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(71) Applicant: **JFE Steel Corporation**
Tokyo 100-0011 (JP)

(72) Inventors:
• **MATSUBARA Kazuki**
Tokyo 100-0011 (JP)

- **OKANO Hiroshi**
Tokyo 100-0011 (JP)
- **TAKAGI Shusaku**
Tokyo 100-0011 (JP)
- **TODA Yuki**
Tokyo 100-0011 (JP)
- **KAGEYAMA Taisuke**
Tokyo 100-0011 (JP)
- **TAKEMURA Yasumasa**
Tokyo 100-0011 (JP)

(74) Representative: **Haseltine Lake Kempner LLP**
One Portwall Square
Portwall Lane
Bristol BS1 6BH (GB)

(54) **SEAMLESS STEEL PIPE, SEAMLESS STEEL PIPE MANUFACTURING METHOD, PRESSURE VESSEL, AND PRESSURE VESSEL MANUFACTURING METHOD**

(57) An object of the present invention is to provide a seamless steel pipe having a high martensite fraction and being thick-walled, and having excellent quench-cracking resistance, which can be extremely suitably used as a member of a pressure vessel and the like. Further, an object thereof is to provide a method for manufacturing a seamless steel pipe, a pressure vessel, and a method for manufacturing a pressure vessel.

A seamless steel pipe has a specific component composition and P satisfies the following formula (1), a degree of segregation of Mn at an inner surface of the steel pipe of less than 1.50, and a metallic microstructure having an area fraction of martensite of 85% or more.

$$[P] \leq 0.042 - 0.002[C] - 0.024[Mn] - 0.001[Mo] - 0.001[Cr] - 0.002[Ni] \quad (1)$$

(where [element] in formula (1) represents a content (mass%) of the element described in the brackets).

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Description

Technical Field

5 **[0001]** The present invention relates to a seamless steel pipe, and relates to a thick-walled seamless steel pipe having a high martensite fraction and excellent quench-cracking resistance, which can be used particularly suitably as a member of a pressure vessel and the like, and to a method for manufacturing the seamless steel pipe. Further, the present invention relates to a pressure vessel and a method for manufacturing the pressure vessel.

10 Background Art

[0002] A seamless steel pipe (also simply referred to as a steel pipe) is used in various applications such as piping and structural members because it is excellent in strength and is relatively inexpensive, and is useful particularly as a member used in a structure such as a pressure vessel in which mitigation of stress concentration is required. As the internal pressure of the steel pipe becomes higher, it is necessary to increase the strength of the steel material, and, in order to reduce the strength of fatigue caused by pressure fluctuation, a design in which the wall thickness of the steel pipe is increased is required. Further, it is preferable to apply, to a pressure vessel, a steel pipe having a high martensite fraction that can secure high strength against fatigue. However, in a steel pipe having a high martensite fraction, being thick-walled and high-strength, when a quenching treatment indispensable for increasing strength is carried out, cracking occurs, and the problem of quench cracking becomes remarkable.

[0003] Therefore, various techniques have been proposed in order to reduce the quench-cracking risk of a high-strength steel pipe.

[0004] For example, Patent Literature 1 proposes a technique for reducing the quench-cracking risk by control of heat treatment so as to optimize thermal stress and transformation stress, by cooling only from the inner surface of a steel pipe.

25 **[0005]** Further, Patent Literature 2 proposes a technique for reducing the quench-cracking risk by reducing, among the component composition of the steel pipe, in particular, the concentration of P.

Citation List

30 Patent Literature

[0006]

PLT1: Japanese Unexamined Patent Application Publication No. Hei 9-104925

35 PLT2: International Publication No. WO 2018/055937

Summary of Invention

Technical Problem

40 **[0007]** In Patent Literature 1 described above, quench-cracking resistance is evaluated in an actual steel-pipe shape, but no view is presented regarding the P concentration, which is known to contribute markedly to quench-cracking resistance.

[0008] On the other hand, in Patent Literature 2 described above, the influence of the P concentration is evaluated, but evaluation is performed using a test piece that is taken from a 1/4 thickness position of the steel pipe and that has a test-piece cross section in which a circular hole is provided in a disk, the wall thickness in the cross section being extremely inhomogeneous and the balance between thermal stress and transformation stress being intentionally deteriorated. In addition, the contribution of segregation of P that inevitably occurs in a process using continuous casting technology cannot be taken into consideration.

50 **[0009]** Further, when manufacturing a steel pipe having a high martensite fraction, being thick-walled and high-strength, it is necessary to secure hardenability, but securing hardenability by adding a large amount of alloying elements leads to an increase in cost. Therefore, it is more important to secure hardenability by the cooling rate, and the cooling rate during quenching is preferably as fast as possible. In addition, a seamless steel pipe, due to being produced by rolling while forming a hole at the sectional center of a solid cylindrical steel material that is cast or forged, unlike the segregation distribution of P in a plate-shaped steel material, segregation of P exists on the inner-surface side of the steel pipe. That is, it is important to consider the balance in a state in which the highest point of the temperature distribution in the wall-thickness direction and the highest point of segregation of P are different. Further, this effect appears more markedly as the wall thickness of the steel pipe becomes thicker. Therefore, it is important to evaluate, in an actual shape, the presence or

absence of quench cracking due to the balance between thermal stress and transformation stress, but in Patent Literature 1 and 2 described above, evaluation in an actual shape is not performed.

[0010] The present invention has been made in view of the above circumstances, and an object thereof is to provide a seamless steel pipe having a high martensite fraction, being thick-walled, and having excellent quench-cracking resistance, which can be used extremely suitably as a member of a pressure vessel and the like. Further, an object is to provide a method for manufacturing a seamless steel pipe, a pressure vessel, and a method for manufacturing a pressure vessel.

Solution to Problem

[0011] As a result of conducting studies to solve the above-described problems, the present inventors found that, by optimizing, in addition to the P concentration in the component composition of a seamless steel pipe, rolling conditions in a pipe-forming process of the seamless steel pipe and heat-treatment conditions after the pipe-forming process, and by a method of controlling segregation of P on the inner-surface side of the seamless steel pipe, excellent quench-cracking resistance can be obtained even in a thick-walled seamless steel pipe. On the other hand, because the P concentration in the seamless steel pipe is designed to be low in order to suppress segregation of P, there was also a problem in that determination of the degree of segregation of P is difficult. Therefore, focusing on Mn, which has a high affinity for P, it was confirmed that a high correlation relationship is observed between the P concentration and the Mn concentration. Further, in the present invention, because the Mn concentration in the steel pipe is designed to be high, evaluation using the degree of segregation of Mn is more reliable when evaluating the degree of segregation of P. Accordingly, the inventors found that quench-cracking resistance can be improved by a method of controlling the degree of segregation of Mn on the inner-surface side of a seamless steel pipe by optimizing rolling conditions in the pipe-forming process of the seamless steel pipe and heat-treatment conditions after the pipe-forming process. The gist of the present invention is described below.

[1] A seamless steel pipe which includes:

a component composition containing, in mass%,

C: 0.20 to 0.60%,

Si: 0.01 to 2.0%,

Mn: 0.5 to 1.2%,

S: 0.010% or less,

O: 0.005% or less,

N: 0.010% or less,

Al: 0.01 to 0.08%,

Mo: 0.005 to 1.0%,

Cr: 0.005 to 3.0%, and

Ni: 0.005 to 3.0%,

optionally one or two or more selected from

Ti: 0.0001 to 0.1%,

Cu: 0.0001 to 5.0%,

Co: 0.0001 to 5.0%,

B: 0.0001 to 0.01%,

V: 0.0001 to 1.0%,

W: 0.0001 to 5.0%,

Nb: 0.0001 to 0.1%,

Zr: 0.0001 to 0.2%,

Hf: 0.0001 to 0.2%,

Ta: 0.0001 to 0.2%,

Sb: 0.0001 to 0.1%,

Sn: 0.0001 to 0.1%,

Ca: 0.0001 to 0.01%,

Mg: 0.0001 to 0.01%, and

REM: 0.0001 to 0.5%, and

the component composition further containing P so as to satisfy following formula (1):

$$[P] \leq 0.042 - 0.002[C] - 0.024[Mn] - 0.001[Mo] - 0.001[Cr] - 0.002[Ni] \quad (1)$$

(where [element] in formula (1) represents a content (mass%) of the element described in the brackets),
 the balance being Fe and unavoidable impurities;
 a degree of segregation of Mn from an inner surface of the steel pipe to a 1/6 wall-thickness position of less than 1.50; and
 a metallic microstructure having an area fraction of martensite of 85% or more.

[2] The seamless steel pipe according to [1], wherein a wall thickness of the steel pipe is 40 mm or more.

[3] The seamless steel pipe according to [1] or [2], wherein, in a region from the inner surface of the steel pipe to a 1/6 wall-thickness position, a number of inclusions having an aspect ratio of 2 or less and a long-side length of 10 μm or more is 10 pieces/100 mm^2 or less.

[4] The seamless steel pipe according to any one of [1] to [3], wherein a cross-sectional hardness is 480 HV or more.

[5] A method for manufacturing a seamless steel pipe according to any one of [1] to [4], the method includes: a pipe-forming step of pipe-forming a heated material such that a ratio of an inner diameter of the steel pipe divided by a wall thickness is 2.0 times or more; and a quenching step of heating the formed steel pipe to a temperature range of 860°C or higher, holding in the temperature range for 30 min or longer, and water-cooling under conditions such that an average cooling rate in a temperature range of 800 to 350°C is 3°C/s or more, wherein, in the water-cooling, the steel pipe is cooled while bringing a cooling medium into contact with an inner surface of the steel pipe at a flow rate of 0.5 m^3/min or more in a state that the steel pipe is rotated in a circumferential direction of the pipe.

[6] The method for manufacturing a seamless steel pipe according to [5], wherein pipe-forming step is performed such that a shape of the steel pipe satisfies the following formula (2):

$$(\text{EXP}(\text{coefficient } K \times \text{wall thickness}) / \text{circumferential cross section area}) \times 10^6 < 210 \quad (2)$$

$$K = \{0.41([C] - 0.24) + 4.58[Mn] + 0.21[Cr] + 0.25[Ni]\} / 100$$

... (3)

(where [element] in formula (3) represents a content (mass%) of the element described in the brackets).

[7] A pressure vessel wherein the seamless steel pipe according to any one of [1] to [4] is used as the pressure vessel.

[8] A method for manufacturing a pressure vessel, the method comprising processing the seamless steel pipe according to any one of [1] to [4].

