

DESCRIPTION

TITLE

STEEL SHEET PILE AND METHOD OF MANUFACTURING SAME

5

TECHNICAL FIELD

[0001] This disclosure relates to a steel sheet pile applied to permanent or temporary structures in the fields of civil engineering and construction, and to a method of manufacturing the same.

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BACKGROUND

[0002] Steel sheet piles are required to have high strength and toughness because they are subjected to high loads when used for quay walls and earth retaining. For example, steel sheet piles with a yield point (hereinafter referred to as “YP”) of 290 MPa or more and even 390 MPa or more are used. Steel sheet piles having a strength of YP of 440 MPa or more may be essential in even more severe environments.

[0003] Adding alloying elements and performing rolling in the non-recrystallization temperature range of austenite are common methods when manufacturing high-strength and high-toughness steel products. However, in the manufacture of steel sheet piles with complex shapes, rolling and forming at high temperatures with less deformation resistance are preferred from the viewpoint of formability, and the addition of alloy which may increase deformation resistance is sometimes limited.

[0004] Although the Japanese Industrial Standards (JIS) for steel sheet piles (SYW) specifies the Charpy absorbed energy at 0 °C, it is expected that steel sheet piles with even higher toughness will be required in the future because steel sheet piles are used even in environments below 0 °C, such as during the cold season in Japan.

[0005] In this background, research and development of high-strength and high-toughness steel sheet piles are being conducted.

JP 2018-83963 A (PTL 1) proposes a steel sheet pile with a YP of 440 MPa or more and high toughness, where more than 0.05 % of Nb is added to the chemical composition.

[0006] JP 2018-90845 A (PTL 2) proposes a steel sheet pile with a YP of 440 MPa or more and high toughness, where the average grain size of ferrite, the

area ratio of martensite austenite constituent, and the number density of precipitates are optimized by adding 0.030 % or more of Nb together with V to the chemical composition and controlling the rolling reduction ratio at 1000 °C or lower.

5 **[0007]** JP 2000-17378 A (PTL 3) proposes a steel sheet pile with high strength, high toughness, and excellent underwater weldability, the steel sheet pile having a chemical composition in which Nb and B are added to a low-carbon steel containing 0.005 % to 0.030 % of C.

10 **[0008]** JP 2006-249513 A (PTL 4) proposes a steel sheet pile with high toughness, where either or both of V and Nb are added to the chemical composition, the rolling reduction ratio in a temperature range of 900 °C or lower, that is, the non-recrystallization temperature range, is controlled, and accelerated cooling is performed after the end of rolling.

15 **[0009]** On the other hand, JP 2002-294392 A (PTL 5) proposes a steel sheet pile with a YP of 340 MPa or more and high toughness, where Nb in inevitable impurities is limited to 0.005 % or less.

20 **[0010]** JP 2007-332414 A (PTL 6) and JP 2008-221318 A (PTL 7) propose steel sheet piles with a YP of 440 MPa or more and $vTrs$ of -10 °C or lower, where water cooling is performed at predetermined locations during hot rolling or after the end of rolling.

CITATION LIST

Patent Literature

25 **[0011]** PTL 1: JP 2018-83963 A
 PTL 2: JP 2018-90845 A
 PTL 3: JP 2000-17378 A
 PTL 4: JP 2006-249513 A
 PTL 5: JP 2002-294392 A
 PTL 6: JP 2007-332414 A
30 PTL 7: JP 2008-221318 A

SUMMARY

(Technical Problem)

35 **[0012]** The techniques described in PTLS 1 and 2 provide steel sheet piles with high strength and high toughness by adding 0.030 % or more of Nb to the chemical composition. However, Nb tends to increase the deformation

resistance during hot rolling regardless of whether it is in solute or precipitation, and it is necessary to strictly control the shape during hot rolling.

[0013] In the technique described in PTL 3, the C content in the chemical composition is as low as 0.005 % to 0.030 %, so that the decarburization process during steelmaking takes a long time, resulting in low productivity in a refining process.

[0014] In the technique described in PTL 4, the rolling reduction ratio in the non-recrystallization temperature range needs to be 20 % or more and the shape during hot rolling needs to be strictly controlled to obtain a steel sheet pile with high toughness, and accelerated cooling of specified parts is required after the end of rolling, which causes unavoidable shape changes such as bending and warping.

[0015] On the other hand, the technique described in PTL 5 proposes a steel sheet pile with a YP of 340 MPa or more and high toughness, where complete recrystallization of austenite is accelerated by limiting the rolling temperature and the rolling reduction ratio in the final pass, and a uniform microstructure is obtained. However, the YP is less than 440 MPa, and further improvement in YP is desired.

[0016] In the techniques described in PTL 6 and 7, water cooling of specified parts is essential to obtain a steel sheet pile with a YP of 440 MPa or more and $vTrs$ of $-10\text{ }^{\circ}\text{C}$ or lower, which causes unavoidable shape changes such as bending and warping.

[0017] It could thus be helpful to stably provide high-strength and high-toughness steel sheet piles with high productivity. As used herein, the high strength refers to a YP of 440 MPa or more, for example, and the high toughness refers to a fracture appearance transition temperature at 50-percent ductile fracture (hereinafter referred to as " $vTrs$ ") of $-10\text{ }^{\circ}\text{C}$ or lower.

(Solution to Problem)

[0018] An effective means of ensuring high toughness is to reduce fracture units caused by refinement of crystal grains. One method of refinement of crystal grains is to use precipitates present inside or at the grain boundary of prior austenite grains as nuclei for ferrite formation. We investigated the mechanism of refinement of crystal grains by precipitates and found that the precipitates should have a certain particle size or larger particle size in order to contribute to the refinement of ferrite grains. It was also found that the critical particle size tends to decrease as the ferrite transformation start

temperature decreases.

[0019] Further, precipitation dispersion strengthening by precipitates is an effective means of ensuring high strength. Assuming that the particle size of the precipitate has the same area ratio, the increase in strength becomes
5 remarkable as the particle size of the precipitates becomes fine.

[0020] Precipitates having a certain particle size or larger particle size are necessary for ensuring high toughness. On the other hand, fine precipitates are effective in ensuring high strength. These two factors are in an antinomic relationship, and conventionally it has been difficult to achieve both high
10 strength and high toughness by utilizing precipitates. One solution to this is to lower the ferrite transformation start temperature by accelerated cooling, but this may undesirably cause bending and warping. Positively performing rolling in the non-recrystallization temperature range is another effective solution, but this requires strict shape control.

[0021] It is effective to have a chemical composition containing V to achieve refinement of crystal grains by precipitates. That is, V precipitates in austenite at relatively high temperatures as V carbonitrides and has a matching interface with ferrite, so that it makes great contribution as nuclei for ferrite formation. Further, it is effective to have a chemical composition containing
15 Nb to ensure high strength. That is, Nb precipitates finely in austenite as Nb carbonitrides with a size on the order of several nanometers mainly by strain-induced precipitation, which is expected to cause dispersion strengthening by precipitates.

