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DESCRIPTION

Title of Invention: THICK-WALLED HIGH-TOUGHNESS HIGH-STRENGTH STEEL PLATE AND METHOD FOR MANUFACTURING THE SAME

Technical Field

[0001]

The present invention relates to a thick-walled high-toughness high-strength steel plate for use in steel structures in construction, bridges, shipbuilding, offshore structures, construction and industrial machinery, tanks, penstocks, and the like and to a method for manufacturing the thick-walled high-toughness high-strength steel plate. In particular, the surface of the steel plate has high toughness, and the inner part of the steel plate has high strength and toughness. The steel plate has a thickness of 100 mm or more and a yield strength of 620 MPa or more.

Background Art

[0002]

In general, steel for use in construction, bridges, shipbuilding, offshore structures, construction and industrial machinery, tanks, penstocks, and other fields is welded to have a desired shape. In recent years, with significantly increasing in size of steel structures, the strength and thickness of steel to be used have also been greatly increased.

[0003]

Despite trying to manufacture a thick-walled high-strength steel plate having a thickness of 100 mm or more and having high strength and toughness in a half-thickness portion (the central portion in the thickness direction), a structure having relatively low strength, such as ferrite, tends to be formed in the half-thickness portion due to a decreased cooling rate. Thus, the addition of large amounts of alloying elements is required to reduce the formation of such a structure.

[0004]

In particular, in order to achieve high strength and toughness of a half-thickness portion of a thick-walled material (a thick-walled steel plate having a thickness of 100 mm or more), it is important to form bainite or a mixed structure of bainite and martensite in the half-thickness portion during quenching. This requires the addition of large amounts of alloying elements, such as Mn, Ni, Cr, and/or Mo.

[0005]

The cooling rate is higher on the surface of a steel plate than in the half-thickness portion. Thus, a martensite structure having low toughness is formed on the surface of the steel plate. Thus, a high-strength steel plate having a thickness of 100 mm or more rarely has both high surface toughness and high strength and toughness of

the inner part thereof.

[0006]

A steel plate related to the present invention is described in the following two pieces of non-patent literature, for example. Non Patent Literature 1 describes a material having a thickness of 210 mm, and Non Patent Literature 2 describes a material having a thickness of 180 mm.

Citation List

Non Patent Literature

[0007]

NPL 1: Nippon Steel Technical Report, 348 (1993), 10-16

NPL 2: Nippon Kokan Technical Report, 107 (1985), 21-30

Summary of Invention

Technical Problem

[0008]

These pieces of non-patent literature describe high strength and toughness of the half-thickness portion. However, these pieces of non-patent literature do not describe the toughness (Charpy impact characteristics) of the surface of a steel plate. In general, thick-walled materials are manufactured by a quenching and tempering process. The formation of a martensite structure on the surface of a steel plate, on which the cooling rate is higher than in the half-thickness portion, deteriorates the

toughness (Charpy impact characteristics) of the surface of the steel plate. However, these pieces of non-patent literature do not describe the manufacture of a steel plate consistently having a tough surface.

[0009]

The present invention has been made to solve such problems and aims to provide a thick-walled high-toughness high-strength steel plate that has high surface toughness and high strength and toughness of the inner part thereof and a method for manufacturing the thick-walled high-toughness high-strength steel plate.

Solution to Problem

[0010]

In order to solve the problems, the present inventors have extensively studied the microstructure control factors that satisfy high toughness of the surface of a thick-walled steel plate having a yield strength of 620 MPa or more and a thickness of 100 mm or more and also satisfy high strength and toughness of the half-thickness portion of the thick-walled steel plate, and have found the following.

[0011]

1. When the cooling rate during the solidification of a raw material steel exceeds 1°C/s , microsegregation competes with the solidification reaction. This reduces microsegregation. In the manufacture of a large piece of

steel, the cooling rate during the solidification of the steel decreases to 1°C/s or less, and consequently microsegregation becomes noticeable. Even in such a case, in order to achieve high toughness of the surface of a steel plate, on which a martensite structure is formed during quenching, it is important to reduce the P content and microsegregation during solidification. When primary crystals during solidification form a δ phase, and the percentage of the δ phase at the beginning of the formation of a γ phase is 30% or more, this results in reduced microsegregation and improved toughness. The percentage % described above refers to % by volume.