Advantageous Effects of Invention

[0012] The seamless steel pipe of the present invention is excellent in quench-cracking resistance as a thick-walled steel pipe having a high martensite fraction.

Description of Embodiments

[0013] Hereinafter, the present invention will be described in detail. The following description shows examples of preferred embodiments of the present invention, and the present invention is not limited thereto. First, the component composition of a seamless steel pipe (also simply referred to as a steel pipe) will be described.

C: 0.20 to 0.60%

[0014] C is an element necessary for increasing the strength of the steel pipe. Strength is an important required property for a structural material. It is preferable that the cross-sectional hardness of the steel pipe after quenching is 480 HV or more, and in order to obtain such cross-sectional hardness, the C content is set to 0.20% or more. The C content is preferably 0.25% or more, more preferably 0.30% or more, still more preferably 0.33% or more, and most preferably 0.35% or more. On the other hand, when the C content exceeds 0.60%, quench cracking may occur when quenching is carried out, and therefore the C content is set to 0.60% or less. In order to reduce the quench-cracking risk, the C content is preferably 0.50% or less, more preferably 0.45% or less, and still more preferably 0.42% or less.

Si: 0.01 to 2.0%

[0015] Si is an element that contributes to an increase in strength of the steel pipe by solid-solution strengthening. In

order to obtain the above effect, the Si content is set to 0.01% or more. The Si content is preferably 0.10% or more, more preferably 0.15% or more, still more preferably 0.18% or more, and most preferably 0.20% or more. On the other hand, when the Si content exceeds 2.0%, the effect is saturated, and furthermore the surface properties of the steel pipe deteriorate and rollability in the pipe-forming process is also reduced. Therefore, the Si content is set to 2.0% or less. The Si content is preferably 1.5% or less, more preferably 1.0% or less, still more preferably 0.5% or less, and most preferably 0.4% or less.

Mn: 0.5 to 1.2%

[0016] Mn is an element that contributes to an increase in strength of the steel pipe by solid-solution strengthening and improvement of hardenability. In order to obtain the above effect, the Mn content is set to 0.5% or more. The Mn content is preferably 0.55% or more, more preferably 0.6% or more, still more preferably 0.65% or more, and most preferably 0.68% or more. On the other hand, when Mn is excessive, rolling becomes difficult in the pipe-forming process, and additionally retained austenite remains, resulting in deterioration of fatigue properties. Further, as described later, excessive inclusion of Mn increases the degree of Mn segregation, thereby increasing the quench-cracking risk. Therefore, the Mn content is set to 1.2% or less. The Mn content is preferably 1.0% or less, more preferably 0.9% or less, and still more preferably 0.88% or less.

S: 0.010% or less

[0017] Excessive S causes hot shortness during hot working and may result in manufacturing defects. Further, S forms MnS inclusions and deteriorates toughness. These effects do not pose a problem when the S content is 0.010% or less. Therefore, the S content is set to 0.010% or less. The S content is preferably 0.005% or less, and more preferably 0.003% or less. On the other hand, excessive reduction of the S content to less than 0.0001% accompanies an increase in desulfurization cost in the steelmaking process. Therefore, the S content is preferably 0.0001% or more, more preferably 0.0002% or more, still more preferably 0.0005% or more, and most preferably 0.001% or more.

O: 0.005% or less

[0018] O exists as an impurity in steel, and when the O content exceeds 0.005%, coarse and high-hardness oxides are formed, which deteriorate mechanical properties such as toughness and additionally increase the quench-cracking risk. Therefore, the O content is set to 0.005% or less. It is preferable that the O content is as small as possible, and is preferably 0.004% or less, more preferably 0.003% or less, and still more preferably 0.002% or less. On the other hand, excessive reduction of the O content to less than 0.0001% accompanies an increase in cost in the steelmaking process. Therefore, the O content is preferably 0.0001% or more, more preferably 0.0002% or more, still more preferably 0.0005% or more, and most preferably 0.001% or more.

N: 0.010% or less

[0019] The influence of N on the strength of steel is small, and when the N content is 0.010% or less, the effects of the present invention are not impaired. Therefore, the N content is set to 0.010% or less. The N content is preferably 0.008% or less, more preferably 0.005% or less, still more preferably 0.0045% or less, and most preferably 0.004% or less. On the other hand, from the viewpoint of improving toughness, it is desirable that the N content is small, but excessive reduction increases cost in the steelmaking process, and therefore the N content is preferably 0.0001% or more, and more preferably 0.001% or more.

Al: 0.01 to 0.08%

[0020] Al is an element effective as a deoxidizing agent in the steelmaking process. In order to obtain the above effect, the Al content is set to 0.01% or more, and preferably 0.02% or more. On the other hand, when the Al content exceeds 0.08%, the effect is saturated, and therefore the Al content is set to 0.08% or less. The Al content is preferably 0.06% or less, more preferably 0.05% or less, and still more preferably 0.04% or less.

Mo: 0.005 to 1.0%

[0021] Mo is an element that improves hardenability, contributes to an increase in strength of the steel pipe, and increases the proportion of non-ferritic microstructures (particularly martensite) in the metallic microstructure by improving hardenability, and is an element necessary for obtaining a high martensite fraction. Further, Mo improves quench-cracking

resistance by suppressing ferrite transformation. In addition, inclusion of Mo reduces the cooling rate required to obtain the above metallic microstructure and can reduce the quench-cracking risk during heat treatment of the steel pipe. In order to obtain the above effects, the Mo content is set to 0.005% or more. The Mo content is preferably 0.008% or more, and more preferably 0.1% or more. On the other hand, when the Mo content exceeds 1.0%, the effect is saturated and causes an increase in cost, and therefore the Mo content is set to 1.0% or less. The Mo content is preferably 0.8% or less, more preferably 0.5% or less, still more preferably 0.3% or less, and most preferably 0.25% or less.

Cr: 0.005 to 3.0%

[0022] Cr is an element that improves hardenability, contributes to an increase in strength of the steel pipe, and increases the proportion of non-ferritic microstructures (particularly martensite) in the metallic microstructure, and is an element necessary for obtaining a high martensite fraction. Further, Cr improves quench-cracking resistance by suppressing ferrite transformation. In addition, inclusion of Cr reduces the cooling rate required to obtain the above metallic microstructure and can reduce the quench-cracking risk during heat treatment of the steel pipe. In order to obtain the above effects, the Cr content is set to 0.005% or more. The Cr content is preferably 0.1% or more, more preferably 0.5% or more, still more preferably 0.7% or more, and most preferably 0.9% or more. On the other hand, when the Cr content exceeds 3.0%, the effect is saturated, and furthermore the prescribed Mn segregation degree cannot be obtained and quench-cracking resistance deteriorates. Therefore, the Cr content is set to 3.0% or less. The Cr content is preferably 2.0% or less, more preferably 1.5% or less, still more preferably 1.3% or less, and most preferably 1.2% or less.

Ni: 0.005 to 3.0%

[0023] Ni is an element that improves hardenability and contributes to an increase in strength of the steel pipe. As a result of improved hardenability, even in a steel pipe having a wall thickness of 40 mm or more, in which portions with slow cooling rates tend to occur, strength can be increased. Further, Ni increases the proportion of non-ferritic microstructures (particularly martensite) in the metallic microstructure by improving hardenability, and is an element necessary for obtaining a high martensite fraction. As a result, Ni improves quench-cracking resistance by suppressing ferrite transformation. In order to obtain the above effects, the Ni content is set to 0.005% or more. The Ni content is preferably 0.01% or more, more preferably 0.5% or more, and still more preferably 0.8% or more. On the other hand, excessive inclusion increases cost, and therefore the Ni content is set to 3.0% or less. Preferably, the Ni content is 2.5% or less, more preferably 2.0% or less, and still more preferably 1.8% or less.

P satisfies the following equation (1):

[0024] It is important that P satisfies the following equation (1).

$$[P] \leq 0.042 - 0.002[C] - 0.024[Mn] - 0.001[Mo] - 0.001[Cr] - 0.002[Ni] \quad (1)$$

(However, in formula (1), [element] represents content (mass %) of the element described in the brackets.) でん

[0025] P is an element that contributes to an increase in strength of the steel pipe by solid-solution strengthening, and also is an element that decreases quench-cracking resistance of the steel pipe.

[0026] As a mechanism of quench cracking, it is known that P trapped at grain boundaries lowers the bonding strength of the grain boundaries. Grain boundaries existing in steel are planar lattice defects in which the crystal structure is disordered, and the density of lattice defects is lower than the density in the matrix in which atoms are arranged regularly and periodically. That is, the volume of the gaps between atoms is large, and contained elements are easily trapped.

[0027] Trapping of P at grain boundaries can be broadly separated into two factors. The first is macro-segregation, which is a concentration distribution within a cross section of the steel material, generated because melting points differ for each element when the steel material is solidified from a liquid to a solid. The second is micro-segregation, which is a concentration distribution within the microstructure of the steel material, generated because contained elements diffuse from within the matrix to grain boundaries during heat treatment of the steel material.

[0028] That is, by reducing each of macro-segregation of P and micro-segregation of P, it is possible to ultimately reduce the quench-cracking risk of the steel pipe obtained. Hereinafter, in the present invention, the description "segregation" is defined as including both macro-segregation and micro-segregation, and also each is distinguished.

[0029] When manufacturing a thick-walled and high-strength seamless steel pipe, it is essential to contain elements that improve hardenability in order to secure hardenability, but the quench-cracking risk increases. Therefore, it is important to secure quench-cracking resistance of the seamless steel pipe by reducing segregation of P.

[0030] In equation (1), which is a condition necessary for reducing segregation of P, the following can be mentioned as

reasons why the P content has a relationship with the contents of C, Mn, Mo, Cr, and Ni.

[0031] C is a solid-solution type atom that contributes to an increase in strength, and is a factor that strongly inhibits movement of dislocations within grains. By this effect, as intragranular strength increases, and the load on grain boundaries becomes relatively large. That is, since the quench-cracking risk increases when C is contained, it is preferable to lower the P content.

[0032] Mn has been conventionally known to have particularly high affinity with P, and reducing micro-segregation of Mn results in reducing micro-segregation of P. That is, since the quench-cracking risk increases when Mn is contained, it is preferable to lower the P content.

[0033] Further, Mo, Cr, and Ni are elements that improve hardenability, and since the quench-cracking risk increases when these elements are contained, it is preferable to lower the P content.

