Ca: 0.0050 % or less

Ca combines with S or O and reduces MnS in the steel, thus improving the toughness and ductility of the steel. To achieve this effect, the Ca content is preferably 0.0005 % or more. If the Ca content is more than 0.0050 %, there is a tendency that the cleanliness decreases and the toughness decreases. The
25 Ca content is therefore preferably 0.0050 % or less.

[0033] Nb: 0.005 % or less

Nb has the effect of refining crystal grains by precipitating into austenite as Nb(C, N) during rolling and suppressing the recrystallization of austenite. To achieve this effect, the Nb content is preferably 0.001 % or more.
30 Meanwhile, Nb tends to increase the deformation resistance during hot rolling regardless of whether it is in a solid solution state or a precipitated state. Particularly in the case where the average rolling reduction ratio per pass in the recrystallization temperature range is 10 % or more as described later, it is advantageous to limit the Nb content to 0.005 % or less. Accordingly, in the
35 case where the chemical composition of the steel contains Nb, the Nb content is preferably 0.005 % or less.

[0034] Ti: 0.025 % or less

Ti has the effect of refining crystal grains by precipitating into austenite as TiN. To achieve this effect, the Ti content is preferably 0.001 % or more. If the Ti content is excessive, the precipitated TiN coarsens and the crystal grains coarsen, which is likely to cause a decrease in toughness. The Ti content is therefore preferably 0.025 % or less.

[0035] REM: 0.005 % or less

REM (rare earth element) combines with S or O and reduces MnS in the steel, thus improving the toughness and ductility of the steel, as with Ca. To achieve this effect, the REM content is preferably 0.001 % or more. If the REM content is more than 0.005 %, there is a tendency that the cleanliness decreases and the toughness decreases. The REM content is therefore preferably 0.005 % or less.

[0036] The balance other than the foregoing elements in the chemical composition of the steel sheet pile according to an embodiment of the present disclosure consists of Fe and inevitable impurities. In the case where the content of any of the elements described above as optionally added components is less than the corresponding preferred lower limit, the element is treated as an inevitable impurity (i.e. regarded as being contained as an inevitable impurity). The total content of the inevitable impurities is such an amount that is inevitably mixed into steel by a typical production method, for example, preferably 0.050 % or less and more preferably 0.040 % or less. For P, S, and B among the inevitable impurities, the following upper limits are placed on their contents.

[0037] P: 0.025 % or less

P exists as an inevitable impurity in the steel. If the P content is excessive, the toughness of the steel decreases. The P content is therefore 0.025 % or less. The P content is desirably as low as possible, and may be 0 %. However, since excessive reduction of the P content prolongs the refining process and causes a decrease in productivity, the P content is preferably 0.005 % or more.

[0038] S: 0.020 % or less

S exists as an inevitable impurity in the steel as with P, and also exists as an A type inclusion. If the S content is excessive, the amount of inclusions is excessively high, and the toughness of the steel decreases. The S content is therefore 0.020 % or less. The S content is desirably as low as possible, and

may be 0 %. However, since excessive reduction of the S content prolongs the refining process and causes a decrease in productivity, the S content is preferably 0.002 % or more.

[0039] B: 0.0003 % or less

5 B is an element that has the effect of increasing the grain boundary strength by segregating at the grain boundaries in the steel. In the case where low-quality raw materials are used, the B content in the steel tends to be more than 0.0003 %. In such a case, coarse grain boundary precipitates form, and the quench hardenability increases to thus promote the formation of martensite-
10 austenite constituents, as a result of which the toughness decreases. The B content is therefore 0.0003 % or less. The B content is preferably 0.0002 % or less. The B content is desirably as low as possible, and may be 0 %.

[0040] Next, the microstructure of the steel sheet pile according to an embodiment of the present disclosure will be described below. The
15 microstructure of the steel sheet pile according to an embodiment of the present disclosure is defined with the web of the steel sheet pile as a representative part. The web has the lowest working ratio among the parts of the steel sheet pile. The web has coarse microstructure. It is therefore most difficult to ensure the strength and the toughness in the web among the parts of the steel sheet
20 pile. Thus, the microstructure is defined with the web as a representative part. Since the target properties according to the present disclosure are obtained as long as the microstructure of the web satisfies the below-described conditions, the microstructure of the parts of the steel sheet pile according to an embodiment of the present disclosure other than the web is not limited. If the
25 microstructure of the web satisfies the below-described conditions, there is a high probability that the parts other than the web have substantially the same microstructure.