[0012]

2. In order to achieve high strength and toughness of the half-thickness portion, in which the cooling rate is much lower than on the surface of a steel plate during cooling after hot working, it is important to appropriately select the steel composition (components) so as to form a martensite and/or bainite microstructure even at a low cooling rate. To this end, the alloy components should be appropriately selected, and in particular the carbon equivalent (C_{eq}) should be 0.65% or more. In addition to the appropriate component design, it is also important to form the desired structure by hot working and heat treatment.

[0013]

3. Refinement of prior γ grain size is effective in improving toughness. Refinement of prior γ grain size before heat treatment, that is, refinement of prior γ grain size just after hot working is important for refinement of prior γ grain size after heat treatment. Thus, it is important to select appropriate hot working conditions and rolling conditions.

[0014]

As a result of further investigation of these findings, the present invention provides the following.

[0015]

[1] A thick-walled high-toughness high-strength steel plate having a thickness of 100 mm or more, containing, on a mass percent basis, C: 0.08% to 0.20%, Si: 0.40% or less, Mn: 0.5% to 5.0%, P: 0.010% or less, S: 0.0050% or less, Cr: 3.0% or less, Ni: 0.1% to 5.0%, Al: 0.010% to 0.080%, N: 0.0070% or less, and O: 0.0025% or less, formulae (1) and (2) being satisfied, the remainder being Fe and incidental impurities, a surface of the steel plate having a toughness (vE-40) of 70 J or more,

$$\text{Ceq}^{\text{IIW}} = \text{C} + \text{Mn}/6 + (\text{Cu} + \text{Ni})/15 + (\text{Cr} + \text{Mo} + \text{V})/5 \geq 0.65 \quad (1)$$

$$(\text{C}_L - \text{C})/\text{C}_L \times 100 \geq 30 \quad (2)$$

wherein C_L is defined by the following formula:

$$\text{C}_L = 0.2 - (-0.1 \times (0.2 - \text{Si}) - 0.03 \times (1.1 - \text{Mn}) - 0.12$$

$$\times (0.2 - \text{Cu}) - 0.11 \times (3 - \text{Ni}) + 0.025 \times (1.2 - \text{Cr}) + 0.1 \times (0.5 - \text{Mo}) + 0.2 \times (0.04 - \text{V}) - 0.05 \times (0.06 - \text{Al})) \quad (3)$$

wherein element symbols in the formulae denote the respective alloy component contents (% by mass), and, in the absence of an element, the element symbol is denoted by 0.

The surface of the steel plate has high toughness, and the inner part of the steel plate has high strength and toughness.

[0016]

[2] The thick-walled high-toughness high-strength steel plate according to [1], further containing, on a mass percent basis, one or two or more of Cu: 0.50% or less, Mo: 1.50% or less, V: 0.400% or less, Nb: 0.100% or less, and Ti: 0.005% to 0.020%.

[0017]

[3] The thick-walled high-toughness high-strength steel plate according to [1] or [2], further containing, on a mass percent basis, one or two of Mg: 0.0001% to 0.0050%, Ta: 0.01% to 0.20%, Zr: 0.005% to 0.1%, Y: 0.001% to 0.01%, B: 0.0030% or less, Ca: 0.0005% to 0.0050%, and REM: 0.0005% to 0.0100%.

[0018]

[4] The thick-walled high-toughness high-strength steel plate according to any one of [1] to [3], wherein the thick-walled high-toughness high-strength steel plate has a yield

strength of 620 MPa or more.

[0019]

[5] The thick-walled high-toughness high-strength steel plate according to any one of [1] to [4], wherein the reduction of area in the thickness direction at half the thickness of the plate is 40% or more.