[0022] Based on the above, we investigated the chemical composition ratio of V and Nb to control precipitates when using a chemical composition in which
25 V and Nb are added in combination. As a result, we found that there is an appropriate range for the chemical composition ratio of V and Nb to achieve both the refinement of crystal grains by using V carbonitrides or complex carbonitrides of V and Nb as nuclei for ferrite formation, and the dispersion
30 strengthening by precipitates.

[0023] Only optimizing the chemical composition ratio of V and Nb is insufficient, so we investigated the rolling conditions that can ensure high productivity, high strength and high toughness, and found that performing rolling effectively just above the non-recrystallization temperature range is an
35 effective means of achieving this. In other words, it is essential to precipitate Nb carbonitrides or complex carbonitrides of V and Nb by strain-induced

precipitation. In this case, it is possible to relax the restrictions on rolling conditions over a wide temperature range as in the past and the rolling reduction ratio (hereinafter also referred to as “CR ratio”) in the non-recrystallization temperature range of austenite, and there is no need to perform accelerated cooling that affects the occurrence of bending and warping.

[0024] We found that, for V precipitates, Nb precipitates and their complex precipitates, a certain area ratio or larger area ratio is required for precipitates with a fine particle size that can contribute to an increase in strength and precipitates with a large particle size that can serve as nuclei for ferrite formation, in order to effectively improve strength and toughness.

[0025] Based on the above, we found a way to provide a steel sheet pile with a high strength of YP of 440 MPa or more and high toughness of vTrs of -10 °C or lower by dispersion strengthening and uniform microstructure refinement by V carbonitrides, Nb carbonitrides, or their complex precipitates. We thus provide the following.

[0026] (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 % to 1.65 %,
sol.Al: 0.080 % or less,
V: 0.005 % to 0.250 %,
Nb: 0.005 % or more and less than 0.030 %, and
N: 0.0010 % to 0.0060 %,
in a range satisfying the following formula (1):

$$-0.010 \leq [\%Nb] - 0.1[\%V] \leq 0.020 \quad (1)$$

where [%V] and [%Nb] are a content of V and Nb in steel in mass%, respectively, with the balance is Fe and inevitable impurities, where 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, and

a microstructure in which an area fraction of ferrite is 70 % or more, an area ratio of martensite austenite constituent is 1.0 % or less, a total area ratio of V carbonitrides, Nb carbonitrides and complex carbonitrides of V and Nb with a particle size of 10 nm or less is 2.6 % or more, and a total area ratio of V carbonitrides, Nb carbonitrides and complex precipitates of V and Nb having a particle size of d in nanometer satisfying the following formula (2) is

0.30 % or more:

$$d \geq 5[(Ae_3 - Ar_3)/Ae_3]^{-0.63} \quad (2)$$

where Ae_3 is equilibrium transformation temperature in °C from austenite to ferrite, and Ar_3 is ferrite transformation start temperature in °C during cooling,

wherein the ferrite has an average grain size of 15 μm or less and a maximum grain size of 40 μm or less, and

the steel sheet pile has a yield point of 440 MPa or more and $vTrs$ of -10 °C or lower.

[0027] The Ae_3 and Ar_3 are determined by the following formulas (3) and (4), respectively.

[Math. 1]

$$Ae_3 = 912 - 203\sqrt{[\%C]} + 45[\%Si] - 30[\%Mn] - 20[\%Cu] - 11[\%Cr] - 15[\%Ni] + 32[\%Mo] \quad (3)$$

$$Ar_3 = 910 - 310[\%C] - 80[\%Mn] - 20[\%Cu] - 15[\%Cr] - 55[\%Ni] - 80[\%Mo] \quad (4)$$

where $[\%C]$, $[\%Si]$, $[\%Mn]$, $[\%Cu]$, $[\%Cr]$, $[\%Ni]$ and $[\%Mo]$ are the content (mass%) of C, Si, Mn, Cu, Cr, Ni and Mo in the steel, respectively.

[0028] 2. The steel sheet pile according to the aspect (1), wherein the chemical composition further contains, in mass%, at least one 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,

Ti: 0.025 % or less, and

REM: 0.005 % or less.

[0029] 3. A method of manufacturing a steel sheet pile with a yield point of 440 MPa or more and $vTrs$ of -10 °C or lower, comprising:

heating a steel material having the chemical composition defined in the aspect (1) or (2) to 1200 °C to 1350 °C, and

subjecting the steel material to hot rolling including rough rolling, intermediate rolling and finish rolling, wherein a cumulative rolling reduction ratio at 900 °C to 1000 °C is 20 % or more, a rolling reduction ratio in non-recrystallization temperature range of austenite is 10 % or more and less than

20 %, and a finish temperature of the intermediate rolling is 650 °C to 900 °C.
(Advantageous Effect)

[0030] According to the present disclosure, it is possible to stably provide high-strength and high-toughness steel sheet piles having a YP of 440 MPa or more and $vTrs$ of -10 °C or lower with high productivity, which is highly useful in industrial terms.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] In the accompanying drawings:
10 FIGS. 1A and 1B illustrate cross-sectional shapes of steel sheet piles;
 FIG. 2 illustrates typical calibers in a hot rolling process of a hat-type steel sheet pile;
 FIG. 3 is a graph illustrating the relationship between the area ratio of precipitates satisfying the formula (2) and the $vTrs$; and
15 FIG. 4 is a graph illustrating the relationship between the area ratio of precipitates with a size of 10 nm or less and the yield point.

DETAILED DESCRIPTION

[0032] A typical example of the form of a steel sheet pile is the hat-type steel sheet pile 1 illustrated in FIG. 1A, and another example is the straight-type steel sheet pile 9 illustrated in FIG. 1B, both of which obtain the final shape via the calibers illustrated in FIG. 2. The details of the form and the manufacturing procedure are described below.

<Steel sheet pile>

25 The following describes the chemical composition and the microstructure of the steel sheet pile of the present disclosure in detail.

[Chemical composition]

 First, the reasons for the limitation on the chemical composition of the steel sheet pile of the present disclosure will be described. In the following description, the “%” representations indicating the content of each element are in “mass%” unless otherwise specified.

 In the present specification, V carbonitride is also referred to as “V precipitate” or “V(C,N)”, Nb carbonitride is also referred to as “Nb precipitate” or “Nb(C,N)”, and complex carbonitride of V and Nb is also referred to as
35 “their complex precipitate” or “(V,Nb)(C,N)”.

[0033] C: 0.05 % to 0.18 %

C is an essential element that combines with V, Nb and N in steel and precipitates as carbonitrides such as V(C,N), Nb(C,N), or (V,Nb)(C,N) to ensure stable strength and toughness of base metal, and the content of C needs to be 0.05 % or more. On the other hand, if the content exceeds 0.18 %, bainite including martensite austenite constituent is formed, and the toughness is greatly deteriorated due to an increase in martensite austenite constituent and an excess of precipitates. Therefore, the C content is set to 0.05 % to 0.18 % in the present disclosure. The C content is preferably 0.10 % or more. The C content is preferably 0.16 % or less.