[0041] It is important that, as the microstructure, the area ratio, average grain size, and maximum grain size of ferrite and the area ratio of martensite-
30 austenite constituents satisfy the following conditions.

[0042] [Ferrite-based microstructure]

 The microstructure of the steel sheet pile is a ferrite-based microstructure. The term “ferrite-based microstructure” refers to a microstructure in which the area ratio of ferrite is 70 % or more. If the area
35 ratio of ferrite is less than 70 %, hard phase increases, which is likely to cause a decrease in toughness. Regarding the upper limit of the area ratio of ferrite,

the area ratio of ferrite is preferably less than 90 % from the viewpoint of ensuring the strength. The residual microstructures other than ferrite are not limited, and examples include pearlite, bainite microstructure including martensite-austenite constituents, and martensite. The total area ratio of the residual microstructures other than ferrite is preferably 30 % or less. The total area ratio of the residual microstructures other than ferrite is preferably more than 10 %. The area ratio of martensite-austenite constituents needs to be limited as described later. The area ratio of each phase can be measured by the measurement method described in the EXAMPLES section below.

10 **[0043]** [Average grain size of ferrite: 15 μm or less, and maximum grain size of ferrite: 40 μm or less]

In the microstructure of the steel sheet pile, the average grain size of ferrite is 15 μm or less, and the maximum grain size of ferrite is 40 μm or less. If the average grain size of ferrite is more than 15 μm or the maximum grain size of ferrite is more than 40 μm , it is difficult to ensure the toughness. To achieve excellent toughness, it is desirable that the average grain size of ferrite is 12 μm or less and the maximum grain size of ferrite is 30 μm or less, and more desirable that the average grain size of ferrite is 10 μm or less and the maximum grain size of ferrite is 25 μm or less. No lower limit is placed on each of the average grain size and maximum grain size of ferrite. The average grain size and maximum grain size of ferrite can each be measured by the measurement method described in the EXAMPLES section below.

20 **[0044]** [Area ratio of martensite-austenite constituents: 1.0 % or less]

In the microstructure of the steel sheet pile, the area ratio of martensite-austenite constituents is 1.0 % or less. If the area ratio of martensite-austenite constituents is more than 1.0 %, it is difficult to ensure the toughness. To achieve better toughness, it is desirable that the area ratio of martensite-austenite constituents is 0.5 % or less. The area ratio of martensite-austenite constituents is desirably as low as possible and may be 0 %, and accordingly no lower limit is placed on the area ratio. The area ratio of martensite-austenite constituents can be measured by the measurement method described in the EXAMPLES section below.

30 **[0045]** Next, a production method for a steel sheet pile according to an embodiment of the present disclosure will be described below.

35 A steel sheet pile is produced by heating a steel material such as a slab having the foregoing chemical composition in a heating furnace and then

subjecting the steel material to hot rolling that includes rough rolling, intermediate rolling, and finish rolling.

FIG. 1 (a) illustrates a hat-shaped steel sheet pile 1, which is a typical example of a steel sheet pile. The hat-shaped steel sheet pile 1 includes a web 2, a pair of flanges 3 and 4 extending obliquely from both ends of the web 2, arm portions 5 and 6 extending in parallel with the web 2 from the sides of the flanges 3 and 4 opposite to the web 2, and claw portions 7 and 8 at the ends of the arm portions 5 and 6.

[0046] As an example, this hat-shaped steel sheet pile is produced in the following manner: After the heating of the steel material, in each of the rough rolling, the intermediate rolling, and the finish rolling, the steel material finally passes through the corresponding caliber illustrated in FIG. 2 to thus be formed. Specifically, in the first rough rolling, the steel material is rolled a plurality of times, and then finally passes through a caliber 13 to form the rough shape of the steel sheet pile. In the intermediate rolling which follows, the thickness of each of the parts corresponding to the web 2, the flanges 3 and 4, the arm portions 5 and 6, and the claw portions 7 and 8 is adjusted, and the steel material finally passes through a caliber 14. In the finish rolling, shape control mainly including claw bending is performed, and the steel material finally passes through a caliber 15 to form the final product shape.

Thus, the hot rolling includes the rough rolling, the intermediate rolling, and the finish rolling. The rough rolling gives the rough shape of the steel sheet pile. The intermediate rolling refers to the rolling from after the rough rolling to before the finish rolling (claw bending (rolling) in the above example), and adjusts the thickness by roll-reducing mainly the part corresponding to the web in the thickness direction. The finish rolling performs final shape control, and includes claw bending in the above example.