[0020]

[6] The method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of [1] to [5],

heating steel to 1200°C to 1350°C, hot-forging the steel at a cumulative rolling reduction of 25% or more, heating the steel to an Ac3 temperature or more and 1200°C or less, hot-rolling the steel at a cumulative rolling reduction of 40% or more, leaving the steel to cool, reheating the steel to the Ac3 temperature or more and 1050°C or less, rapidly cooling the steel from the Ac3 temperature or more to a lower temperature selected from 350°C or less and an Ar3 temperature or less, and tempering the steel at a temperature in the range of 450°C to 700°C.

[0021]

[7] The method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of [1] to [5],

heating steel to 1200°C to 1350°C, hot-forging the steel

at a cumulative rolling reduction of 25% or more, heating the steel to an A_{c3} temperature or more and 1200°C or less, hot-rolling the steel at a cumulative rolling reduction of 40% or more, rapidly cooling the steel from the A_{r3} temperature or more to a lower temperature selected from 350°C or less and an A_{r3} temperature or less, and tempering the steel at a temperature in the range of 450°C to 700°C .

[0022]

[8] The method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of [1] to [5],

heating steel to 1200°C to 1350°C , slabbing the steel at a cumulative rolling reduction of 40% or more, heating the steel to an A_{c3} temperature or more and 1200°C or less, hot-rolling the steel at a cumulative rolling reduction of 40% or more, leaving the steel to cool, reheating the steel to the A_{c3} temperature or more and 1050°C or less, rapidly cooling the steel from the A_{c3} temperature or more to a lower temperature selected from 350°C or less and an A_{r3} temperature or less, and tempering the steel at a temperature in the range of 450°C to 700°C .

[0023]

[9] The method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of [1] to [5],

heating steel to 1200°C to 1350°C, slabbing the steel at a cumulative rolling reduction of 40% or more, heating the steel to an Ac3 temperature or more and 1200°C or less, hot-rolling the steel at a cumulative rolling reduction of 40% or more, rapidly cooling the steel from the Ar3 temperature or more to a lower temperature selected from 350°C or less and an Ar3 temperature or less, and tempering the steel at a temperature in the range of 450°C to 700°C.

Advantageous Effects of Invention

[0024]

The present invention provides a thick-walled high-toughness high-strength steel plate having a thickness of 100 mm or more and having a yield strength of 620 MPa or more and high toughness. The thick-walled high-toughness high-strength steel plate can be used to manufacture steel structures having high safety.

Description of Embodiments

[0025]

Embodiments of the present invention will be described below. The present invention is not limited to these embodiments.

[0026]

<Thick-Walled High-Toughness High-Strength Steel Plate>

A thick-walled high-toughness high-strength steel plate according to the present invention has a composition

containing, on a mass percent basis, C: 0.08% to 0.20%, Si: 0.40% or less (including 0%), Mn: 0.5% to 5.0%, P: 0.010% or less (including 0%), S: 0.0050% or less (including 0%), Cr: 3.0% or less (including 0%), Ni: 0.1% to 5.0%, Al: 0.010% to 0.080%, N: 0.0070% or less (including 0%), and O: 0.0025% or less (including 0%). Each of the components will be described below. The symbol "%" in the component content refers to "% by mass".

[0027]

C: 0.08% to 0.20%

C is an element useful for achieving the strength necessary for structural steel at low cost. This effect requires a C content of 0.08% or more. In a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding, however, a C content of more than 0.20% significantly deteriorates toughness of the base metal and weld. Thus, the C content has an upper limit of 0.20%. The C content preferably ranges from 0.08% to 0.14%.

[0028]

Si: 0.40% or less

Si is added for deoxidation. When another element is added for deoxidation, however, a steel plate according to the present invention does not necessarily contain Si. In a steel structure manufactured from a thick-walled high-

toughness high-strength steel plate by welding, a Si content of more than 0.40% significantly deteriorates toughness of the base metal and heat-affected zone. Thus, the Si content is 0.40% or less, preferably 0.05% to 0.3%, more preferably 0.1% to 0.3%.

[0029]

Mn: 0.5% to 5.0%

Mn is added to ensure high strength of the base metal. This effect is insufficient at a Mn content of less than 0.5%. A Mn content of more than 5.0% promotes center segregation, results in a larger casting defect of the slab, and deteriorates mechanical properties of the base metal in a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding. Thus, the Mn content has an upper limit of 5.0%. The Mn content preferably ranges from 0.6% to 2%, more preferably 0.6% to 1.6%.