[0034] In addition, Cr and Ni are transition metals of the fourth period in the periodic table, like Mn, and, compared with other contained elements, are less likely to inhibit diffusion of Mn atoms in the Fe matrix. In other words, Mn atoms become more likely to diffuse. That is, Cr and Ni are elements having an effect of promoting micro-segregation of Mn, and since the quench-cracking risk increases also when Cr and Ni are contained, it is preferable to lower the P content.

[0035] Note that, in a case of a seamless steel pipe in which macro-segregation exists on the inner-surface side of the steel pipe, by satisfying equation (1), it becomes possible to suppress cracking (quench cracking) generated on the inner surface of the steel pipe at the time of quenching.

[0036] However, excessive reduction of the P content decreases production efficiency and causes an increase in refining cost, and therefore the P content is preferably 0.001% or more.

[0037] The components described above are elements that are essential in the present invention.

[0038] In one embodiment of the present invention, the steel pipe has a component composition containing the above elements, and the balance being Fe and unavoidable impurity elements.

[0039] Here, "unavoidable impurities" are impurities that are unavoidably mixed in from raw materials, a manufacturing process, manufacturing facilities, and the like, and are permitted to be contained within a range that does not hinder the object of the present invention. As raw materials, for example, iron ore, reduced iron, scrap, and the like can be mentioned. As impurities, for example, Zn, Pb, As, Bi, and the like can be mentioned.

[0040] In another embodiment of the present invention, the component composition of the steel pipe can further optionally contain one or more kinds of the following elements. Elements to be contained as needed as appropriate are one or two more kinds selected from Ti: 0.0001 to 0.1%, Cu: 0.0001 to 5.0%, Co: 0.0001 to 5.0%, B: 0.0001 to 0.01%, V: 0.0001 to 1.0%, W: 0.0001 to 5.0%, Nb: 0.0001 to 0.1%, Zr: 0.0001 to 0.2%, Hf: 0.0001 to 0.2%, Ta: 0.0001 to 0.2%, Sb: 0.0001 to 0.1%, Sn: 0.0001 to 0.1%, Ca: 0.0001 to 0.01%, Mg: 0.0001 to 0.01%, and REM: 0.0001 to 0.5%.

Ti: 0.0001 to 0.1%

[0041] Ti contributes to an increase in strength of the steel pipe. In order to obtain the above effect, when Ti is contained, the Ti content is set to 0.0001% or more. The Ti content is preferably 0.0010% or more, more preferably 0.0015% or more, still more preferably 0.002% or more, and most preferably 0.01% or more. On the other hand, when the Ti content exceeds 0.1%, the effect is saturated and causes an increase in cost. Therefore, when Ti is contained, the Ti content is set to 0.1% or less. For cost suppression, the Ti content is preferably 0.05% or less, more preferably 0.04% or less, and still more preferably 0.03% or less.

Cu: 0.0001 to 5.0%

[0042] Cu is an element that improves hardenability, contributes to an increase in strength of the steel pipe, and suppresses coarsening of prior austenite grains, thereby improving various properties of the steel pipe. In order to obtain the above effects, when Cu is contained, the Cu content is set to 0.0001% or more. The Cu content is preferably 0.001% or more, more preferably 0.1% or more, and still more preferably 0.2% or more. On the other hand, when the Cu content exceeds 5.0%, the effect is saturated and causes an increase in cost. Therefore, when Cu is contained, the Cu content is set to 5.0% or less. The Cu content is preferably 4.3% or less, more preferably 4.0% or less, still more preferably 3.0% or less, and, for cost suppression, most preferably 2.0% or less.

Co: 0.0001 to 5.0%

[0043] Co is an element that improves hardenability, contributes to an increase in strength of the steel pipe, and suppresses coarsening of prior austenite grains, thereby improving various properties of the steel pipe. In order to obtain the above effects, when Co is contained, the Co content is set to 0.0001% or more. The Co content is preferably 0.001% or more, more preferably 0.1% or more, and still more preferably 0.2% or more. On the other hand, when the Co content exceeds 5.0%, the effect is saturated and causes an increase in cost. Therefore, when Co is contained, the Co content is

set to 5.0% or less. The Co content is preferably 4.0% or less, more preferably 3.0% or less, and, for cost suppression, still more preferably 2.0% or less.

B: 0.0001 to 0.01%

[0044] B is an element that improves hardenability, contributes to an increase in strength of the steel pipe, and suppresses coarsening of prior austenite grains, thereby improving various properties of the steel pipe. In order to obtain the above effects, when B is contained, the B content is set to 0.0001% or more. The B content is preferably 0.0005% or more, more preferably 0.001% or more, and still more preferably 0.002% or more. On the other hand, when the B content exceeds 0.01%, the effect is saturated and causes an increase in cost. Therefore, when B is contained, the B content is set to 0.01% or less. The B content is preferably 0.008% or less, more preferably 0.006% or less, and, for cost suppression, still more preferably 0.005% or less, and most preferably 0.004% or less.

V: 0.0001 to 1.0%

[0045] V contributes to an increase in strength of the steel pipe. In order to obtain the above effect, when V is contained, the V content is set to 0.0001% or more. The V content is preferably 0.0005% or more, more preferably 0.0010% or more, still more preferably 0.0020% or more, and most preferably 0.01% or more. On the other hand, when the V content exceeds 1.0%, the effect is saturated and causes an increase in cost. Therefore, when V is contained, the V content is set to 1.0% or less. The V content is preferably 0.8% or less, and, for cost suppression, more preferably 0.5% or less, still more preferably 0.4% or less.

W: 0.0001 to 5.0%

[0046] W contributes to an increase in strength of the steel pipe. In order to obtain the above effect, when W is contained, the W content is set to 0.0001% or more. The W content is preferably 0.0005% or more, more preferably 0.0010% or more, still more preferably 0.0020% or more, and most preferably 0.1% or more. On the other hand, when the W content exceeds 5.0%, the effect is saturated and causes an increase in cost. Therefore, when W is contained, the W content is set to 5.0% or less. The W content is preferably 4.0% or less, more preferably 3.0% or less, still more preferably 2.0% or less, and most preferably 1.7% or less.

Nb: 0.0001 to 0.1%

[0047] Nb contributes to an increase in strength of the steel pipe. In order to obtain the above effect, when Nb is contained, the Nb content is set to 0.0001% or more. The Nb content is preferably 0.0005% or more, more preferably 0.0010% or more, and still more preferably more than 0.001%. On the other hand, when the Nb content exceeds 0.1%, the effect is saturated and causes an increase in cost. Therefore, when Nb is contained, the Nb content is set to 0.1% or less. The Nb content is preferably 0.08% or less, and, for cost suppression, more preferably 0.06% or less, still more preferably 0.05% or less, and most preferably 0.045% or less.

Zr: 0.0001 to 0.2%, Hf: 0.0001 to 0.2%, Ta: 0.0001 to 0.2%

[0048] Zr, Hf, and Ta contribute to an increase in strength of the steel pipe. In order to obtain the above effect, when Zr, Hf, and Ta are respectively contained, the Zr content, the Hf content, and the Ta content are respectively set to 0.0001% or more. The Zr content, the Hf content, and the Ta content are each preferably 0.0002% or more, more preferably each 0.0005% or more, still more preferably each 0.0010% or more, and most preferably each 0.01% or more. On the other hand, when the Zr content, the Hf content, and the Ta content each exceed 0.2%, the effect is saturated and causes an increase in cost. Therefore, when Zr, Hf, and Ta are respectively contained, the Zr content, the Hf content, and the Ta content are each set to 0.2% or less. The Zr content, the Hf content, and the Ta content are preferably each 0.1% or less, and, for cost suppression, more preferably each 0.09% or less, still more preferably each 0.08% or less, and most preferably each 0.07% or less.

Sb: 0.0001 to 0.1%

[0049] Sb is an element effective for suppressing a decrease in strength of the steel pipe by suppressing denitriding, deboronization, and the like. In order to obtain such effects, when Sb is contained, the Sb content is set to 0.0001% or more. The Sb content is preferably 0.002% or more, more preferably 0.005% or more, and still more preferably 0.01% or more. When the Sb content exceeds 0.1%, embrittlement of the steel pipe may be caused. Therefore, when Sb is contained, the

Sb content is set to 0.1% or less. The Sb content is preferably 0.08% or less, more preferably 0.07% or less, and still more preferably 0.06% or less.

Sn: 0.0001 to 0.1%

[0050] Sn is an element effective for suppressing a decrease in strength of the steel pipe by suppressing pearlite. In order to obtain such effects, when Sn is contained, the Sn content is set to 0.0001% or more. The Sn content is preferably 0.0002% or more, more preferably 0.005% or more, and still more preferably 0.01% or more. When the Sn content exceeds 0.1%, embrittlement of the steel pipe may be caused. Therefore, when Sn is contained, the Sn content is set to 0.1% or less. The Sn content is preferably 0.08% or less, more preferably 0.05% or less, and still more preferably 0.04% or less.

Ca: 0.0001 to 0.01%, Mg: 0.0001 to 0.01%

[0051] Ca and Mg contribute to improvement of an inclusion state. In order to obtain the above effect, when Ca and Mg are respectively contained, the Ca content and the Mg content are respectively set to 0.0001% or more. Preferably, the Ca content and the Mg content are each 0.001% or more, and more preferably each 0.002% or more. On the other hand, when the Ca content and the Mg content each exceed 0.01%, the effect is saturated and causes an increase in cost. Therefore, when Ca and Mg are respectively contained, the Ca content and the Mg content are each set to 0.01% or less. The Ca content and the Mg content are preferably each 0.008% or less, and, for cost suppression, more preferably each 0.005% or less, and still more preferably each 0.004% or less.

REM: 0.0001 to 0.5%

[0052] REM (Rare Earth Metals) contributes to improvement of an inclusion state. In order to obtain the above effect, when REM is contained, the REM content is set to 0.0001% or more. The REM content is preferably 0.001% or more, more preferably 0.002% or more, and still more preferably 0.01% or more. On the other hand, when the REM content exceeds 0.5%, the effect is saturated and causes an increase in cost. Therefore, when REM is contained, the REM content is set to 0.5% or less. The REM content is preferably 0.3% or less, and, for cost suppression, more preferably 0.28% or less, and still more preferably 0.25% or less. REM is a general term for Sc, Y, and 15 elements from lanthanum (La) of atomic number 57 to lutetium (Lu) of atomic number 71, and the REM content here is the total content of these elements.

[0053] Next, the degree of segregation in the seamless steel pipe will be described.