[0047] In the case of steel sheet piles other than the hat-shaped steel sheet pile described above, for example, steel sheet piles different in product shape such as web thickness and claw portions as in a straight steel sheet pile 9 illustrated in FIG. 1 (b), the number of rolling passes and the rolling temperature in hot rolling may be different. Nonetheless, the production methods for such steel sheet piles are fundamentally the same in that rough rolling, intermediate rolling, and finish rolling (including claw bending) are performed, and thus all such production methods are included in the production method for a steel sheet pile according to an embodiment of the present disclosure. In the straight

steel sheet pile 9 illustrated in FIG. 1 (b), a straight part between a left claw portion 11 and a right claw portion 12 is a web 10.

[0048] It is important that the steel material is heated to 1200 °C to 1350 °C, and then in the hot rolling, the average rolling reduction ratio per pass in the range of 900 °C to 1150 °C is 10 % or more, the cumulative rolling reduction ratio in the range of 800 °C to 1150 °C is 60 % or more, and the finish temperature in the intermediate rolling is 650 °C to 900 °C. The following temperature specifications are all based on the surface temperature of the steel material or the material to be rolled. The temperature of the steel material or the material to be rolled can be measured with a radiation thermometer.

[0049] [Heating temperature of steel material: 1200 °C to 1350 °C]

Before performing the hot rolling, the steel material needs to be heated to 1200 °C to 1350 °C. If the heating temperature is less than 1200 °C, the dissolution of V in the steel is insufficient. This coarsens the precipitates, and makes it difficult to ensure the strength and the toughness. Moreover, there is a risk that the deformation resistance in hot conditions increases and a roll crack occurs. If the heating temperature is more than 1350 °C, the crystal grains coarsen, making it difficult to ensure the toughness. In addition, the heating time increases and the productivity decreases. The heating temperature of the steel material is therefore 1200 °C to 1350 °C. The heating temperature of the steel material is preferably 1250 °C to 1350 °C.

[0050] [Average rolling reduction ratio per pass in the range of 900 °C to 1150 °C: 10 % or more]

It is important that the average rolling reduction ratio per pass in the range of 900 °C to 1150 °C (hereafter also simply referred to as “average rolling reduction ratio”) is 10 % or more. As a result of the average rolling reduction ratio being 10 % or more, the recrystallization of austenite is facilitated to obtain uniform and fine crystal grains. This significantly improves the YP and the toughness. The average rolling reduction ratio is preferably 12 % or more.

The average rolling reduction ratio can be calculated using the following formula (1):

$$R = 100 \{1 - (T_f/T_s)^{1/n}\} \quad \dots (1)$$

where R is the average rolling reduction ratio (%), T_f and T_s are respectively the thickness (mm) of the material to be rolled (the part corresponding to the web) at 900 °C and the thickness (mm) of the material to

be rolled at 1150 °C, and n is the number of rolling passes in the range of 900 °C to 1150 °C. As the number of rolling passes, the number of rolling passes in each of which at least one of the rolling start temperature and the rolling finish temperature is in the range of 900 °C to 1150 °C is counted. For example,
5 a rolling pass in which the rolling start temperature is 1160 °C and the rolling finish temperature is 1100 °C is counted as one pass in the number of rolling passes. The thickness can be controlled by the roll gap of the mill.

[0051] In rolling performed by a plurality of mills, such as tandem rolling, rolling is continuously performed without sufficient time for recrystallization, and strain accumulates. Accordingly, in such continuous rolling, one pass is
10 regarded as being from biting to biting release.

[0052] The average rolling reduction ratio is preferably 20 % or less, from the viewpoint of shape control. If the average rolling reduction ratio is less than 10 %, recovery or partial recrystallization of austenite is noticeable, causing
15 the crystal grains to be coarse and mixed-grain-sized. This may make it difficult to ensure the toughness.

[0053] If the hot rolling is in the temperature range exceeding 1150 °C, the grain growth of austenite is significant and the refining effect is poor. Accordingly, the rolling reduction ratio in this temperature range is not limited.
20 As long as the below-described desired cumulative rolling reduction ratio in the temperature range of 800 °C to 1150 °C is achieved, the rolling reduction ratio in the temperature range below 900 °C need not be limited.

[0054] [Cumulative rolling reduction ratio in the range of 800 °C to 1150 °C: 60 % or more]

25 In addition to the above, it is also important that the cumulative rolling reduction ratio in the range of 800 °C to 1150 °C (hereafter also simply referred to as “cumulative rolling reduction ratio”) is 60 % or more. If the cumulative rolling reduction ratio is less than 60 %, the average grain size of ferrite in the microstructure will end up being more than 15 µm, making it difficult to ensure
30 the toughness. The cumulative rolling reduction ratio is preferably 70 % or more. Although no upper limit is placed on the cumulative rolling reduction ratio, the cumulative rolling reduction ratio is preferably 90 % or less from the viewpoint of the risk of roll crack.