[0030]

P: 0.010% or less

In a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding, a P content of more than 0.010% significantly deteriorates toughness of the base metal and heat-affected zone. Thus, the P content is preferably minimized (may be zero) and is limited to 0.010% or less.

[0031]

S: 0.0050% or less

In a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding, a S content of more than 0.0050% significantly deteriorates toughness of the base metal and heat-affected zone. Thus, the S content is preferably minimized (may be zero) and is 0.0050% or less.

[0032]

Cr: 3.0% or less

Cr is an element effective in strengthening the base metal. However, an excessively high Cr content deteriorates weldability. Thus, the Cr content is 3.0% or less, preferably 0.1% to 2%, more preferably 0.7% to 1.7%. The Cr content may be 0%.

[0033]

Ni: 0.1% to 5.0%

Ni is an element useful for improving the strength of steel and the toughness of the heat-affected zone. This effect requires a Ni content of 0.1% or more. However, a Ni content of more than 5.0% significantly deteriorates economic efficiency. Thus, the Ni content has an upper limit of 5.0%. The Ni content preferably ranges from 0.4% to 4%, more preferably 0.8% to 3.8%.

[0034]

Al: 0.010% to 0.080%

Al is added for sufficient deoxidation of molten steel. An Al content of less than 0.010% is insufficient for the effect. On the other hand, an Al content of more than 0.080% deteriorates toughness of the base metal due to an increased dissolved Al content in the base metal in a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding. Thus, the Al content is 0.080% or less, preferably 0.030% to 0.080%, more preferably 0.030% to 0.070%.

[0035]

N: 0.0070% or less

N, together with Ti, forms a nitride and thereby performs refinement of the structure and improves the toughness of the base metal and heat-affected zone in a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding. The toughness can be improved by a constituent other than N. Thus, a steel plate according to the present invention does not necessarily contain N. When trying to produce this effect with N, the N content is preferably 0.0015% or more. In a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding, however, a N content of more than 0.0070% deteriorates toughness of the base metal due to an increased dissolved N content in the

base metal and deteriorates toughness of the heat-affected zone due to the formation of coarse carbonitride. Thus, the N content is 0.0070% or less, preferably 0.006% or less, more preferably 0.005% or less.

[0036]

O: 0.0025% or less

An O content of more than 0.0025% significantly deteriorates toughness due to the formation of a hard oxide in steel. Thus, the O content is preferably minimized (may be zero) and is 0.0025% or less.

[0037]

In addition to these elements, a thick-walled high-toughness high-strength steel plate according to the present invention can contain at least one of Cu, Mo, V, Nb, and Ti in order to further improve strength and/or toughness.

[0038]

Cu: 0.50% or less

Cu can improve the strength of steel without reducing toughness. A Cu content of more than 0.50% may cause a crack on the surface of a steel plate during hot working. Thus, the Cu content, if any, is 0.50% or less.

[0039]

Mo: 1.50% or less

Mo contributes to high strength of the base metal in a steel structure manufactured from a thick-walled high-

toughness high-strength steel plate by welding. However, a Mo content of more than 1.50% results in increased hardness and deteriorates toughness due to the precipitation of alloy carbide. Thus, the Mo content, if any, has an upper limit of 1.50%. The Mo content preferably ranges from 0.2% to 0.8%.

[0040]

V: 0.400% or less

V contributes to improved strength and toughness of the base metal in a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding. V precipitates as VN and is effective in decreasing the amount of dissolved N. However, a V content of more than 0.400% deteriorates toughness due to the precipitation of hard VC. Thus, the V content, if any, is preferably 0.400% or less, more preferably 0.01% to 0.1%.

[0041]

Nb: 0.100% or less

Nb is effective in improving the strength of the base metal. A Nb content of more than 0.100% deteriorates toughness of the base metal. Thus, the Nb content has an upper limit of 0.100%. The Nb content is preferably 0.025% or less.