10 **[0034]** Si: 0.05 % to 0.55 %

Si is an element that increases the strength of base metal by solid solution strengthening, and the content of Si needs to be 0.05 % or more. On the other hand, excessive Si contributes to the formation of martensite austenite constituent, which deteriorates the toughness. Therefore, the Si content is set to 0.55 % or less. Thus, the Si content is set to 0.05 % to 0.55 %. The Si content is preferably 0.10 % or more. The Si content is preferably 0.50 % or less.

[0035] Mn: 1.00 % to 1.65 %

Mn, like Si, is a relatively inexpensive element that increases the strength of steel, and therefore it is an element necessary for increasing the strength. However, when the Mn content is less than 1.00 %, the effect is insufficient. On the other hand, a Mn content exceeding 1.65 % contributes to the formation of upper bainite including martensite austenite constituent, which greatly deteriorates the toughness. Therefore, the Mn content is set to 1.00 % to 1.65 %. The Mn content is preferably 1.10 % or more. The Mn content is preferably 1.60 % or less.

[0036] sol.Al: 0.080 % or less

Al is an element added as a deoxidizer. However, since the effect of Al as a deoxidizer saturates when the content as sol.Al exceeds 0.080 %, the content of sol.Al is set to 0.080 % or less. The lower limit is not particularly limited. However, it is preferably 0.001 % or more for deoxidation. It is more preferably 0.003 % or more. It is preferably 0.060 % or less.

[0037] V: 0.005 % to 0.250 %

V is an important element that precipitates in austenite as V(C,N) or (V,Nb)(C,N) during rolling or cooling and functions as nucleation sites of ferrite, thereby refining crystal grains. V also has an effect of increasing the

strength of base metal by dispersion strengthening as precipitates, and it is an essential element for ensuring strength and toughness. To achieve the above effects, the V content needs to be 0.005 % or more. On the other hand, if the V content exceeds 0.250 %, it causes precipitation embrittlement, which greatly deteriorates the toughness of base metal. Therefore, the V content is set to 0.005 % to 0.250 %. The V content is preferably 0.075 % or more. It is more preferably more than 0.080 %. The V content is preferably 0.200 % or less.

[0038] Nb: 0.005 % or more and less than 0.030 %

Nb precipitates in austenite as Nb(C,N) or (V,Nb)(C,N) with a size on the order of several nanometers mainly by strain-induced precipitation during rolling, which has the effect of suppressing austenite recrystallization and refining crystal grains. Nb also has an effect of increasing the strength of base metal by dispersion strengthening as precipitates, and it is an essential element for ensuring strength and toughness. To achieve the above effects, the Nb content needs to be 0.005 % or more. It is preferably 0.010 % or more. On the other hand, Nb increases the deformation resistance in hot work, and it tends to deteriorate the toughness due to precipitation embrittlement when the content is 0.030 % or more. Therefore, the Nb content is set to less than 0.030 %. It is preferably 0.025 % or less.

[0039] N: 0.0010 % to 0.0060 %

N is a useful element that combines with V, Nb and C in steel and forms V(C,N), Nb(C,N) or (V,Nb)(C,N) to improve the strength and toughness of base metal, and the content of N needs to be 0.0010 % or more. However, if the N content exceeds 0.0060 %, the toughness of base metal is greatly deteriorated due to precipitation embrittlement. Therefore, the N content is set to 0.0010 % to 0.0060 % in the present disclosure. The N content is preferably 0.0015 % or more. The N content is preferably 0.0055 % or less.

[0040] In the present disclosure, it is important that V and Nb should satisfy the relationship of the following formula (1) where the contents (mass%) of V and Nb are [%V] and [%Nb], respectively, in addition to each element satisfying the above range.

$$-0.010 \leq [\%Nb] - 0.1[\%V] \leq 0.020 \quad (1)$$

[0041] We evaluated the strength and the toughness of various steel sheet piles with steel compositions in the above ranges. As a result, we found that the balance of amounts of precipitated V(C,N), Nb(C,N) or (V,Nb)(C,N) is

important for obtaining excellent strength and toughness. Specifically, when the value calculated by $[\%Nb] - 0.1[\%V]$ is less than -0.010, that is, when the V content is too high, V precipitates in large amounts as V(C,N) or (V,Nb)(C,N) at high temperatures and coarsens, and the amount of finely precipitated Nb(C,N) or (V, Nb)(C, N) due to strain-induced precipitation decreases, which deteriorates the strength.

[0042] In other words, by controlling the value calculated by the above formula, which is a parameter based on the contents of V and Nb, to -0.010 or more, V functions as nucleation sites of ferrite and uniformly refines the microstructure, so that it is possible to ensure sufficient size and quantity of precipitated V(C,N) or (V,Nb)(C,N) that contributes to the improvement of toughness, and it is possible to ensure a sufficient amount of finely precipitated Nb(C,N) or (V,Nb)(C,N) that contributes to an increase in strength. On the other hand, when the value of $[\%Nb] - 0.1[\%V]$ exceeds 0.020, that is, when the Nb content is too high, the precipitation of V(C,N) or (V,Nb)(C,N) of sufficient size and quantity, which serves as nucleation sites of ferrite and contributes to the improvement of toughness, decreases, and the toughness of base metal is deteriorated. Therefore, in the present disclosure, the value calculated by $[\%Nb] - 0.1[\%V]$ is set in the range of -0.010 to 0.020. The value calculated by the above formula is preferably -0.005 or more. It is preferably 0.015 or less.

[0043] In the chemical composition of the present disclosure, the balance other than the above elements is Fe and inevitable impurities. Among the inevitable impurities, the upper limits for the contents of P, S and B are set as follows.

[0044] P: 0.025 % or less

P is present in steel as an inevitable impurity. However, an excessive P content deteriorates the toughness of steel, so that the P content is set to 0.025 % or less. The P content is preferably as low as possible, and it may be 0 %. However, an excessive reduction in P content leads to a decrease in productivity due to lengthening of a refining process, so that the P content is preferably 0.005 % or more.

[0045] S: 0.020 % or less

S, like P, is an inevitable impurity in steel, and it also exists as an A-type inclusion. An excessive S content causes an excessive increase in A-type inclusions, which deteriorates the toughness of steel. Therefore, the S content is set to 0.020 % or less. The S content is preferably as low as

possible, and it may be 0 %. However, an excessive reduction in S content leads to a decrease in productivity due to lengthening of a refining process, so that the S content is preferably 0.002 % or more.

[0046] B: 0.0003 % or less

5 B is an element that segregates at grain boundaries in steel, and it has an effect of increasing the grain boundary strength. When low-quality raw materials are used, the steel may contain more than 0.0003 % of B. In this case, coarse grain boundary precipitates are formed, and the quench hardenability increases, which accelerates the formation of martensite
10 austenite constituent and deteriorates the toughness. Therefore, the B content is set to 0.0003 % or less. It is preferably 0.0002 % or less.

[0047] The above are the basic chemical composition of the present disclosure, and the chemical composition may contain at least one of the following elements as needed.

15 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,
20 Ti: 0.025 % or less, and
 REM: 0.005 % or less.