The cumulative rolling reduction ratio can be calculated using the
35 following formula (2):

$$R' = 100\{1 - (T_L / T_s)\} \quad \dots (2)$$

where R' is the cumulative rolling reduction ratio (%), and T_L and T_s are respectively the thickness (mm) of the material to be rolled (the part corresponding to the web) at 800 °C and the thickness (mm) of the material to be rolled at 1150 °C.

5 **[0055]** [Finish temperature of intermediate rolling: 650 °C to 900 °C]

The finish temperature of the intermediate rolling for forming the web and the flanges (i.e. the finish temperature of the final rolling pass in the intermediate rolling) is 650 °C to 900 °C. If the finish temperature of the intermediate rolling is more than 900 °C, it is difficult to satisfy either of the
10 foregoing two rolling conditions, and the average grain size of ferrite in the microstructure will end up being more than 15 μm or the maximum grain size of ferrite in the microstructure will end up being more than 40 μm . This makes it difficult to ensure the toughness. If the finish temperature of the intermediate rolling is less than 650 °C, the rolling load in the intermediate rolling increases,
15 increasing the risk of roll crack in the intermediate mill.

As mentioned above, the intermediate rolling refers to the rolling from after the rough rolling to before the finish rolling (claw bending (rolling) in the above example), and adjusts the thickness by roll-reducing mainly the part corresponding to the web in the thickness direction. The finish rolling performs
20 final shape control. That is, the finish rolling does not mean only the final pass of the hot rolling, but refers to the rolling process of performing final shape adjustment after the intermediate rolling. The finish rolling is performed from the viewpoint of formability and does not significantly influence the properties. Accordingly, the finish rolling conditions are not limited.

25 **[0056]** The production method for a steel sheet pile according to an embodiment of the present disclosure does not need accelerated cooling during rolling (rough rolling, intermediate rolling, and finish rolling) in the hot rolling or after the hot rolling (finish rolling (claw bending rolling)) for the purpose of improving the strength and the toughness. Accelerated cooling causes shape
30 changes such as deflection and camber, and thus is undesirable in terms of production. Hence, it is desirable to perform air cooling after the hot rolling (finish rolling (claw bending rolling)). Cooling with water that is inevitably applied in terms of shape control during rolling or mist water in the cooling bed does not influence the properties of the steel sheet pile.

35 **[0057]** As a result of performing chemical composition adjustment, rolling, and cooling according to the foregoing conditions, a steel sheet pile having

excellent mechanical properties, specifically, high strength of 440 MPa or more in YP and vT_{rs} of $-10\text{ }^{\circ}\text{C}$ or less can be obtained. The production conditions other than the above are not limited, and may be according to conventional methods. For example, it is preferable that the number of rolling passes in the rough rolling is 5 to 20, the number of rolling passes in the intermediate rolling is 1 to 5, and the number of rolling passes in the finish rolling is 1 to 3. The rolling passes in the range of $900\text{ }^{\circ}\text{C}$ to $1150\text{ }^{\circ}\text{C}$ include, for example, rolling passes by the rough rolling and the intermediate rolling. The rolling passes in the range of $800\text{ }^{\circ}\text{C}$ to $1150\text{ }^{\circ}\text{C}$ include, for example, rolling passes by the rough rolling and the intermediate rolling, and may optionally further include rolling passes by the finish rolling. The finish temperature of the finish rolling is preferably $550\text{ }^{\circ}\text{C}$ to $700\text{ }^{\circ}\text{C}$. The cross-sectional shape of the steel sheet pile according to an embodiment of the present disclosure is not limited, and examples include a hat shape, a U shape, a combination thereof, and a straight shape. Moreover, the thickness of the web and the shape of the claw portions are not limited.

EXAMPLES

[0058] The structures and function effects according to the present disclosure will be described in more detail below by way of examples. The present disclosure is not limited to the following examples, and modifications can be made as appropriate within the range in which the subject matter of the present disclosure is applicable, with such modifications being also included in the technical scope of the present disclosure.