[0054] Degree of segregation of Mn from the inner surface of the steel pipe to a 1/6 wall-thickness position is less than 1.50

[0055] As also described above, P has a high affinity with Mn. Since P is a direct factor of the quench-cracking risk, in the present invention, the P content (P concentration) is controlled to be low. Basically, suppression of segregation of P is necessary, but the concentration of Mn, which has a high affinity with P, is higher than the concentration of P, and reliability of analysis results by EPMA is high. Further, the P concentration and the Mn concentration have a high correlation relationship. Therefore, by suppressing segregation of Mn, segregation of P can also be surely suppressed. Accordingly, in evaluating the degree of segregation of P in the seamless steel pipe, the degree of segregation of Mn is used as an evaluation index.

[0056] Further, in the case of a plate-shaped steel material (steel plate) produced by rolling a continuously cast slab, macro-segregation exists in the plate thickness (wall thickness) central portion, and therefore the effect of mitigation of macro-segregation by rolling is smaller than that of a seamless steel pipe. This is for the following reason. In the pipe-forming process of a seamless steel pipe, because a hole is pierced by a piercing machine at the center of a billet as a material having a cylindrical shape, and the billet is rolled to form a pipe shape, the position of macro-segregation that existed at the billet center is arranged on the inner-surface side of the seamless steel pipe in the pipe shape. That is, the inner-surface side of the seamless steel pipe, where macro-segregation of P is high, has the highest quench-cracking risk. On the other hand, because the billet center is pierced and rolled while pressing the billet outer surface, the amount of plastic deformation is higher on the inner-surface side of the steel pipe than on the outer-surface side of the steel pipe, and mitigation of macro-segregation of P on the inner-surface side of the steel pipe is expected by rolling. From this, it is important to control segregation of P, that is, segregation of Mn on the inner-surface side of the seamless steel pipe.

[0057] Therefore, in evaluating the degree of segregation of Mn of the seamless steel pipe, it is important to produce and evaluate the seamless steel pipe. At that time, it was found that, for the degree of segregation of Mn, it is sufficient to use, as a reference, a local concentration of Mn in the vicinity of a 1/4 wall-thickness position from the outer surface of the steel pipe, and to use a ratio of the segregation concentration of Mn in a segregation region on the inner-surface side of the steel pipe, that is, from the inner surface of the steel pipe to a 1/6 wall-thickness position. Here, the reason why the local concentration of Mn near a 1/4 wall-thickness position from the outer surface of the steel pipe is used as the reference local concentration of Mn is that the vicinity of the 1/4 wall-thickness position from the outer surface of the steel pipe is a region

having no macro-segregation and having an average component composition, is a region that is away also from the outer surface of the steel pipe where plastic deformation occurs due to a pressing load, and is a region that can also be positioned farther away from the inner surface of the steel pipe. On the other hand, as the segregation concentration of Mn, the segregation concentration of Mn from the inner surface of the steel pipe to a 1/6 wall-thickness position, which is the segregation region on the inner-surface side of the steel pipe, is used.

[0058] In order to reduce the quench-cracking risk, it is necessary that the degree of segregation of Mn is less than 1.50, and it is preferably 1.45 or less, more preferably 1.44 or less, and still more preferably 1.43 or less. In addition, the lower limit of the degree of segregation of Mn is not particularly limited, but from the viewpoint of cost suppression, it is preferably 1.00 or more, and more preferably 1.10 or more.

[0059] A method for calculating the degree of segregation of Mn is as shown below.

[0060] In order to quantitatively evaluate segregation of P on the inner-surface side of the seamless steel pipe, in the present invention, the degree of segregation of Mn is used. The degree of segregation of Mn is defined as a value obtained by dividing a segregation concentration of Mn from the inner surface of the seamless steel pipe to a 1/6 wall-thickness position by a local concentration of Mn near a 1/4 wall-thickness position from the outer surface of the steel pipe. The measurement method of the degree of segregation of Mn is as shown below.

[0061] In evaluation of the degree of segregation of Mn, attention was focused on mapping analysis by an electron probe microanalyzer (Electron Probe Micro Analyzer; EPMA), which can measure a local concentration of an element. First, a test piece for mapping analysis is taken so that a cross section in the C-direction (rolling perpendicular direction) of the steel pipe becomes an observation surface, and the observation surface is mirror-finished. Next, on the above observation surface, when the wall thickness of the steel pipe is t , the local concentration of Mn as a reference is obtained by performing mapping analysis of the Mn concentration in region 1 surrounded by a length of $t/6$ (mm) in the wall-thickness direction centered at the 1/4 wall-thickness position from the outer surface of the steel pipe ($\pm t/12$ (mm) in the wall-thickness direction with the 1/4 wall-thickness position from the outer surface of the steel pipe as a reference) and a length of 10 (mm) in the circumferential direction, and by performing analysis described later, and calculating. Also, the segregation concentration of Mn is obtained by performing mapping analysis of the Mn concentration in region 2 surrounded by a length of $t/6$ (mm) in the wall-thickness direction (a length of $t/6$ (mm) in the wall-thickness direction with the surface of the inner surface of the steel pipe as a reference) and a length of 10 (mm) in the circumferential direction, and by performing analysis described later, and calculating. Here, in the mapping analysis of the Mn concentration, for both region 1 and region 2, the analysis pitch may be determined so that mapping data of 40,000 points are obtained, and mapping data may be acquired. Next, the obtained mapping data of 40,000 points are statistically analyzed to calculate the degree of segregation of Mn. The reference local concentration of Mn is an average value of mapping data obtained by excluding outliers from all mapping data obtained in region 1. The outliers are mapping data that are less than 0.05 times and mapping data that are larger than 5 times the Mn concentration (Mn content) obtained by check analysis of the steel pipe. Further, the segregation concentration of Mn is an average value in mapping data of the top 1% having high Mn concentrations, in mapping data obtained by excluding outliers from all mapping data obtained in region 2. At this time, mapping analysis of region 1 is performed for three fields of view, the local concentrations of Mn calculated for the three fields of view are summed, and the value obtained by dividing by 3 is taken as the local concentration of Mn. Similarly, mapping analysis of region 2 is also performed for three fields of view, the segregation concentrations of Mn calculated for the three fields of view are summed, and the value obtained by dividing by 3 is taken as the segregation concentration of Mn. The ratio of the segregation concentration of Mn to the local concentration of Mn obtained in this manner (the value obtained by dividing the segregation concentration of Mn from the inner surface of the seamless steel pipe to a 1/6 wall-thickness position by the local concentration of Mn near a 1/4 wall-thickness position from the outer surface of the steel pipe) is calculated as the degree of segregation of Mn.

[0062] Next, reasons for limiting the metallic microstructure of the seamless steel pipe of the present invention will be described.

Area fraction of martensite: 85% or more

[0063] If martensite occupying the metallic microstructure is less than 85%, fatigue strength of the seamless steel pipe decreases. Therefore, in the present invention, from the viewpoint of improving fatigue strength of the seamless steel pipe, the total of the area fractions of martensite in the metallic microstructure of the seamless steel pipe is set to 85% or more. The total of the area fractions of martensite is preferably 88% or more, more preferably 90% or more, still more preferably 92% or more, and most preferably 94% or more. On the other hand, the upper limit of the area fraction of martensite is not particularly limited, and may be 100% or less.

[0064] In one embodiment of the present invention, the metallic microstructure may be composed of martensite. Further, in another embodiment of the present invention, the metallic microstructure may contain other microstructures in addition to martensite. The other microstructures are not particularly limited and may be any microstructures. Examples of the other microstructures include bainite, ferrite, pearlite, retained austenite, and the like. When the metallic microstructure contains

bainite, the area fraction of bainite is preferably 10% or less, and more preferably 5% or less. The area fraction of bainite may be 0% or more. When the metallic microstructure contains ferrite, the area fraction of ferrite is preferably 2% or less, and more preferably 1% or less. The area fraction of ferrite may be 0% or more. When the metallic microstructure contains pearlite, the area fraction of pearlite is preferably 2% or less, and more preferably 1% or less. The area fraction of pearlite may be 0% or more. In the present invention, "high martensite fraction" means that martensite is 85% or more in terms of area fraction. The area fractions of the above metallic microstructures can be measured by the method described in Examples.

[0065] From each of the obtained seamless steel pipes, a test piece is taken so that an observation position is at a central portion in the longitudinal direction of the seamless steel pipe and at a 1/4 wall-thickness position from the outer surface of the steel pipe. Here, a surface composed of the wall-thickness direction and the circumferential direction (so-called "C cross section") is used as an observation surface. The observation surface is etched using a 3 vol.% nital solution. Thereafter, the observation surface is observed using a scanning electron microscope (SEM) at an appropriate magnification between 1,000 and 5,000 times, and a microstructure image is obtained. The obtained microstructure image is analyzed to evaluate the type of the metallic microstructures and the area fraction of respective metallic microstructures. Further, the area fraction of retained austenite is obtained by chemically polishing the observation surface and by X-ray diffraction. As an incident X-ray, a Co-K α radiation source is used, and the area fraction of retained austenite is calculated from an intensity ratio of ferrite (200), (211), and (220) planes and austenite (200), (220), and (311) planes.

[0066] Next, the wall thickness of the seamless steel pipe of the present invention will be described.

Wall thickness of the steel pipe is 40 mm or more (preferred condition)

[0067] When a seamless steel pipe is used for a pressure vessel, as the wall thickness of the steel pipe becomes larger, the stress applied to the pressure vessel that occurs becomes smaller, and therefore it is possible to design a pressure vessel that can withstand pressure up to a higher pressure. Therefore, the wall thickness of the steel pipe of the present invention is preferably 40 mm or more. The wall thickness of the steel pipe is more preferably 45 mm or more, and still more preferably 50 mm or more.

[0068] On the other hand, when the wall thickness of a seamless steel pipe becomes larger, the volume of the seamless steel pipe becomes larger. That is, the total amount of heat that the seamless steel pipe itself can store increases. In the quenching step, heat is removed from the inner surface and the outer surface of the steel pipe by a cooling medium, and therefore the temperature at the wall-thickness center of the steel pipe becomes higher than the inner surface and the outer surface of the steel pipe. On the other hand, the inner surface and the outer surface of the steel pipe constantly become the same temperature as a medium such as water used in water cooling, and a temperature gradient occurs. This effect becomes remarkable with an increase in wall thickness. When the temperature gradient is large, the balance between thermal stress and transformation stress deteriorates, and the quench-cracking risk increases. In addition, for a steel pipe having the same outer diameter, when the wall thickness increases, the inner diameter becomes smaller. Because the steel pipe is a thick-walled steel pipe, during quenching, a temperature distribution exists in which the temperature is lowest at the inner surface and the outer surface of the steel pipe and is highest at the wall-thickness center. When the inner surface and the outer surface of the steel pipe are sufficiently cooled, since the heat exchange efficiency at the inner surface and the outer surface of the steel pipe can be regarded as the same, no clear difference occurs between the temperature gradient from the wall-thickness center to the outer surface and the temperature gradient from the wall-thickness center to the inner surface. On the other hand, when the difference in circumferential length is compared with the wall-thickness center as a reference, it is a positive value at the outer surface, but it becomes a negative value at the inner surface.