[0048] Cu: 0.50 % or less

 Cu is an element that can further increase the strength of steel by solid solution strengthening. To obtain this effect, the Cu content is preferably 0.01
25 % or more. However, if the content exceeds 0.50 %, Cu cracking is likely to occur. Therefore, when Cu is contained in the chemical composition of the steel, the content is preferably 0.50 % or less.

[0049] Ni: 0.50 % or less

 Ni, like Cu, is an element that dissolves in steel and increases the
30 strength of the steel without deteriorating the ductility and toughness. To obtain this effect, the Ni content is preferably 0.01 % or more. It is particularly preferable to add Ni in combination with Cu to suppress Cu cracking. On the other hand, an excessive Ni content contributes to the formation of martensite austenite constituent, and Ni is an expensive element.
35 From these points of view, the Ni content is preferably 0.50 % or less.

[0050] Cr: 0.50 % or less

Cr is an element that can further increase the strength of steel by solid solution strengthening. To obtain this effect, the Cr content is preferably 0.01 % or more. On the other hand, an excessive Cr content contributes to the formation of martensite austenite constituent, so that the Cr content is preferably 0.50 % or less.

[0051] Mo: 0.30 % or less

Mo is an element that can further increase the strength of steel by solid solution strengthening. To obtain this effect, the Mo content is preferably 0.01 % or more. On the other hand, an excessive Mo content contributes to the formation of martensite austenite constituent, so that the Mo content is preferably 0.30 % or less.

[0052] Ca: 0.0050 % or less

Ca combines with S and O to reduce MnS in steel, thereby improving the toughness and ductility of the steel. To obtain this effect, the Ca content is preferably 0.0005 % or more. On the other hand, if the Ca content exceeds 0.0050 %, the cleanliness decreases, which tends to deteriorate the toughness. Therefore, the Ca content is preferably 0.0050 % or less.

[0053] Ti: 0.025 % or less

Ti precipitates in austenite as TiN and has an effect of refining crystal grains. To obtain this effect, the Ti content is preferably 0.001 % or more. On the other hand, if Ti is excessively contained, precipitated TiN is coarsened and crystal grains are coarsened, which tends to deteriorate the toughness. Therefore, the Ti content is preferably 0.025 % or less.

[0054] REM: 0.005 % or less

REM (rare earth elements), like Ca, combines with S and O to reduce MnS in steel, thereby improving the toughness and ductility of the steel. To obtain this effect, the REM content is preferably 0.001 % or more. On the other hand, if the REM content exceeds 0.005 %, the cleanliness decreases, which tends to deteriorate the toughness. Therefore, the REM content is preferably 0.005 % or less.

[0055] Next, the microstructure of the steel sheet pile of the present disclosure will be described. In the present disclosure, it is enough to specify the microstructure of a web portion of the steel sheet pile. This is because the web portion has the lowest amount of deformation and a coarse microstructure, which renders it the most difficult portion to ensure strength and toughness. Therefore, if the web portion satisfies the microstructure conditions described

below, the other portions also satisfy the microstructure conditions described below.

[0056] It is essential for the microstructure that the area fraction of ferrite should be 70 % or more, the area ratio of martensite austenite constituent should be 1.0 % or less, the average grain size of ferrite should be 15 μm or less, and the maximum grain size of ferrite should be 40 μm or less.

[0057] [Ferrite-based microstructure]

The microstructure of the steel sheet pile is a ferrite-based microstructure. A ferrite-based microstructure refers to a microstructure in which the area ratio of ferrite is 70 % or more. If the area ratio of ferrite is less than 70 %, the hard phase increases, and the toughness may deteriorate. The upper limit of the area ratio of ferrite is preferably less than 90 % from the viewpoint of ensuring strength. Although the second phase is not particularly limited, examples thereof include pearlite, bainite microstructure including martensite austenite constituent, and martensite. Note that the area ratio of martensite austenite constituent is limited as described below.

[0058] [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 , the YP decreases, and it is difficult to ensure toughness. To obtain even better strength and toughness, the average grain size of ferrite is desirably 12 μm or less, and the maximum grain size of ferrite is desirably 30 μm or less. The average grain size and the maximum grain size of ferrite can be measured according to the measurement method described in the Examples section below.

The lower limit of the average grain size of ferrite is not particularly limited. However, it is preferably 5 μm or more and more preferably 10 μm or more from the viewpoint of ensuring tensile strength. The lower limit of the maximum grain size of ferrite is not particularly limited. However, it is preferably 20 μm or more and more preferably 25 μm or more also from the viewpoint of ensuring tensile strength.

[0059] [Area ratio of martensite austenite constituent: 1.0 % or less]

In the microstructure of the steel sheet pile, the area ratio of martensite austenite constituent is 1.0 % or less. If the area ratio of martensite austenite

constituent is more than 1.0 %, it is difficult to ensure toughness. To obtain better toughness, the area ratio of martensite austenite constituent is desirably 0.5 % or less. There is no lower limit for the area ratio of martensite austenite constituent, because it is preferably as small as possible and it may be 0 %.

5 The area ratio of martensite austenite constituent can be measured according to the measurement method described in the Examples section below.

[0060] Because dispersion strengthening by precipitates and uniform microstructure refinement by precipitates are effective in obtaining a steel sheet pile with high strength and high toughness, we further investigated the
10 particle size and the area ratio of the precipitates.

Steel materials with various chemical compositions within the chemical composition range of the present disclosure were subjected to hot rolling to form various steel sheet piles, and then the steel sheet piles were subjected to air cooling (cooling rate: 0.50 °C/s). A sample was collected from each steel
15 sheet pile after air cooling. After performing surface treatment by electropolishing, the sample was observed by transmission electron microscopy (hereinafter, referred to as “TEM”) to measure the particle size and the area ratio of precipitates containing V carbonitrides, Nb carbonitrides, and complex carbonitrides of V and Nb. The particle size and the area ratio of the
20 precipitates were measured according to the method described below.

[0061] A test piece for Charpy impact test was collected from each of the various steel sheet piles, and the fracture appearance transition temperature at 50-percent ductile fracture (vTrs) was determined. The measurement of vTrs was performed according to the method described in the Examples section
25 below.

[0062] The results of the vTrs measurement are illustrated in FIG. 3 as a relationship to the area ratio of the precipitates. The properties of the precipitates can be summarized by the following formula (2).

$$d \geq 5[(Ae_3 - Ar_3)/Ae_3]^{-0.63} \quad (2)$$

30 where d is the particle size in nanometer of the precipitate, Ae₃ is the equilibrium transformation temperature in °C from austenite to ferrite, and Ar₃ is the ferrite transformation start temperature in °C during cooling. Ae₃ and Ar₃ are determined by the following formulas (3) and (4), respectively.

[Math. 2]

35
$$Ae_3 = 912 - 203\sqrt{([\%C])} + 45[\%Si] - 30[\%Mn] - 20[\%Cu] - 11[\%Cr] - 15[\%Ni] + 32[\%Mo] \quad (3)$$

$$Ar_3 = 910 - 310[\%C] - 80[\%Mn] - 20[\%Cu] - 15[\%Cr] - 55[\%Ni] - 80[\%Mo] \quad (4)$$

where [%C], [%Si], [%Mn], [%Cu], [%Cr], [%Ni] and [%Mo] are the content (mass%) of C, Si, Mn, Cu, Cr, Ni and Mo in the steel, respectively.