[0059] Steel materials having the steel compositions shown in Table 1 (with the balance consisting of Fe and inevitable impurities) were prepared using a continuous caster, and each subjected to heating and hot rolling under the conditions shown in Table 2 to produce a hat-shaped steel sheet pile including the web 2, the pair of flanges 3 and 4 extending obliquely from both ends of the web 2, the arm portions 5 and 6 extending in parallel with the web 2 so as to expand to the left and right, and the claw portions 7 and 8 at the ends of the arm portions 5 and 6 as illustrated in FIG. 1. Cooling after the hot rolling was performed by air cooling. The conditions other than the above were according to conventional methods.

[0060] [Table 1]

Steel sample No.		Chemical composition (mass%)														Remarks		
		C	Si	Mn	Al	V	N	P	S	B	Cu	Ni	Cr	Mo	Ca		Nb	Ti
1	0.13	0.10	1.25	0.031	0.135	0.0052	0.013	0.019	0.0001	-	-	-	-	-	-	-	-	-
2	0.18	0.54	1.63	0.019	0.127	0.0060	0.018	0.010	0.0002	-	-	-	-	-	-	-	-	-
3	0.09	0.30	1.57	0.017	0.263	0.0041	0.010	0.003	0.0002	-	-	-	-	-	-	-	-	-
4	0.05	0.15	1.28	0.036	0.101	0.0011	0.016	0.007	0.0003	-	-	-	-	-	-	-	-	-
5	0.17	0.11	1.45	0.031	0.296	0.0026	0.020	0.006	0.0002	-	-	-	-	-	-	-	-	-
6	0.13	0.31	1.45	0.016	0.051	0.0056	0.011	0.009	0.0003	-	-	-	-	-	-	-	-	-
7	0.08	0.23	1.11	0.035	0.167	0.0045	0.017	0.008	0.0002	-	-	-	-	-	-	-	-	-
8	0.06	0.06	1.02	0.039	0.098	0.0050	0.017	0.010	0.0002	-	-	-	-	-	-	-	-	-
9	0.12	0.29	1.34	0.026	0.178	0.0033	0.021	0.007	0.0003	-	-	0.33	-	-	-	-	-	-
10	0.07	0.26	1.42	0.043	0.217	0.0049	0.011	0.006	0.0002	0.26	-	-	-	-	-	-	-	-
11	0.16	0.45	1.34	0.049	0.174	0.0059	0.023	0.010	0.0001	-	0.20	-	-	-	-	-	-	-
12	0.09	0.31	1.31	0.021	0.050	0.0036	0.015	0.005	0.0002	-	-	-	0.24	-	-	-	-	-
13	0.13	0.34	1.28	0.027	0.062	0.0054	0.013	0.003	0.0001	-	-	-	-	0.0018	-	-	-	-
14	0.08	0.46	1.16	0.050	0.199	0.0052	0.014	0.009	0.0002	-	-	-	-	-	0.004	-	-	-
15	0.13	0.26	1.52	0.034	0.278	0.0039	0.010	0.008	0.0001	-	-	-	-	-	-	0.022	-	-
16	0.11	0.51	1.23	0.015	0.256	0.0037	0.013	0.008	0.0001	-	-	-	-	-	-	-	-	0.003

[Table I](cont'd)

Steel sample No.	Chemical composition (mass%)																Remarks	
	C	Si	Mn	Al	V	N	P	S	B	Cu	Ni	Cr	Mo	Ca	Nb	Ti		REM
17	0.04	0.38	1.35	0.036	0.072	0.0043	0.019	0.012	0.0001	-	-	-	-	-	-	-	-	Comparative steel
18	0.19	0.31	1.30	0.046	0.179	0.0049	0.022	0.008	0.0003	-	-	-	-	-	-	-	-	
19	0.12	0.04	1.39	0.018	0.110	0.0051	0.015	0.015	0.0001	-	-	-	-	-	-	-	-	
20	0.06	0.57	1.49	0.036	0.260	0.0019	0.014	0.006	0.0001	-	-	-	-	-	-	-	-	
21	0.15	0.55	0.98	0.022	0.167	0.0025	0.013	0.007	0.0001	-	-	-	-	-	-	-	-	
22	0.12	0.12	1.66	0.028	0.057	0.0026	0.015	0.008	0.0001	-	-	-	-	-	-	-	-	
23	0.10	0.53	1.32	0.026	0.166	0.0019	0.027	0.009	0.0002	-	-	-	-	-	-	-	-	
24	0.10	0.21	1.31	0.031	0.084	0.0044	0.017	0.021	0.0002	-	-	-	-	-	-	-	-	
25	0.05	0.10	1.64	0.035	0.048	0.0029	0.012	0.013	0.0002	-	-	-	-	-	-	-	-	
26	0.13	0.16	1.24	0.020	0.303	0.0042	0.018	0.007	0.0001	-	-	-	-	-	-	-	-	
27	0.09	0.43	1.15	0.046	0.245	0.0008	0.018	0.004	0.0002	-	-	-	-	-	-	-	-	
28	0.17	0.22	1.35	0.031	0.179	0.0061	0.014	0.004	0.0001	-	-	-	-	-	-	-	-	
29	0.11	0.40	1.31	0.021	0.060	0.0031	0.012	0.004	0.0004	-	-	-	-	-	-	-	-	
30	0.14	0.34	1.45	0.029	0.041	0.0020	0.018	0.008	0.0002	0.33	0.28	-	-	-	0.001	-	-	
31	0.15	0.35	1.42	0.019	0.051	0.0033	0.018	0.003	0.0002	-	-	-	-	-	0.035	0.009	-	
32	0.15	0.35	1.45	0.041	-	0.0042	0.021	0.006	-	-	-	-	-	-	0.013	0.012	-	
33	0.16	0.36	1.00	0.020	-	0.0039	0.015	0.007	0.0001	0.23	0.90	-	-	-	-	-	-	