[0069] Even after transformation from a face-centered cubic structure to a body-centered cubic structure is completed during quenching, a temperature gradient exists, and the side closer to the inner surface and the outer surface thermally contracts first. That is, it changes in a direction in which the difference in circumferential-length from the wall-thickness center decreases. At the outer surface, the difference in circumferential-length is positive, and since it changes in a direction in which the absolute value of the difference decreases, the thermal stress generated also decreases. On the other hand, at the inner surface, since the difference in circumferential-length is negative, it changes in a direction in which the absolute value of the difference increases, and therefore the thermal stress generated increases. That is, as the wall thickness increases, the quench-cracking risk at the inner surface increases, and therefore it is preferable that the wall thickness is smaller. Therefore, the wall thickness is preferably 70 mm or less, more preferably 65 mm or less, and still more preferably 60 mm or less.

[0070] Next, inclusions of the seamless steel pipe will be described.

[0071] Because inclusions have higher hardness than the Fe matrix and are difficult to deform, it is known that, when thermal stress occurs, inclusions become sources of stress concentration. That is, inclusions increase the quench-cracking risk.

[0072] In the region from the inner surface of the steel pipe to a 1/6 wall-thickness position, the number of inclusions

having an aspect ratio of 2 or less and a long-side length of 10 μm or more is 10 pieces/100 mm^2 or less (preferred condition).

[0073] It is known that inclusions include types such as sulfide-based inclusions, oxide-based inclusions, and nitride-based inclusions.

[0074] In rolling in the pipe-forming process, because inclusions having low hardness elongate during rolling, the shape of an inclusion can be characterized by the length of a long side and the length of a short side when the inclusion shape is assumed to be an elliptical shape. A value obtained by dividing the length of the long side by the length of the short side is defined as an aspect ratio.

[0075] The higher the hardness of an inclusion, the smaller the elongation during rolling becomes, and the smaller the aspect ratio becomes. On the other hand, with respect to quench-cracking resistance, the higher the hardness of an inclusion, the higher the quench-cracking risk becomes.

[0076] In particular, in the inner-surface side of the steel pipe, which is a region where segregation exists, that is, in the region from the inner surface of the steel pipe to a 1/6 wall-thickness position, inclusions that have an aspect ratio of 2 or less after rolling and have a long-side length of 10 μm or more act as starting points of occurrence of quench cracking and become causes of an increased quench-cracking risk. That is, in order to reduce the quench-cracking risk, the number of inclusions having a small aspect ratio is important. If the number of inclusions having an aspect ratio of 2 or less and a long-side length of 10 μm or more is 10 pieces/100 mm^2 or less, irregular quench cracking does not occur. Therefore, in the region from the inner surface of the steel pipe to a 1/6 wall-thickness position, it is preferable that the number of inclusions having an aspect ratio of 2 or less and a long-side length of 10 μm or more is 10 pieces/100 mm^2 or less. It is more preferable that the number of inclusions having an aspect ratio of 2 or less and a long-side length of 10 μm or more is 8 pieces/100 mm^2 or less, it is still more preferable that it is 5 pieces/100 mm^2 or less, and it is most preferable that it is 4.8 pieces/100 mm^2 or less. The lower limit of the above number of inclusions is not particularly limited, but from the viewpoint of cost suppression, it is preferable that it is 1 piece/100 mm^2 or more. Further, the above number of inclusions can be measured by the method described in Examples.

[0077] Note that, similarly to macro-segregation, in the billet center, which is a final solidification portion, the amount of inclusions becomes larger. Therefore, in a seamless steel pipe obtained using a billet, inclusions become most numerous on the inner-surface side of the seamless steel pipe. As mentioned above, because the inner-surface side of the seamless steel pipe has a high quench-cracking risk due to the influence of segregation, it is preferable that inclusions on the inner-surface side of the seamless steel pipe are fewer. Here, the "inner-surface side of the steel pipe" is a region from the inner surface of the steel pipe to a 1/6 wall-thickness position where macro-segregation exists. Note that the size of inclusions can be controlled by controlling the reduction amount when producing the seamless steel pipe from the material (billet).

[0078] Next, the cross-sectional hardness of the seamless steel pipe will be described.

[0079] Assuming that the seamless steel pipe of the present invention is used for a pressure vessel, from the viewpoint of fatigue design, the cross-sectional hardness is preferably 480 HV or more. The cross-sectional hardness is more preferably 520 HV or more, still more preferably 530 HV or more, and most preferably 540 HV or more. On the other hand, the upper limit of the cross-sectional hardness is not particularly limited, but is preferably 700 HV or less, and more preferably 650 HV or less. In addition, the cross-sectional hardness can be measured by the method described in Examples.

[0080] Next, a method for manufacturing the seamless steel pipe of the present invention will be described.

Material (billet)

[0081] As the material (billet) used for pipe forming of the seamless steel pipe, from the viewpoint of productivity, it is preferable to use a material produced by continuous casting. In continuous casting, when the mold becomes large, control of the solidification process becomes difficult; therefore, in order to stably mass-produce, the billet diameter is preferably 400 mm or less, more preferably 350 mm or less, and still more preferably 345 mm or less. On the other hand, the lower limit of the billet diameter is not particularly limited, but it is preferably 320 mm or more, and more preferably 330 mm or more.

[0082] Further, since macro-segregation in a billet is improved by hot forging, for example, it is also effective to hot-forge a rectangular material produced by continuous casting into a circular material (billet).

(Pipe-forming step)

[0083] Pipe forming such that a ratio of an inner diameter of the steel pipe divide by a wall thickness becomes 2.0 times or more

Macro-segregation at the billet center can be dissipated in a piercing process when forming a seamless steel pipe, by plastically deforming by rolling from a solid billet to a hollow seamless steel pipe. In rolling, when it is assumed that the wall thickness becomes thick and the quench-cracking risk becomes high, the amount of plastic deformation when forming the seamless steel pipe by rolling from the billet can be increased by increasing the inner diameter. It is preferable that the ratio

obtained by dividing the inner diameter of the steel pipe by the wall thickness is 2.0 times or more. Since the larger this ratio is, the larger the amount of plastic deformation is, it is preferably 3.0 times or more, more preferably 4.0 times or more, still more preferably 4.1 times or more, and most preferably 4.2 times or more. Further, the upper limit of the above ratio is not particularly limited, but from the viewpoint of securing a rolling amount, it is preferably 8.0 times or less, and more preferably 7.0 times or less.

[0084] Further, in order to increase the amount of plastic deformation, it is also effective to expand the pipe to an outer diameter larger than the billet diameter, and it is preferable that the outer diameter of the seamless steel pipe is larger than 1.0 times the billet diameter, more preferably 1.1 times or more, and still more preferably 1.2 times or more. Further, from the viewpoint of handling, it is preferable to be 2.0 times or less. Note that, in the pipe-forming step, piercing and rolling are essential requirements. Further, it is preferable to carry out pipe expansion as necessary.

[0085] In the pipe-forming step, the shape of the steel pipe satisfies the following equation (2) (preferred condition)

$$(\text{EXP}(\text{coefficient } K \times \text{wall thickness}) / \text{circumferential cross section area}) \times 10^6 < 210 \quad (2)$$

$$K = \{0.41([C] - 0.24) + 4.58[Mn] + 0.21[Cr] + 0.25[Ni]\} / 100$$

$$\dots (3)$$

(In equation (3), [element] represents the content (mass%) of the element described in the brackets)

[0086] An increase in the wall thickness of the steel pipe increases the area of the circumferential cross section. That is, because the volume of the seamless steel pipe increases and the total amount of heat of the seamless steel pipe increases, there is also an effect of lowering the cooling rate at the time of quenching and lowering the quench-cracking risk. As described above, an increase in wall thickness has both a positive factor and a negative factor with respect to the quench-cracking risk, and it is preferable to optimize the balance thereof in consideration of productivity.

[0087] Further, because the temperature difference between the inner surface and the outer surface of the seamless steel pipe and the wall-thickness center is affected by thermal conductivity, it is affected by contribution of the component composition. Generally, physical property values (thermal conductivity) in carbon steel, manganese steel, chromium steel, nickel steel, and the like are measured, and C, Mn, Cr, and Ni contribute greatly.

[0088] Since the quench-cracking risk is reduced by satisfying equation (2), it is preferable to satisfy equation (2). The right-hand side in equation (2) is more preferably 208 or less, and still more preferably 205 or less. Further, from the viewpoint of pipe-forming efficiency, the left-hand side of equation (2) is preferably 40 or more. The coefficient K in equation (2) is obtained by the above equation (3).

(Quenching step)

Heating to a temperature range of 860°C or higher, and holding in the temperature range for 30 min or longer

[0089] In the following, the temperature to be described means, unless otherwise stated, all refers to a 1/4 position from the inner surface.

[0090] Immediately before quenching, it is held at a temperature in an austenite region. Since it is a temperature region existing as a solid, dissipation of macro-segregation cannot be expected, but since diffusion of atoms occurs actively and de-trapping of contained elements from grain boundaries is expected, it is effective for improvement of micro-segregation.

[0091] The frequency of diffusion depends on temperature and time, and when the temperature is less than 860°C, the de-trapping effect is weak; therefore, the temperature is set to 860°C or higher. The temperature is preferably 865°C or higher, more preferably 870°C or higher, and still more preferably 875°C or higher. On the other hand, an increase in temperature promotes coarsening of prior austenite crystal grains and not only causes a decrease in fatigue strength but also causes an increase in heating cost; therefore, it is preferably 950°C or lower, more preferably 930°C or lower, still more preferably 900°C or lower, and most preferably 890°C or lower. The holding time is set to 30 min or longer for homogenization. The holding time is preferably 35 min or longer, more preferably 40 min or longer, and still more preferably 45 min or longer. Further, since an increase in holding time causes a decrease in productivity, it is preferably 90 min or shorter, more preferably 60 min or shorter, and still more preferably 55 min or shorter.