5 **[0063]** FIG. 3 illustrates the relationship between the area ratio and the fracture appearance transition temperature (°C) (hereinafter referred to as “vTrs”) for V carbonitrides, Nb carbonitrides, and their complex precipitates with a precipitate particle size satisfying the formula (2). It was found that when the total area ratio of the V carbonitrides, Nb carbonitrides, and their
10 complex precipitates with a precipitate particle size satisfying the formula (2) is 0.30 % or more, the vTrs is -10 °C or lower. The total area ratio is preferably 0.35 % or more.

The upper limit of the total area ratio is not particularly limited, but it is preferably 1.00 % or less from the viewpoint of preventing excessive
15 precipitation embrittlement.

[0064] Further, a test piece for tensile test was collected from each of the various steel sheet piles to determine the YP (0.2 % proof stress). The measurement of YP was performed according to the method described in the Examples section below. The relationship between the measured YP and the
20 area ratio of V carbonitrides, Nb carbonitrides and their complex precipitates with a particle size of 10 nm or less, which were extracted from the measurement results of the particle size and the area ratio of the precipitates described above, is illustrated in FIG. 4. The reason for focusing on the area ratio of V carbonitrides, Nb carbonitrides and their complex precipitates with
25 a particle size of 10 nm or less is that the Orowan stress related to strengthening by precipitation is inversely proportional to the particle size of precipitate, so that it is an indicator when utilizing strengthening by precipitation. FIG. 4 indicates that when the total area ratio of V carbonitrides, Nb carbonitrides and their complex precipitates with a particle size of 10 nm or less is 2.6 % or more,
30 the YP is 440 MPa or more. The total area ratio is preferably 4.0 % or more.

The upper limit of the total area ratio is not particularly limited, but it is preferably 10.0 % or less from the viewpoint of preventing excessive precipitation embrittlement.

[0065] <Method of manufacturing steel sheet pile>

35 The following describes a method of manufacturing the steel sheet pile of the present disclosure.

The steel sheet pile is manufactured by heating a steel material such as a slab having the above-described chemical composition in a heating furnace and then subjecting the steel material to hot rolling including rough rolling, intermediate rolling and finish rolling.

FIG. 1A illustrates a typical example of a steel sheet pile, which is a hat-type steel sheet pile 1. The hat-type steel sheet pile 1 has a web 2, a pair of flanges 3 and 4 extending inclined from the two ends of the web 2, arms 5 and 6 extending parallel to the web 2 from opposite sides of the flanges 3 and 4 to the web 2, and claws 7 and 8 at the ends of the arms 5 and 6.

[0066] The hat-type steel sheet pile may be manufactured by, for example, heating the steel material and then forming the steel material by finally passing it through the calibers as illustrated in FIG. 2 in rough rolling, intermediate rolling and finish rolling, respectively. Specifically, after the steel material is rolled a plurality of times in the initial rough rolling, it finally passes through the caliber 13 to obtain a rough shape of the steel sheet pile. In the subsequent intermediate rolling, the steel material finally passes through the caliber 14 while adjusting the thickness of the portions to be the web 2, flanges 3 and 4, arms 5 and 6, and claws 7 and 8. In the finish rolling, shape control that mainly includes claw-bending forming is performed, and finally the steel material passes through the caliber 15 to obtain the final product shape.

[0067] For steel sheet piles other than the hat-type steel sheet pile described above, such as the straight-type steel sheet pile 9 illustrated in FIG. 1B that has a different web thickness and a different product shape including the claws, there may be differences in the number of rolling passes and rolling temperature in hot rolling. However, there is no fundamental difference in that the steel sheet pile is manufactured by rough rolling, intermediate rolling and finish rolling (including claw-bending forming), and all of them are included in the manufacturing method of the present disclosure. In the straight-type steel sheet pile 9 illustrated in FIG. 1B, the straight portion located between left and right claws 11 and 12 is a web 10.

[0068] It is essential that the steel material should be heated to 1200 °C to 1350 °C and then be subjected to hot rolling under the following conditions: a cumulative rolling reduction ratio of 20 % or more at 900 °C to 1000 °C, a rolling reduction ratio (hereinafter also referred to as “CR ratio”) of 10 % or more and less than 20 % in the non-recrystallization temperature range of austenite, and finish temperature of 650 °C to 900 °C for intermediate rolling.

[0069] [Heating temperature of steel material: 1200 °C to 1350 °C]

During the hot rolling, the steel material needs to be heated to 1200 °C to 1350 °C. If the heating temperature is lower than 1200 °C, there is a risk that the dissolution of V and Nb in the steel components is insufficient, which coarsens the precipitates and renders it difficult to ensure strength, and that the deformation resistance increases during hot work, which leads to cracking of rolling rolls. On the other hand, if the heating temperature exceeds 1350 °C, the crystal grains are coarsened, which renders it difficult to ensure toughness, and the heating time increases, which decrease the productivity. Therefore, the heating temperature of the steel material is set to 1200 °C to 1350 °C. It is preferably 1250 °C or higher.

[0070] [Cumulative rolling reduction ratio at 900 °C to 1000 °C: 20 % or more]

It is important that the cumulative rolling reduction ratio at 900 °C to 1000 °C should be 20 % or more. When the rolling reduction ratio just above the non-recrystallization temperature range is 20 % or more, Nb carbonitrides or complex precipitates of Nb and V with a size on the order of several nanometers are precipitated in austenite due to strain-induced precipitation, which significantly improves YP. It is preferably 25 % or more. The upper limit is not particularly limited, but it is preferably 30 % or less from the viewpoint of manufacturability.

[0071] [CR ratio: 10 % or more and less than 20 %]

In addition to the above, it is important that the CR ratio should be 10 % or more. If the CR ratio is less than 10 %, the grains in the final microstructure are coarsened, and the average grain size of ferrite becomes larger than 15 µm or the maximum grain size of ferrite becomes larger than 40 µm, rendering it difficult to ensure toughness. Further, if the CR ratio is 20 % or more, the rolling load increases, and it is necessary to strictly control the shape. Therefore, the CR ratio is set to less than 20 %. It is preferably 13 % or more. It is preferably 18 % or less. The CR ratio can be adjusted by increasing or decreasing the gap between rolls during sheet passing.

[0072] [Finish temperature of intermediate rolling: 650 °C to 900 °C]

The finish temperature of the intermediate rolling in which the web and flange are formed is set to 650 °C to 900 °C. If the temperature exceeds 900 °C, it is difficult to satisfy either of the above two rolling conditions. Eventually, there is a possibility that the average grain size of ferrite in the microstructure becomes larger than 15 µm or the maximum grain size of ferrite

becomes larger than 40 μm , which renders it difficult to ensure toughness. It is preferably 850 $^{\circ}\text{C}$ or lower. On the other hand, if the temperature is lower than 650 $^{\circ}\text{C}$, the rolling load in the intermediate rolling increases, and the risk of cracking of rolls in the intermediate rolling mill increases. It is preferably
5 700 $^{\circ}\text{C}$ or higher. As mentioned above, the intermediate rolling refers to the rolling after the rough rolling, which provides a rough shape of the steel sheet pile, and before the claw-bending rolling, and it is mainly the rolling in which a portion to be the web is rolled in the thickness direction.