*1 Underlines indicate outside the applicable range.

[0061] For each obtained steel sheet pile, steel sheet pile microstructure observation, a tensile test, and a toughness test were conducted. The evaluation methods are as follows.

[0062] <Microstructure observation>

5 A test piece was collected from a position of 1/4 of the web thickness of the web of the steel sheet pile, and used for microstructure observation. Before the observation, the collected test piece was surface-polished and etched with nital. After this, cross-sectional observation with
10 100 magnification was performed in the thickness direction of the web using an optical microscope to identify the type of microstructure. In an observation field of $800\ \mu\text{m} \times 600\ \mu\text{m}$, ferrite, pearlite, and bainite and martensite were converted into three gradations of white, black, and gray respectively for discrimination by image analysis using a watershed algorithm, to obtain the area ratio of each microstructure. For the average grain size of ferrite, the area
15 of each crystal grain of ferrite in the observation field was calculated by image analysis using a watershed algorithm same as above, the equivalent circle diameter of each crystal grain was taken to be the grain size of ferrite, and the average value in the observation field was calculated. As the maximum grain size of ferrite, the maximum value of the equivalent circle diameters in the
20 observation field was used. Here, the average grain size of ferrite was calculated using only crystal grains having a grain size of $3\ \mu\text{m}$ or more in equivalent circle diameter observable in the observation field. For the observation of martensite-austenite constituents, the same test piece as above was subjected to two-step etching treatment of electrolytic etching and nital
25 etching to dissolve cementite, and ten or more observation fields were randomly observed using a SEM with about 1000 magnification and the area ratio of martensite-austenite constituents was determined by the same image analysis as above.

[0063] <Tensile test>

30 A JIS No. 1A tensile test piece defined in JIS Z 2201 was collected from a position of 1/4 of the web thickness of the web of the steel sheet pile so that the tensile direction would be the longitudinal direction, and a tensile test was conducted in accordance with JIS Z 2241 to determine the yield point (YP) and the tensile strength (TS).

35 **[0064]** <Toughness test>

 A 2-mm V-notch Charpy impact test piece defined in JIS Z 2202 was

collected from a position of 1/4 of the web thickness of the web of the steel sheet pile, and a Charpy impact test was conducted in accordance with JIS Z 2242. The impact test was conducted in the temperature range of -80 °C to 40 °C, and the absorbed energy (vE_0) at 0 °C and the fracture appearance transition temperature ($vTrs$) at a percent ductile fracture of 50 % were determined.

5 **[0065]** The examination results are shown in Table 2. The test results of the steel sheet piles of Examples (Nos. 1 to 17 in Table 2) produced under the predetermined production conditions using conforming steel satisfying the predetermined chemical composition all satisfied the desired properties (yield stress YP: 440 MPa or more, fracture appearance transition temperature $vTrs$ at a percent ductile fracture of 50 %: -10 °C or less). In each Example, no significant shape changes such as deflection and camber occurred, demonstrating that the steel sheet pile can be produced stably with high productivity.

10 **[0066]** In each Comparative Example (Nos. 18 to 38 in Table 2) not satisfying the predetermined chemical composition and/or the predetermined production conditions, at least one of the yield stress and the fracture appearance transition temperature ($vTrs$) at a percent ductile fracture of 50 % did not satisfy the required properties.