[0092] Water cooling under conditions such that an average cooling rate in a temperature range of 800 to 350°C is 3°C/s or more

[0093] The water cooling after the above heating and holding is essential for ensuring an area fraction of martensite of 85% or more. In addition, the average cooling rate in the temperature range of 800 to 350°C is set to 3°C/s or more. Since a faster average cooling rate is expected to result in a larger area fraction of martensite, it is preferably 4°C/s or more, more

preferably 5°C/s or more, still more preferably 5.5°C/s or more, and most preferably 6°C/s or more. On the other hand, the upper limit of the average cooling rate is not particularly limited, but it is preferably 15°C/s or less, and more preferably 10°C/s or less. The average cooling rate is obtained by dividing the temperature difference in the temperature range of 800 to 350°C by the time required to cool this temperature range.

[0094] In the water cooling, bringing a cooling medium into contact with the inner surface of the steel pipe at a flow rate of 0.5 m³/min or more in a state that the steel pipe is rotated in the circumferential direction of the pipe

[0095] It is important to remove a vapor film generated during water cooling. The outer surface of the seamless steel pipe has a high degree of freedom of equipment, and even with a device having a simple structure, it is possible to realize removal of the vapor film, but there are many equipment constraints for removal of the vapor film on the inner surface of the steel pipe. Therefore, it is necessary to bring a cooling medium into contact with the inner surface of the steel pipe, and, for example, an appropriate method such as a method of running a jet flow of the cooling medium may be used, and the flow rate is 0.5 m³/min or more. The flow rate is preferably 0.55 m³/min or more, more preferably 0.58 m³/min or more, still more preferably 0.6 m³/min or more, and most preferably 0.65 m³/min or more. The upper limit of the flow rate is not particularly limited, but from the viewpoint of reducing equipment load, it is preferably 1.5 m³/min or less.

[0096] In addition, in order to shorten a time during which thermal stress is generated, it is important to remove heat remaining in the steel pipe even after martensite transformation is completed, and the jet-flow injection time is preferably 3 min or longer, more preferably 5 min or longer, still more preferably 5.5 min or longer, and most preferably 6 min or longer. Note that, since a vapor film is generated in an initial stage of injection, after 90 s from injection, the flow rate may be reduced to less than 0.5 m³/min and 0.05 m³/min or more. In addition, it is preferable that the steel-pipe surface temperature after completion of injection is 50°C or lower. Since the cooling medium needs to have a function of sufficiently cooling, water of 50°C or lower may be used. The temperature of the water is more preferably 45°C or lower, and still more preferably 40°C or lower. The temperature of the water is preferably 2°C or higher.

[0097] Further, in order to mitigate a heat distribution caused by rolling thickness deviation, during injection of the jet flow, it is preferable to rotate the seamless steel pipe in the circumferential direction of the pipe at a rotational speed of 10 rpm or more. It is more preferable to set the rotational speed to 12 rpm or more, and still more preferable to set it to 15 rpm or more. On the other hand, the upper limit of the rotational speed is not particularly limited, but it is preferable to set it to a rotational speed of 1,200 rpm or less.

[0098] Note that the quenching step refers to a series of steps of heating, holding, and water cooling after the pipe-forming step.

[0099] Since the seamless steel pipe is cooled while rotating at high speed, it is difficult to directly measure temperature using a general temperature measurement method of attaching a thermocouple and to calculate the average cooling rate during quenching. Therefore, a CCT diagram may be prepared, and the average cooling rate may be determined by correlating with hardness measured in the steel pipe after quenching.

[0100] Note that, as cooling equipment, appropriate equipment such as immersion equipment, mist cooling equipment, shower cooling equipment, and the like may be used, but basically, since cooling is most uniform by immersing the entire steel pipe in water, rotating it, and running a jet flow on the inner surface of the steel pipe, it is preferable to use immersion equipment.

[0101] In another embodiment of the present invention, the processing described later can be further performed.

[0102] A decarburized layer generated on the surface of the steel pipe at the time of quenching is more brittle than a matrix phase of the steel pipe and is liable to generate cracking. In addition, rolling defects also become starting points of cracking. Therefore, it is also effective to perform machining such as cutting or polishing, and shot blasting, or both, to remove the decarburized layer and rolling defects.

[0103] Further, in order to suppress corrosion of the inner surface of the seamless steel pipe, it is also effective to apply rust-preventive oil or to apply coating.

[0104] When cooling the seamless steel pipe, since heat transfer at the inner surface and the outer surface is dominant, the outer surface having a larger surface area of the steel pipe is cooled more efficiently. Therefore, in a temperature distribution with respect to the wall-thickness direction, a position having the highest temperature moves from the wall-thickness center toward the inner-surface side. In that case, a load on the outer surface becomes large, and the risk that quench cracking occurs on the outer surface becomes high. Although the outer surface does not have macro-segregation like the inner surface, it is affected by micro-segregation; therefore, an extremely large wall thickness is not preferable. Accordingly, as a relationship between an inner diameter and an outer diameter, it is preferable that a value obtained by dividing a difference between an outer circumferential length and an inner circumferential length by a circumferential length at the wall-thickness center is 0.45 or less, and it is more preferable that it is 0.40 or less. The lower limit is not particularly limited, but it is preferable that it is 0.10 or more.

[0105] Next, the pressure vessel and a method for manufacturing the pressure vessel will be described.

[0106] The seamless steel pipe of the present invention can be used as a pressure vessel having high pressure, such as a pressure vessel for compressed fluid and a pressure vessel for high-pressure gas, and having specifications in which a requirement for roundness is high as compared with, for example, an electric resistance welded pipe.

[0107] For example, when the seamless steel pipe of the present invention is used for a pressure vessel, a pressure vessel can be produced by performing necessary processing on the seamless steel pipe. The processing is not particularly limited, and examples thereof include processing for rendering defects on the inner surface of the steel pipe harmless, and processing for attaching a lid to an end portion of the steel pipe. Examples of the processing for rendering defects on the inner surface of the steel pipe harmless include, for example, cutting the inner surface of the steel pipe with a tool, grinding the inner surface of the steel pipe with a grindstone, and shot-blasting the inner surface of the steel pipe. Further, examples of the processing for attaching a lid include, for example, providing a screw (thread) for screwing the lid onto the end portion of the steel pipe, and forming a flange for tightening the lid with a bolt.

EXAMPLES

[0108] Next, Examples will be described.

[0109] A heated material (billet) having the component composition shown in Table 1 was pierced, expanded, and rolled as shown in Table 2 to form into a pipe such that a ratio of an inner diameter of a steel pipe divided by a wall thickness is 2.0 times or more. A quenching step under the conditions shown in Table 2 was carried out, and a seamless steel pipe having an outer diameter and a wall thickness shown in Table 2 was produced. In a cooling during the quenching step, the steel pipe was immersed in water, and cooling was performed while bringing a cooling medium into contact with an inner surface of the steel pipe at a flow rate of 0.5 m³/min or more in a state that the steel pipe was rotated in the circumferential direction of the pipe. From a central portion in the longitudinal direction of each obtained seamless steel pipe, test pieces for microstructure observation, evaluation of the degree of segregation of Mn (EPMA observation), and inclusion investigation were taken.

(Average cooling rate in the quenching step)

[0110] Since it is difficult to directly measure the average cooling rate of a rotating steel pipe with a thermocouple or the like, evaluation was performed by attaching a thermocouple to the center of the wall thickness and actually measuring, using a test piece having the same wall thickness obtained by dividing, into four in the circumferential direction, a steel pipe having a length of 500 mm taken from an end portion of the obtained steel pipe. Based on the idea that the water-cooling process of the steel pipe can be simulated only by immersing the test piece in water at room temperature, since, in the water-cooling process of the steel pipe, a difference in cooling rate in the wall-thickness direction is reduced by continuously bringing the cooling medium into contact with the inner surface of the steel pipe, and additionally a difference in cooling rate in the circumferential direction is reduced by rotation of the steel pipe, measurement was performed by the above method. For each steel type described in Table 2, four test pieces were produced, and an average value of cooling rates in a temperature range of 800 to 350°C was taken as an average cooling rate of the steel pipe. The average cooling rate is as shown in Table 2.

(Microstructure observation)

[0111] From each of the seamless steel pipes, a test piece was taken so that an observation position was a central portion in the longitudinal direction of the seamless steel pipe and a 1/4 wall-thickness position from the outer surface of the steel pipe. Here, a surface composed of the wall-thickness direction and the circumferential direction (so-called "C cross section") was taken as an observation surface (10 mm × 10 mm). First, for the observation surface, an area fraction of retained austenite was calculated by the following method. The area fraction of retained austenite was obtained by chemically polishing the observation surface and by X-ray diffraction. As an incident X-ray, a Co-K α radiation source was used, and the area fraction of retained austenite was calculated from an intensity ratio of ferrite (200), (211), and (220) planes and austenite (200), (220), and (311) planes.

[0112] Next, after mirror-polishing the observation surface, etching was performed using an aqueous picric acid solution, and polishing was performed so that prior γ grain boundaries remained, and the size and morphology of the prior γ grain boundaries were grasped using an optical microscope at an appropriate magnification between 100 and 500 times. These are indicators of martensite, that is, the size and morphology of martensite were grasped. Further, after mirror-polishing the observation surface, etching was performed using a 3 vol.% nital solution, and, from comparison of images by nital etching and picric-acid etching, it was confirmed that the morphology of the prior γ grain boundaries was not extremely flattened, and that the inside of the prior γ grains was in a fine lath-like state, and that the microstructure was predominantly martensitic (85% or more). Thereafter, using an optical microscope at an appropriate magnification between 100 and 500 times for the microstructure etched with the above nital, coarse grains were judged as ferrite, and an area fraction of ferrite was calculated. Thereafter, by observing the cross section etched with nital by using a scanning electron microscope (SEM) at an appropriate magnification between 1,000 and 10,000 times, a region in which lamellar carbides were confirmed was judged as pearlite, and an area fraction of pearlite was calculated. An area fraction

obtained by subtracting the area fractions of retained austenite, ferrite, and pearlite from the whole (taken as 100%) was taken as an area fraction of martensite.