[0073] The steel sheet pile of the present disclosure does not require
10 accelerated cooling during rolling or after claw-bending rolling to improve strength and toughness. Accelerated cooling is undesirable in terms of production because it causes shape changes such as bending and warping. Therefore, it is desirable to perform air cooling after the claw-bending rolling. Water that is unavoidably applied from the viewpoint of shape control during
15 rolling, and cooling such as one using mist water in a cooling bed do not affect the properties of the steel sheet pile of the present disclosure.

[0074] By performing composition adjustment, rolling and cooling according to the above conditions, the steel sheet pile can obtain excellent mechanical properties of a high strength of YP of 440 MPa or more and $v\text{Trs}$ of -10 $^{\circ}\text{C}$ or
20 lower. Note that the steel sheet piles covered by the present disclosure include a hat-type one, a U-type one, combinations thereof, and a straight one, regardless of their cross-sectional shape, and are not particularly limited in terms of web thickness and claw shape.

25 EXAMPLES

[0075] The following describes the structures and function effects of the present disclosure in more detail, by way of examples. Note that the present disclosure is not restricted by any means to these examples and may be changed appropriately within the range conforming to the purpose of the present
30 disclosure, all of such changes being included within the technical scope of the present disclosure.

[0076] In a continuous casting machine, steel materials with the chemical compositions listed in Tables 1-1 and 1-2 were prepared and subjected to heating and hot rolling under the conditions listed in Tables 2-1 and 2-2 to
35 obtain a hat-type steel sheet pile having a web 2, a pair of flanges 3 and 4 extending inclined from the two ends of the web 2, arms 5 and 6 extending in

a direction that spreads left and right parallel to the web 2, and claws 7 and 8 at the ends of the arms 5 and 6, as illustrated in FIG. 1A.

[0077] [Table 1-1]

Steel sample No.		Chemical composition (mass%)																Remarks		
		C	Si	Mn	P	S	Al	V	Nb	N	B	Cr	Cu	Ni	Mo	Ca	Ti		REM	[%Nb]-0.1[%V]
1	0.05	0.22	1.11	0.016	0.010	0.015	0.237	0.027	0.0043	0.0003	-	-	-	-	-	-	-	-	0.003	Conforming steel
2	0.14	0.49	1.30	0.023	0.009	0.034	0.108	0.028	0.0019	0.0003	-	-	-	-	-	-	-	-	0.017	
3	0.05	0.36	1.49	0.018	0.014	0.039	0.095	0.006	0.0041	0.0001	-	-	-	-	-	-	-	-	-0.004	
4	0.10	0.05	1.22	0.014	0.020	0.038	0.200	0.026	0.0035	0.0002	-	-	-	-	-	-	-	-	0.006	
5	0.14	0.45	1.07	0.014	0.009	0.035	0.083	0.010	0.0016	0.0002	-	-	-	-	0.0011	-	-	-	0.002	
6	0.07	0.40	1.16	0.013	0.003	0.048	0.036	0.024	0.0031	0.0001	-	-	-	-	-	-	-	-	0.020	
7	0.18	0.25	1.00	0.011	0.003	0.030	0.006	0.021	0.0036	0.0002	0.20	-	-	0.18	-	-	-	-	0.020	
8	0.14	0.37	1.64	0.018	0.006	0.036	0.158	0.023	0.0023	0.0002	-	-	-	-	-	-	-	-	0.007	
9	0.12	0.17	1.56	0.025	0.007	0.026	0.111	0.014	0.0013	0.0002	-	-	-	-	-	-	-	-	0.003	
10	0.08	0.26	1.19	0.019	0.007	0.024	0.177	0.024	0.0028	0.0003	0.38	-	-	-	-	-	-	-	0.006	
11	0.12	0.07	1.19	0.022	0.016	0.045	0.131	0.022	0.0011	0.0003	-	0.25	-	-	-	-	-	-	0.009	
12	0.13	0.53	1.52	0.010	0.009	0.033	0.101	0.012	0.0059	0.0001	-	-	0.42	-	-	-	-	-	0.002	
13	0.11	0.22	1.62	0.023	0.006	0.042	0.092	0.019	0.0023	0.0003	-	-	-	0.10	-	-	-	-	0.010	
14	0.16	0.51	1.01	0.016	0.006	0.016	0.104	0.028	0.0029	0.0003	-	-	-	-	0.0017	-	-	-	0.018	
15	0.08	0.54	1.08	0.010	0.008	0.023	0.096	0.024	0.0032	0.0001	-	-	-	-	-	0.024	-	-	0.014	
16	0.09	0.25	1.22	0.011	0.010	0.023	0.105	0.012	0.0021	0.0002	-	-	-	-	-	-	-	0.002	0.002	

[Table 1-2]

Steel sample No.		Chemical composition (mass%)																Remarks		
		C	Si	Mn	P	S	Al	V	Nb	N	B	Cr	Cu	Ni	Mo	Ca	Ti		REM	[%Nb]-0.1[%V]
17	0.04	0.48	1.40	0.016	0.004	0.018	0.191	0.019	0.0010	0.0003	-	-	-	-	-	-	-	-	0.000	Comparative steel
18	0.19	0.34	1.22	0.023	0.004	0.048	0.124	0.028	0.0013	0.0001	-	-	-	-	-	-	-	-	0.016	
19	0.14	0.04	1.15	0.012	0.009	0.028	0.242	0.024	0.0030	0.0003	-	-	-	-	-	-	-	-	0.000	
20	0.10	0.56	1.41	0.021	0.010	0.034	0.220	0.012	0.0037	0.0001	-	-	-	-	-	-	-	-	-0.010	
21	0.05	0.09	0.97	0.013	0.013	0.048	0.063	0.018	0.0019	0.0001	-	-	-	-	-	-	-	-	0.012	
22	0.08	0.54	1.66	0.014	0.010	0.039	0.051	0.010	0.0025	0.0002	-	-	-	-	-	-	-	-	0.005	
23	0.06	0.43	1.16	0.026	0.010	0.039	0.237	0.011	0.0034	0.0002	-	-	-	-	-	-	-	-	-0.013	
24	0.18	0.11	1.32	0.019	0.021	0.023	0.166	0.019	0.0024	0.0002	-	-	-	-	-	-	-	-	0.002	
25	0.12	0.33	1.03	0.020	0.009	0.018	0.004	0.020	0.0053	0.0001	-	-	-	-	-	-	-	-	0.020	
26	0.11	0.14	1.41	0.014	0.016	0.048	0.252	0.025	0.0047	0.0001	-	-	-	-	-	-	-	-	0.000	
27	0.13	0.19	1.08	0.014	0.020	0.033	0.140	0.004	0.0037	0.0001	-	-	-	-	-	-	-	-	-0.010	
28	0.10	0.14	1.61	0.018	0.014	0.041	0.103	0.030	0.0020	0.0002	-	-	-	-	-	-	-	-	0.020	
29	0.11	0.37	1.44	0.021	0.013	0.023	0.053	0.020	0.0009	0.0002	-	-	-	-	-	-	-	-	0.015	
30	0.09	0.35	1.56	0.017	0.012	0.048	0.177	0.014	0.0062	0.0002	-	-	-	-	-	-	-	-	-0.004	
31	0.15	0.08	1.32	0.017	0.004	0.017	0.180	0.014	0.0033	0.0004	-	-	-	-	-	-	-	-	-0.004	
32	0.14	0.23	1.31	0.012	0.003	0.036	0.160	0.005	0.0043	0.0001	-	-	-	-	-	-	-	-	-0.011	
33	0.17	0.49	1.50	0.024	0.011	0.029	0.053	0.026	0.0028	0.0003	-	-	-	-	-	-	-	-	0.021	
34	0.13	0.15	1.50	0.016	0.012	0.022	0.090	0.020	0.0040	0.0001	-	0.30	0.60	-	-	-	-	-	0.011	
35	0.15	0.35	1.16	0.018	0.003	0.019	0.051	0.035	0.0043	0.0002	-	-	-	-	-	-	-	-	0.030	