[0067] [Table 2]

Test No.	Steel sample No.	Heating temperature of steel material [°C]	Hot rolling conditions			Microstructure				Steel properties				Remarks
			Average rolling reduction ratio per pass in range of 900°C to 1150°C [%]	Cumulative rolling reduction ratio in range of 800°C to 1150°C [%]	Finish temperature of intermediate rolling [°C]	Area ratio of ferrite [%]	Average grain size of ferrite [μm]	Maximum grain size of ferrite [μm]	Area ratio of martensite-austenite constituents [%]	TS: tensile strength [MPa]	YP: yield stress [MPa]	vE0 [J]	vTrs [°C]	
1	1	1320	14	71	727	80	12	29	0.0	612	484	219	-19	Example
2	2	1220	14	87	818	71	10	36	0.9	629	517	165	-12	
3	3	1340	12	60	742	78	14	35	0.0	597	475	217	-22	
4	4	1280	12	73	740	88	15	36	0.0	573	474	180	-15	
5	5	1270	14	83	796	81	9	33	0.0	672	512	178	-13	
6	6	1290	19	61	725	82	8	18	0.0	554	446	282	-31	
7	7	1310	10	69	783	85	10	36	0.0	587	476	233	-27	
8	8	1280	12	90	816	87	8	27	0.0	578	469	285	-36	
9	9	1280	15	84	722	77	9	24	0.0	627	492	257	-25	
10	10	1350	13	64	724	84	14	30	0.2	562	473	228	-21	
11	11	1200	11	61	773	79	13	34	0.1	650	501	201	-19	
12	12	1300	12	69	798	78	13	35	0.0	553	443	251	-24	
13	13	1310	18	67	659	77	13	26	0.0	581	442	199	-16	
14	14	1280	10	70	728	72	15	39	0.8	611	479	197	-17	
15	15	1290	10	75	890	77	11	36	0.0	610	498	203	-24	
16	16	1290	12	72	796	76	12	30	0.0	620	491	223	-20	
17	3	1340	15	60	731	83	9	27	0.0	615	502	264	-30	

[Table 2]

[Table 2](cont'd)

Test No.	Steel sample No.	Heating temperature of steel material [°C]	Hot rolling conditions			Microstructure				Steel properties				Remarks
			Average rolling reduction ratio per pass in range of 900°C to 1150°C [%]	Cumulative rolling reduction ratio in range of 800°C to 1150°C [%]	Finish temperature of intermediate rolling [°C]	Area ratio of ferrite [%]	Average grain size of ferrite [μm]	Maximum grain size of ferrite [μm]	Area ratio of martensite-austenite constituents [%]	TS: tensile strength [MPa]	YP: yield stress [MPa]	vE0 [J]	vTrs [°C]	
18	<u>17</u>	1310	13	74	821	90	13	33	0.0	527	<u>422</u>	250	-22	Comparative Example
19	<u>18</u>	1200	14	62	789	<u>69</u>	9	16	<u>1.2</u>	675	522	128	<u>-6</u>	
20	<u>19</u>	1290	15	81	748	79	10	22	0.0	568	<u>427</u>	222	-24	
21	<u>20</u>	1280	11	71	751	77	14	37	<u>1.1</u>	562	449	133	<u>-9</u>	
22	<u>21</u>	1350	10	85	824	75	14	36	0.1	561	<u>438</u>	165	-15	
23	<u>22</u>	1300	15	71	732	<u>67</u>	13	24	<u>1.3</u>	584	460	109	<u>-5</u>	
24	<u>23</u>	1290	17	63	779	80	9	19	0.0	592	471	127	<u>-8</u>	
25	<u>24</u>	1290	11	66	822	84	15	36	0.0	573	454	144	<u>-7</u>	
26	<u>25</u>	1340	11	74	761	88	<u>16</u>	<u>41</u>	0.0	520	<u>429</u>	138	<u>-9</u>	
27	<u>26</u>	1210	14	67	707	81	9	26	0.0	628	506	139	<u>-8</u>	
28	<u>27</u>	1270	19	73	705	85	12	24	0.0	531	<u>435</u>	206	-20	
29	<u>28</u>	1330	11	65	737	74	11	28	0.4	612	495	130	<u>-5</u>	
30	<u>29</u>	1260	13	70	788	75	10	25	<u>1.1</u>	573	458	124	<u>-6</u>	
31	<u>30</u>	1290	11	<u>58</u>	<u>1050</u>	77	<u>20</u>	35	0.0	559	<u>436</u>	155	<u>-9</u>	
32	<u>31</u>	1280	<u>7</u>	83	755	83	9	<u>42</u>	1.0	591	445	142	<u>-4</u>	
33	<u>32</u>	1300	<u>7</u>	77	784	76	15	<u>43</u>	1.0	568	<u>435</u>	190	<u>-9</u>	
34	<u>33</u>	1300	<u>8</u>	90	859	75	14	<u>44</u>	<u>1.3</u>	561	<u>429</u>	92	<u>3</u>	
36	2	1290	<u>9</u>	69	780	70	13	<u>42</u>	0.8	606	478	123	<u>-4</u>	
37	15	1330	11	<u>58</u>	857	79	<u>17</u>	38	0.1	579	463	146	<u>-7</u>	
38	3	1330	12	<u>55</u>	<u>904</u>	88	<u>19</u>	37	0.0	567	440	171	<u>-8</u>	