(Inclusions)

[0113] Investigation of inclusions was performed for a region from the inner surface of the steel pipe to a 1/6 wall-thickness position, which is a segregation region on the inner-surface side of the steel pipe. Specifically, it was performed by taking, from the inner surface of the obtained steel pipe, a test piece for inclusion measurement having dimensions of 20 mm in the longitudinal direction of the steel pipe, 5 mm in the circumferential direction, and 15 mm in the wall-thickness direction. The test piece was resin-embedded so that a surface composed of the longitudinal direction and the wall-thickness direction of the steel pipe (so-called "L cross section") became an observation surface, and after mirror polishing, optical microscope observation was performed to measure number density of inclusions having an aspect ratio of 2 or less and a long-side length of 10 μm or more in an area of 10 mm $\times$ 10 mm (100 mm²). Note that, for each level of the steel pipe, ten test pieces for inclusion investigation were taken, and an arithmetic average of the total number of inclusions having an aspect ratio of 2 or less and a long-side length of 10 μm or more measured as described above using these ten test pieces was taken as the number of inclusions (inclusion number density) of the steel pipe of that level. Note that the aspect ratio and the long-side length of inclusions are values obtained in conformity with JIS G 0555:2020 (Microscopic test method for nonmetallic inclusions of steel).

(Degree of segregation of Mn)

[0114] For evaluation of the degree of segregation of Mn, a test piece taken so that a cross section in the C-direction (rolling perpendicular direction) of the steel pipe became an observation surface, and having a mirror-finished observation surface, was used. On the above observation surface, when the wall thickness of the steel pipe is t , the local concentration of Mn as a reference was calculated by performing mapping analysis of the Mn concentration in region 1 surrounded by a length, in the wall-thickness direction, of $t/6$ (mm) with the 1/4 wall-thickness position from the outer surface of the steel pipe as a center (a length in the wall-thickness direction of $\pm t/12$ (mm) with the 1/4 wall-thickness position from the outer surface of the steel pipe as a reference) and a length of 10 (mm) in the circumferential direction, and by performing analysis described later. Further, the segregation concentration of Mn was calculated by performing mapping analysis of the Mn concentration in region 2 surrounded by a length of $t/6$ (mm) in the wall-thickness direction and a length of 10 (mm) in the circumferential direction, and by performing analysis described later. Here, in mapping analysis of the Mn concentration, for both region 1 and region 2, mapping data were obtained by determining an analysis pitch so that mapping data of 40,000 points were obtained. Next, the obtained mapping data of 40,000 points were statistically analyzed, and the degree of segregation of Mn was calculated. The reference local concentration of Mn was taken as an average value of mapping data obtained by excluding outliers from all mapping data obtained in region 1. The outliers were taken as mapping data that are less than 0.05 times and mapping data that are larger than 5 times the Mn concentration (Mn content) obtained by check analysis of the steel pipe. Further, the segregation concentration of Mn was taken as an average value of mapping data of the top 1% having high Mn concentrations, in mapping data obtained by excluding outliers from all mapping data obtained in region 2. At this time, mapping analysis of region 1 was performed for three fields of view, the local concentrations of Mn calculated for the three fields of view were summed, and the value obtained by dividing by 3 was taken as the local concentration of Mn. Similarly, mapping analysis of region 2 was also performed for three fields of view, the segregation concentrations of Mn calculated for the three fields of view were summed, and the value obtained by dividing by 3 was taken as the segregation concentration of Mn. The degree of segregation of Mn was calculated as the ratio of the segregation concentration of Mn to the local concentration of Mn obtained in this manner. Note that the above mapping analysis was performed by EPMA as described in the embodiment.

(Cross-sectional hardness)

[0115] Cross-sectional hardness was measured by taking a test piece so that a 1/4 wall-thickness position from the outer surface of the steel pipe became an evaluation position, and, in conformity with JIS 2244 "Vickers hardness test-Test method," measuring hardness at five points using a load of 10 kgf at the 1/4 wall-thickness position from the outer surface of the steel pipe, and taking an average value thereof.

(Quench-cracking resistance)

[0116] The presence or absence of occurrence of quench cracking was evaluated in conformity with JIS G 0582 "Automatic ultrasonic inspection method for steel pipes." A threshold used as a criterion for determining the presence or absence of occurrence of quench cracking was set to 5% of the wall thickness, and a steel pipe satisfying this criterion was

judged to have no quench cracking. First, twenty steel pipes for each level shown in Table 2 were prepared, and quench-cracking resistance was evaluated. That is, the presence or absence of occurrence of quench cracking in the obtained steel pipes was confirmed, and, among the twenty steel pipes, a proportion of the number of steel pipes in which quench cracking did not occur, that is, $(\text{number of steel pipes in which quench cracking did not occur}/20) \times 100 (\%)$ was taken as a quench-cracking pass rate. Quench-cracking resistance was judged as pass when the quench-cracking pass rate was 90% or more.

[0117] As can be seen from the results shown in Table 2, the seamless steel pipes satisfying the conditions of the present invention had a metallic microstructure having a high martensite fraction, but satisfied a prescribed degree of segregation of Mn, satisfied a quench-cracking pass rate of 90% or more in heat treatment, and was excellent in quench-cracking resistance.

[0118] Thus, the seamless steel pipe of the present invention has sufficient quench-cracking resistance even though a martensite fraction is high. Further, it can be judged that fatigue strength is excellent because the martensite fraction is high. As a result, it becomes possible to supply a thick-walled seamless steel pipe.

[Table 1]

Steel type	Component composition (mass%)										Right-hand side of Equation (1)	Satisfaction of Equation (1)	Remarks
	C	Si	Mn	S	O	N	Al	Mo	Cr	Ni	P	Others	
A	0.38	0.23	0.79	0.005	0.002	0.0034	0.03	0.25	1.05	0.01	0.018	-	Inventive steel
B	0.43	0.24	0.76	0.003	0.001	0.0062	0.03	0.22	0.80	2.04	0.015	-	Inventive steel
C	0.38	0.23	0.82	0.005	0.002	0.0034	0.03	0.25	0.65	2.95	0.013	-	Inventive steel
D	0.33	0.25	0.61	0.004	0.001	0.0051	0.03	0.30	0.91	0.02	0.023	-	Inventive steel
E	0.38	0.21	1.06	0.004	0.001	0.0041	0.03	0.28	1.04	0.04	0.013	-	Inventive steel
F	0.41	0.22	0.56	0.005	0.002	0.0042	0.04	0.21	1.09	0.01	0.024	-	Inventive steel
G	0.55	0.93	0.82	0.005	0.001	0.0035	0.03	0.16	2.84	0.01	0.009	-	Inventive steel
H	0.21	0.25	0.84	0.004	0.002	0.0028	0.03	0.19	0.99	0.01	0.016	-	Inventive steel
I	0.35	0.27	0.80	0.004	0.001	0.0036	0.04	0.48	1.04	0.01	0.018	-	Inventive steel
J	0.37	0.20	0.81	0.003	0.001	0.0039	0.03	0.23	1.02	0.03	0.022	-	Comparative steel
K	0.37	0.23	0.81	0.005	0.002	0.0031	0.04	0.28	1.07	0.01	0.021	-	Comparative steel
L	0.42	0.23	0.83	0.004	0.001	0.0049	0.03	0.24	0.95	1.91	0.017	-	Comparative steel
M	0.33	0.24	0.81	0.004	0.001	0.0031	0.03	0.22	0.92	0.02	0.023	-	Comparative steel
N	0.36	0.29	1.25	0.004	0.002	0.0032	0.03	0.19	0.99	0.01	0.012	-	Comparative steel
Q	0.38	0.23	0.75	0.005	0.002	0.0034	0.03	0.25	0.35	3.51	0.017	-	Comparative steel
P	0.38	0.23	0.85	0.005	0.002	0.0034	0.03	0.25	3.21	0.01	0.018	-	Comparative steel
Q	0.63	0.27	0.67	0.004	0.001	0.0036	0.04	0.28	0.72	1.02	0.023	-	Comparative steel

(continued)

Steel type	Component composition (mass%)											Right-hand side of Equation (1)	Satisfaction of Equation (1)	Remarks
	C	Si	Mn	S	O	N	Al	Mo	Cr	Ni	P	Others		
<u>R</u>	<u>0.19</u>	0.26	<u>0.44</u>	0.004	0.002	0.0036	0.04	0.31	1.12	0.02	0.024	-	O	Comparative steel
<u>S</u>	0.35	0.27	0.54	0.004	0.001	0.0036	0.04	0.28	1.04	0.01	0.029	-	<u>×</u>	Comparative steel
T	0.37	0.25	0.81	0.004	0.001	0.0036	0.04	0.29	1.02	1.53	0.015	B:0.002, Ti:0.02	O	Inventive steel
U	0.36	0.29	0.87	0.004	0.001	0.0050	0.04	0.28	1.01	0.02	0.013	Cu:1.05, Co:0.99	O	Inventive steel
V	0.39	0.21	0.73	0.005	0.002	0.0036	0.03	0.34	0.98	0.01	0.017	V:0.38, Nb:0.041	O	Inventive steel
W	0.34	0.56	0.67	0.006	0.003	0.0036	0.04	0.15	1.07	0.02	0.016	W:1.7, Zr:0.02, Ta:0.05	O	Inventive steel
X	0.41	0.31	0.81	0.004	0.001	0.0036	0.03	0.27	0.78	0.01	0.008	Hf:0.07, Sb:0.06, Sn:0.04	O	Inventive steel
Y	0.38	0.46	0.75	0.006	0.002	0.0030	0.04	0.25	1.09	0.01	0.020	Ca:0.002, Mg:0.003, REM:0.25	O	Inventive steel
Z	0.42	1.01	0.85	0.009	0.004	0.0090	0.07	0.17	1.08	0.03	0.017	-	O	Inventive steel
AA	0.37	0.23	0.81	0.005	0.002	0.0034	0.03	0.25	1.05	0.01	0.014	Cu:0.06	O	Inventive steel
AB	0.35	0.24	0.78	0.006	0.002	0.0035	0.03	0.25	1.04	2.05	0.012	Cu:0.43, Sn:0.03	O	Inventive steel
AC	0.36	0.25	0.75	0.003	0.001	0.0031	0.04	0.17	0.98	1.98	0.009	Cu:4.10	O	Inventive steel
Those underlined are outside the scope of the present invention														

[Table 2]