Underlined if it is outside the scope of the present disclosure.

Comparative steel

[0078] The obtained steel sheet piles were subjected to observation of microstructure of steel sheet pile, observation of precipitate, a tensile test, and a toughness test. The methods of the evaluations are described below.

[0079] <Observation of microstructure>

5 A test piece was collected from the 1/4 web-thickness position of the web of the steel sheet pile, and the microstructure was observed. The surface of the collected test piece was polished and etched with nital prior to the observation. Next, using an optical microscopy, the thickness-direction cross section of the web was observed at 100x to identify the type of microstructure, and in a field of view of 800 μm $\times$ 600 μm , ferrite, pearlite, bainite, and martensite were distinguished by image interpretation by converting them into three gradations of white, black, and gray, respectively, and the area ratio of each microstructure was obtained. The average grain size of ferrite was obtained by calculating the area of each crystal grain of ferrite in the field of view also by image interpretation using the divided algorithm, taking the equivalent circle diameter of each crystal grain as the grain size of ferrite, and determining the average value in the field of view. The maximum grain size of ferrite was the largest equivalent circle diameter in the field of view. Further, for the observation of martensite austenite constituent, the same test piece as above was subjected to two-step etching treatment of electrolytic etching and nital etching to dissolve cementite, at least 10 fields of view were randomly observed using a scanning electron microscope (SEM) at about 1000x magnification, and the area ratio of martensite austenite constituent was determined by image interpretation in the same manner as above.

25 **[0080]** <Observation of precipitate>

 A sample was collected from the 1/4 web-thickness position of the web of the steel sheet pile and subjected to surface treatment by electropolishing, and then the sample was observed using a transmission electron microscope (TEM) at 200000x for 30 fields of view. For precipitates with a particle size of 1 nm or more, V carbonitrides, Nb carbonitrides, and their complex precipitates were identified using a dark field method and a mass spectrometer (EDS), each precipitate was counted, and the total area ratio of the precipitates occupying the field of view was calculated. Note that the precipitate was regarded as an ellipse, and the average of the major and minor axes was taken as the particle size.

35 **[0081]** <Tensile test>

A JIS No. 1A tensile test piece specified in JIS Z2241 was collected from the 1/4 web-thickness position of the web of the steel sheet pile with the tensile direction being the longitudinal direction, and a tensile test was conducted in accordance with JIS Z2241 to determine the yield point (YP) and the tensile strength (TS).

[0082] <Toughness test>

A 2 mm V-notch test piece for Charpy impact test (V-notch depth 2 mm) specified in JIS Z2242 was collected from the 1/4 web-thickness position of the web of the steel sheet pile, and a Charpy impact test was conducted according to JIS Z2242. The impact test was conducted in a temperature range of -80 °C to 40 °C, and the absorbed energy at 0 °C (vE₀) and the fracture appearance transition temperature at 50-percent ductile fracture (vTrs) were determined.

[0083] Tables 2-1 and 2-2 list the results of the above evaluations. The test results of steel sheet piles (No. 1 to 17 in Table 2-1) prepared with the manufacturing method according to the present disclosure using the conforming steel satisfying the chemical composition according to the present disclosure all had the desired properties (yield point YP: 440 MPa or more, and fracture appearance transition temperature at 50-percent ductile fracture vTrs: -10 °C or lower).

[0084] On the other hand, the comparative examples (Nos. 18 to 38 and 41 in Table 2-2), where either or both of the steel composition of the steel sheet pile and the manufacturing method did not satisfy the conditions of the present disclosure, did not have the required properties in terms of either yield point or fracture appearance transition temperature at 50-percent ductile fracture (vTrs).

[0085] In all of the comparative examples (No. 39, 40, and 42 in Table 2-2) that did not satisfy the conditions of the manufacturing method of the present disclosure, the rolling load during intermediate rolling was too large and exceeded the load capacity of the rolls, so that the rolling was stopped.

[0086] [Table 2-1]

No.		Hot rolling conditions				Metallic microstructure					Steel properties				Remarks	
		Steel sample No.	Heating temperature [°C]	Rolling reduction at 900 °C to 1000 °C [%]	CR ratio [%]	Finish temperature of intermediate rolling [°C]	Area ratio of ferrite [%]	Average ferrite grain size [μm]	Maximum ferrite grain size [μm]	Area ratio of martensite austenite constituent [%]	Area ratio of precipitate with particle size of 10 nm or less [%]	Area ratio of precipitate satisfying formula (2) [%]	TS: Tensile strength [MPa]	YP: Yield point [MPa]		Impact absorbed energy vE ₀ [J]
1	1	1300	30	17	776	88	13	38	0.0	3.5	0.33	602	481	220	-19	Example
2	2	1240	22	17	821	76	14	38	0.0	4.9	0.30	633	501	167	-12	
3	3	1230	31	12	724	87	7	16	0.0	4.2	0.44	581	473	255	-30	
4	4	1290	30	10	842	80	11	29	0.0	4.4	0.34	575	470	247	-25	
5	5	1200	36	19	799	74	6	18	0.1	3.1	0.49	587	462	281	-35	
6	6	1310	30	16	732	82	15	39	0.0	2.6	0.37	583	441	186	-15	
7	7	1300	39	15	756	71	13	30	0.9	2.7	0.38	558	444	182	-14	
8	8	1240	23	13	759	73	14	28	0.8	4.1	0.35	599	474	194	-23	
9	9	1260	36	12	737	77	10	27	0.7	4.0	0.38	574	478	243	-28	
10	10	1320	20	18	841	85	12	35	0.0	4.8	0.32	620	495	218	-22	
11	11	1260	29	16	678	81	9	25	0.0	3.6	0.41	610	472	274	-30	
12	12	1280	36	12	739	73	12	31	0.8	5.1	0.38	645	496	250	-24	
13	13	1330	29	15	853	82	12	30	0.0	4.4	0.36	619	479	201	-17	
14	14	1320	28	12	677	75	14	35	0.4	5.2	0.31	631	506	163	-12	
15	15	1270	30	10	846	80	8	15	0.8	4.6	0.40	608	477	259	-26	
16	16	1340	36	11	870	85	11	33	0.0	4.7	0.36	604	492	222	-20	
17	10	1240	33	19	652	84	10	28	0.0	3.9	0.35	596	488	209	-18	

* 1 Underlined if it is outside the scope of the present disclosure.