*1 Underlines indicate outside the applicable range.

REFERENCE SIGNS LIST

5	[0068]	1	hat-shaped steel sheet pile
		2	web
		3	flange
		4	flange
		5	arm portion
		6	arm portion
		7	claw portion
		8	claw portion
10		9	straight steel sheet pile
		10	web
		11	claw portion
		12	claw portion
15	pile	13	caliber of final pass in rough rolling of hat-shaped steel sheet
		14	caliber of final pass in intermediate rolling of hat-shaped steel
		15	caliber of final pass in finish rolling of hat-shaped steel sheet
			sheet pile
			pile

CLAIMS

[Claim 1] A steel sheet pile comprising:

a chemical composition containing, in mass%,

5 C: 0.05 % to 0.18 %,

Si: 0.05 % to 0.55 %,

Mn: 1.00 % to 1.65 %,

sol.Al: 0.080 % or less,

V: 0.050 % to 0.300 %, and

10 N: 0.0010 % to 0.0060 %

with a balance consisting of Fe and inevitable impurities, where contents of P, S, and B as the inevitable impurities are P: 0.025 % or less, S: 0.020 % or less, and B: 0.0003 % or less respectively;

15 a microstructure that is a ferrite-based microstructure and in which an average grain size of ferrite is 15 μm or less, a maximum grain size of ferrite is 40 μm or less, and an area ratio of martensite-austenite constituents with respect to the microstructure is 1.0 % or less;

a yield stress of 440 MPa or more; and

vTrs of -10 °C or less.

20

[Claim 2] The steel sheet pile according to claim 1, wherein the chemical composition further contains, in mass%, one or more selected from the group consisting of

Cu: 0.50 % or less,

25 Ni: 0.50 % or less,

Cr: 0.50 % or less,

Mo: 0.30 % or less,

Ca: 0.0050 % or less,

Nb: 0.005 % or less,

30 Ti: 0.025 % or less, and

REM: 0.005 % or less.

[Claim 3] A production method for a steel sheet pile having: a microstructure that is a ferrite-based microstructure and in which an average grain size of ferrite is 15 μm or less, a maximum grain size of ferrite is 40 μm or less, and an area ratio of martensite-austenite constituents with respect to

35

the microstructure is 1.0 % or less; a yield stress of 440 MPa or more; and v_{Trs} of -10 °C or less, the production method comprising:

heating a steel material to 1200 °C to 1350 °C, the steel material having a chemical composition containing, in mass%,

- 5 C: 0.05 % to 0.18 %,
 Si: 0.05 % to 0.55 %,
 Mn: 1.00 % to 1.65 %,
 sol.Al: 0.080 % or less,
 V: 0.050 % to 0.300 %, and
10 N: 0.0010 % to 0.0060 %

with a balance consisting of Fe and inevitable impurities, where contents of P, S, and B as the inevitable impurities are P: 0.025 % or less, S: 0.020 % or less, and B: 0.0003 % or less respectively; and

- subjecting the steel material to hot rolling in which an average rolling
15 reduction ratio per pass in a range of 900 °C to 1150 °C is 10 % or more, an
cumulative rolling reduction ratio in a range of 800 °C to 1150 °C is 60 % or
more, and a finish temperature of intermediate rolling is 650 °C to 900 °C.

- [Claim 4] The production method for a steel sheet pile according to claim
20 3, wherein the chemical composition further contains, in mass%, one or more
selected from the group consisting of

- Cu: 0.50 % or less,
 Ni: 0.50 % or less,
 Cr: 0.50 % or less,
25 Mo: 0.30 % or less,
 Ca: 0.0050 % or less,
 Nb: 0.005 % or less,
 Ti: 0.025 % or less, and
 REM: 0.005 % or less.