Level	Steel type	Manufacturing step				Microstructure of seamless steel pipe						Material properties of seamless steel pipe	Quenching-cracking resistance	Remarks
		Heating		Cooling		Segregation degree of Mn	Segregation degree evaluation	Number of inclusions (/100mm ²)	Inclusion evaluation	Area fraction of microstructure (%)	Area fraction judgment evaluation	Hardness (HV)	Quenching-cracking pass rate (%)	
1	A	820	30	7	Average cooling rate in temperature range of 800 to 350°C	1.55	×	5.2	○	90	○	563	60	Comparative example
2	A	860	15	7	Time (min)	1.53	×	5.3	○	95	○	559	70	Comparative example
3	A	860	30	7	Temperature (°C)	1.47	○	5.4	○	100	○	555	100	Example
4	A	860	30	1	Satisfaction of Equation (2)	1.49	○	8.5	○	55	×	421	100	Comparative example
5	A	860	30	7	Left-hand side of Equation (2)	1.47	○	5.4	○	100	○	552	90	Example
6	A	860	15	5	Inner diameter (mm)	1.52	×	7.2	○	85	○	548	80	Comparative example
7	A	860	30	5	Wall thickness (mm)	1.45	○	7.3	○	85	○	541	90	Example
8	A	860	60	5	Outer diameter (mm)	1.42	○	7.9	○	90	○	535	100	Example
9	A	900	15	5	Outer diameter (mm)	1.51	×	7.6	○	85	○	537	80	Comparative example
10	A	900	30	5	Inner diameter (mm)	1.42	○	7.8	○	85	○	534	100	Example
11	A	900	30	5	Left-hand side of Equation (2)	1.42	○	7.8	○	85	○	536	100	Example

(continued)

Level	Steel type	Dimensions					Manufacturing step			Microstructure of seamless steel pipe						Material properties of seamless steel pipe	Quenching-cracking resistance	Remarks
							Heating		Cooling									
							Temperature (°C)	Time (min)										
		Outer diameter (mm)	Wall thickness (mm)	Inner diameter (mm)	Left-hand side of Equation (2)	Satisfaction of Equation (2)	860	30	5	Segregation degree of Mn	Segregation degree evaluation	Number of inclusions (/100mm ²)	Inclusion evaluation	Area fraction of microstructure (%)	Area fraction judgment equation	Hardness (HV)	Quenching-cracking pass rate (%)	
12	A	356	60	236	186	○	860	30	5	1.47	○	8.7	○	85	○	533	90	Example
13	A	356	70	216	244	×	860	30	<u>2</u>	1.49	○	9.5	○	<u>80</u>	×	462	90	Comparative example
14	A	306	55	196	197	○	860	30	5	1.45	○	8.9	○	85	○	539	90	Example
15	A	306	70	166	295	×	860	30	<u>2</u>	1.49	○	12.7	×	<u>75</u>	×	453	90	Comparative example
16	A	356	65	226	212	×	860	30	13	1.48	○	9.5	○	90	○	521	90	Example
17	B	406	61	284	200	○	860	30	5	1.48	○	8.2	○	95	○	559	90	Example
18	C	406	52	302	198	○	860	30	5	1.44	○	8.8	○	95	○	550	100	Example
19	C	406	42	322	149	○	860	30	5	1.41	○	8.6	○	100	○	543	90	Example
20	D	406	40	326	73	○	860	30	7	1.42	○	4.3	○	90	○	513	100	Example
21	E	406	40	326	170	○	860	30	7	1.48	○	6.7	○	100	○	562	100	Example
22	F	406	40	326	68	○	860	30	8	1.42	○	3.5	○	95	○	572	100	Example
23	G	406	42	322	137	○	860	30	6	1.46	○	5.6	○	95	○	587	100	Example
24	H	406	41	324	112	○	860	30	7	1.47	○	8.2	○	95	○	484	100	Example
25	I	406	40	326	105	○	860	30	7	1.39	○	2.4	○	95	○	538	100	Example

(continued)

Level	Steel type	Dimensions					Manufacturing step		Microstructure of seamless steel pipe						Material properties of seamless steel pipe	Quenching resistance	Remarks	
							Heating											Cooling
		Outer diameter (mm)	Wall thickness (mm)	Inner diameter (mm)	Left-hand side of Equation (2)	Satisfaction of Equation (2)	Temperature (°C)	Time (min)	Average cooling rate in temperature range of 800 to 350°C	Segregation degree of Mn	Inclusion evaluation	Area fraction ofM microstructure (%)	Area fraction judgment equation	Quenching rate (%)				
26	J	406	42	322	111	○	860	30	7	1.43	○	1.4	○	95	○	544	80	Comparative example
								Heating	Cooling									
Outer diameter (mm)	Wall thickness (mm)	Inner diameter (mm)	Left-hand side of Equation (2)	Satisfaction of Equation (2)	Average cooling rate in temperature range of 800 to 350°C	Segregation degree of Mn	Segregation degree evaluation	Number of inclusions (/100mm ²)	Inclusion evaluation	Area fraction ofM microstructure (%)	Hardness (HV)	Quenching rate (%)						
27	K	406	61	284	173	○	860	30	5	1.47	○	4.4	○	95	○	539	70	Comparative example
28	L	406	61	284	243	×	860	30	5	1.50	×	6.1	○	100	○	549	40	Comparative example
29	M	406	40	326	105	○	860	30	8	1.46	○	5.9	○	95	○	511	80	Comparative example

(continued)

[illegible]

Claims

1. A seamless steel pipe comprising:

a component composition containing, in mass%,

C: 0.20 to 0.60%,

Si: 0.01 to 2.0%,

Mn: 0.5 to 1.2%,

S: 0.010% or less,

O: 0.005% or less,

N: 0.010% or less,

Al: 0.01 to 0.08%,

Mo: 0.005 to 1.0%,

Cr: 0.005 to 3.0%, and

Ni: 0.005 to 3.0%,

optionally one or two or more selected from

Ti: 0.0001 to 0.1%,

Cu: 0.0001 to 5.0%,

Co: 0.0001 to 5.0%,

B: 0.0001 to 0.01%,

V: 0.0001 to 1.0%,

W: 0.0001 to 5.0%,

Nb: 0.0001 to 0.1%,

Zr: 0.0001 to 0.2%,

Hf: 0.0001 to 0.2%,

Ta: 0.0001 to 0.2%,

Sb: 0.0001 to 0.1%,

Sn: 0.0001 to 0.1%,

Ca: 0.0001 to 0.01%,

Mg: 0.0001 to 0.01%, and

REM: 0.0001 to 0.5%, and

the component composition further containing P so as to satisfy the following formula (1):

$$[P] \leq 0.042 - 0.002[C] - 0.024[Mn] - 0.001[Mo] - 0.001[Cr] - 0.002[Ni] \quad (1)$$

(where [element] in formula (1) represents a content (mass%) of the element described in the brackets),
the balance being Fe and unavoidable impurities;

a degree of segregation of Mn from an inner surface of the steel pipe to a 1/6 wall-thickness position of less than 1.50; and

a metallic microstructure having an area fraction of martensite of 85% or more.

2. The seamless steel pipe according to claim 1, wherein a wall thickness of the steel pipe is 40 mm or more.

3. The seamless steel pipe according to claim 1 or 2, wherein, in a region from the inner surface of the steel pipe to a 1/6 wall-thickness position, a number of inclusions having an aspect ratio of 2 or less and a long-side length of 10 μm or more is 10 pieces/100 mm^2 or less.

4. The seamless steel pipe according to any one of claims 1 to 3, wherein a cross-sectional hardness is 480 HV or more.

5. A method for manufacturing a seamless steel pipe according to any one of claims 1 to 4, the method comprising:

a pipe-forming step of pipe-forming a heated material such that a ratio of an inner diameter of the steel pipe divided by a wall thickness is 2.0 times or more; and

a quenching step of heating the formed steel pipe to a temperature range of 860°C or higher, holding in the temperature range for 30 min or longer, and water-cooling under conditions such that an average cooling rate in a temperature range of 800 to 350°C is 3°C/s or more, wherein, in the water-cooling, the steel pipe is cooled while bringing a cooling medium into contact with an inner surface of the steel pipe at a flow rate of 0.5 m^3/min or more in a state that the steel pipe is rotated in a circumferential direction of the pipe.

6. The method for manufacturing a seamless steel pipe according to claim 5, wherein the pipe-forming step is performed such that a shape of the steel pipe satisfies the following formula (2):

$$(\text{EXP}(\text{coefficient } K \times \text{wall thickness}) / \text{circumferential cross section area}) \times 10^6 < 210 \quad (2)$$

$$K = \{0.41([C]-0.24) + 4.58[Mn] + 0.21[Cr] + 0.25[Ni]\} / 100 \quad (3)$$

(where [element] in formula (3) represents a content (mass%) of the element described in the brackets).

7. A pressure vessel wherein the seamless steel pipe according to any one of claims 1 to 4 is used as the pressure vessel.
8. A method for manufacturing a pressure vessel, the method comprising processing the seamless steel pipe according to any one of claims 1 to 4.

INTERNATIONAL SEARCH REPORT

International application No.

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A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; *C21D 7/06*(2006.01)i; *C21D 8/10*(2006.01)i; *C21D 9/08*(2006.01)i; *C22C 38/60*(2006.01)i
FI: C22C38/00 301Z; C21D8/10 A; C21D9/08 E; C22C38/60; C21D7/06 A

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C38/00-38/60; C21D7/06; C21D8/10; C21D9/08

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2025
Registered utility model specifications of Japan 1996-2025
Published registered utility model applications of Japan 1994-2025

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2014-012890 A (JFE STEEL CORPORATION) 23 January 2014 (2014-01-23) entire text, all drawings	1-8
A	JP 2018-070970 A (NIPPON STEEL & SUMITOMO METAL CORPORATION) 10 May 2018 (2018-05-10) entire text, all drawings	1-8
A	JP 2019-183218 A (NIPPON STEEL CORPORATION) 24 October 2019 (2019-10-24) entire text, all drawings	1-8
A	WO 2016/038810 A1 (JFE STEEL CORPORATION) 17 March 2016 (2016-03-17) entire text	1-8
A	WO 2018/025778 A1 (NIPPON STEEL & SUMITOMO METAL CORPORATION) 08 February 2018 (2018-02-08) entire text, all drawings	1-8

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

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Date of the actual completion of the international search

15 April 2025

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Name and mailing address of the ISA/JP

Japan Patent Office (ISA/JP)
3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915
Japan

Authorized officer

Telephone No.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2025/004597

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Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
JP 2014-012890 A	23 January 2014	(Family: none)	
JP 2018-070970 A	10 May 2018	(Family: none)	
JP 2019-183218 A	24 October 2019	(Family: none)	
WO 2016/038810 A1	17 March 2016	US 2017/0283918 A1 entire document	
WO 2018/025778 A1	08 February 2018	US 2019/0177813 A1 entire document	

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP HEI9104925 A [0006]
- WO 2018055937 A [0006]