* 2 Formula (2): $d \geq 5[(Ae_3 - Ar_3)/Ae_3]^{-0.63}$, where d is the particle size in nanometer of the precipitate,

Ae₃ is the equilibrium transformation temperature in °C from austenite to ferrite, and Ar₃ is the ferrite transformation start temperature in °C during cooling

[Table 2-2]

No.		Steel sample No.	Hot rolling conditions			Metallic microstructure						Steel properties				Remarks		
			Heating temperature [°C]	Rolling reduction at 900 °C to 1000 °C [%]	CR ratio [%]	Finish temperature of intermediate rolling [°C]	Area ratio of ferrite [%]	Average ferrite grain size [μm]	Maximum ferrite grain size [μm]	Area ratio of martensite austenite constituent [%]	Area ratio of precipitate with particle size of 10 nm or less [%]	Area ratio of precipitate satisfying formula (2) [%]	TS: Tensile strength [MPa]	YP: Yield point [MPa]	Impact absorbed energy vE ₀ [J]		vTrs [°C]	
18	17	1200	29	13	722	91	16	43	0.0	2.4	0.31	510	421	138	-9	Comparative Example		
19	18	1300	33	12	877	69	10	26	1.1	5.2	0.40	663	519	118	-5			
20	19	1270	29	18	851	77	12	30	0.0	3.1	0.37	576	436	222	-20			
21	20	1240	31	16	705	79	14	38	1.1	3.3	0.39	592	455	120	-8			
22	21	1330	35	12	750	88	13	36	0.0	3.4	0.33	547	428	255	-25			
23	22	1300	37	15	799	69	14	37	1.2	3.1	0.30	566	442	134	-9			
24	23	1260	40	13	679	87	10	30	0.0	4.5	0.43	594	477	122	-6			
25	24	1270	21	12	674	73	11	32	0.6	4.3	0.41	590	479	101	-5			
26	25	1280	36	18	793	77	17	42	0.0	2.5	0.28	512	431	125	-8			
27	26	1270	28	16	755	82	12	33	0.0	6.5	0.42	592	508	135	-9			
28	27	1240	35	12	757	76	16	41	0.0	2.4	0.29	567	431	139	-9			
29	28	1340	24	15	781	81	12	29	0.4	6.4	0.37	624	505	94	-4			
30	29	1230	34	12	780	80	16	42	0.0	2.5	0.28	538	418	140	-8			
31	30	1280	35	10	722	84	9	20	0.0	6.6	0.41	646	527	121	-6			
32	31	1280	25	11	767	86	13	36	1.1	4.0	0.35	616	483	117	-8			
33	32	1240	26	19	831	75	10	27	0.2	2.5	0.44	527	439	225	-20			
34	33	1270	39	13	682	74	17	41	0.7	2.7	0.28	640	448	140	-7			
35	35	1280	56	12	840	83	8.8	41	0.8	2.7	0.26	593	445	142	-7			
36	8	1260	18	11	693	80	12	27	0.8	2.4	0.38	500	410	214	-19			
37	15	1250	26	9	855	83	16	43	0.9	4.4	0.40	536	453	138	-8			
38	10	1370	22	17	776	87	17	42	0.0	4.4	0.34	625	500	159	-9			
39	3	1190	20	19	-	Rolling stopped												
40	1	1300	31	22	-	Rolling stopped												
41	3	1310	21	9	904	86	17	44	0.1	4.2	0.41	574	466	99	-7			
42	11	1290	25	17	640	Rolling stopped												

* 1 Underlined if it is outside the scope of the present disclosure.

* 2 Formula (2): $d \geq 5[(\text{Ae}_3 - \text{Ar}_3)/\text{Ae}_3]^{0.63}$, where d is the particle size in nanometer of the precipitate,

Ae₃ is the equilibrium transformation temperature in °C from austenite to ferrite, and Ar₃ is the ferrite transformation start temperature in °C during cooling.

REFERENCE SIGNS LIST

5	[0087]	1	Hat-type steel sheet pile
		2	Web
		3	Flange
		4	Flange
		5	Arm
		6	Arm
		7	Claw
		8	Claw
10		9	Straight-type steel sheet pile
		10	Web
		11	Claw
		12	Claw
15		13	Caliber of final pass in rough rolling of hat-type steel sheet pile
		14	Caliber of final pass in intermediate rolling of hat-type steel sheet pile
		15	Caliber of final pass in finish rolling of hat-type steel sheet 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: 0.005 % to 0.250 %,

10 Nb: 0.005 % or more and less than 0.030 %, and

N: 0.0010 % to 0.0060 %,

in a range satisfying the following formula (1):

$$-0.010 \leq [\%Nb] - 0.1[\%V] \leq 0.020 \quad (1)$$

15 where [%V] and [%Nb] are a content of V and Nb in steel in mass%, respectively, with the balance is Fe and inevitable impurities, where 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, and

a microstructure in which an area fraction of ferrite is 70 % or more, an area ratio of martensite austenite constituent is 1.0 % or less, a total area ratio of V carbonitrides, Nb carbonitrides and complex carbonitrides of V and Nb with a particle size of 10 nm or less is 2.6 % or more, and a total area ratio of V carbonitrides, Nb carbonitrides and complex precipitates of V and Nb having a particle size of d in nanometer satisfying the following formula (2) is 0.30 % or more,

25
$$d \geq 5[(Ae_3 - Ar_3)/Ae_3]^{-0.63} \quad (2)$$

where Ae_3 is equilibrium transformation temperature in °C from austenite to ferrite, and

Ar_3 is ferrite transformation start temperature in °C during cooling, wherein

30 the ferrite has an average grain size of 15 μm or less and a maximum grain size of 40 μm or less, and

the steel sheet pile has a yield point of 440 MPa or more and $vTrs$ of -10 °C or lower.

35 [Claim 2] The steel sheet pile according to claim 1, wherein the chemical composition further contains, in mass%, at least one selected from the group

consisting of

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

- 10 [Claim 3] A method of manufacturing a steel sheet pile with a yield point of 440 MPa or more and $vTrs$ of -10 °C or lower, comprising:

heating a steel material having the chemical composition according to claim 1 or 2 to 1200 °C to 1350 °C, and

- 15 subjecting the steel material to hot rolling including rough rolling, intermediate rolling and finish rolling, wherein a cumulative rolling reduction ratio at 900 °C to 1000 °C is 20 % or more, a rolling reduction ratio in non-recrystallization temperature range of austenite is 10 % or more and less than 20 %, and a finish temperature of the intermediate rolling is 650 °C to 900 °C.