[0042]

Ti: 0.005% to 0.020%

Ti forms TiN during heating and effectively suppresses the coarsening of austenite. In a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding, Ti improves the toughness of the base metal and heat-affected zone. However, a Ti content of more than 0.020% results in coarsening of Ti nitride and deteriorates toughness of the base metal. Thus, the Ti content, if any, ranges from 0.005% to 0.020%, preferably 0.008% to 0.015%.

[0043]

In addition to these components, a thick-walled high-toughness high-strength steel plate according to the present invention can further contain at least one of Mg, Ta, Zr, Y, B, Ca, and REM to improve the material quality.

[0044]

Mg: 0.0001% to 0.0050%

Mg forms a stable oxide at high temperatures, effectively suppresses the coarsening of prior γ grains in the heat-affected zone, and is effective in improving the toughness of the weld. These effects require a Mg content of 0.0001% or more. However, a Mg content of more than 0.0050% results in an increased number of inclusions and deteriorates toughness. Thus, the Mg content, if any, is preferably 0.0050% or less, more preferably 0.0001% to 0.015%.

[0045]

Ta: 0.01% to 0.20%

The addition of an adequate amount of Ta is effective in improving strength. More specifically, a Ta content of 0.01% or more is effective. However, a Ta content of more than 0.20% deteriorates toughness due to formation of precipitates. Thus, the Ta content, if any, ranges from 0.01% to 0.20%.

[0046]

Zr: 0.005% to 0.1%

Zr is an element effective in improving strength. A Zr content of 0.005% or more is effective in producing this effect. However, a Zr content of more than 0.1% deteriorates toughness due to the formation of a coarse precipitate. Thus, the Zr content, if any, ranges from 0.005% to 0.1%.

[0047]

Y: 0.001% to 0.01%

Y forms a stable oxide at high temperatures, effectively suppresses the coarsening of prior γ grains in the heat-affected zone, and is effective in improving the toughness of the weld. An Y content of 0.001% or more is effective in producing these effects. However, an Y content of more than 0.01% results in an increased number of inclusions and deteriorates toughness. Thus, the Y content,

if any, ranges from 0.001% to 0.01%.

[0048]

B: 0.0030% or less

B segregates at austenite grain boundaries, suppresses ferrite transformation from the grain boundaries, and improves hardenability. However, a B content of more than 0.0030% deteriorates hardenability and toughness due to the precipitation of B as a carbonitride. Thus, the B content is 0.0030% or less. The B content, if any, preferably ranges from 0.0003% to 0.0030%, more preferably 0.0005% to 0.002%.

[0049]

Ca: 0.0005% to 0.0050%

Ca is an element useful for the morphology control of a sulfide inclusion. This effect requires a Ca content of 0.0005% or more. However, a Ca content of more than 0.0050% deteriorates cleanliness and toughness. Thus, the Ca content, if any, is preferably 0.0050% or less, more preferably 0.0005% to 0.0025%.

[0050]

REM: 0.0005% to 0.0100%

Like Ca, REM forms an oxide and a sulfide in steel and is effective in improving the material quality. This effect requires a REM content of 0.0005% or more. However, the effect levels off at a REM content of 0.0100% or more. Thus,

the REM content, if any, is 0.0100% or less, preferably 0.0005% to 0.005%.

[0051]

These optional elements in amounts below the lower limits do not reduce the advantages of the present invention. Thus, the optional elements in amounts below the lower limits are considered to be contained as incidental impurities.

[0052]

$$Ceq^{IIW} \geq 0.65\%$$

In the present invention, an appropriate alloy component needs to be added to ensure that a half-thickness portion of a thick-walled high-toughness high-strength steel plate having a thickness of 100 mm or more has a yield strength of 620 MPa or more and high toughness. More specifically, as represented by the following formula (1), alloying element contents need to be adjusted such that the carbon equivalent (Ceq^{IIW}) is 0.65% or more.

$$Ceq^{IIW} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5 \geq 0.65 \quad (1)$$

The element symbols in the formula denote the corresponding element contents (% by mass). In the absence of an element, the element symbol is denoted by 0.

[0053]

$$(C_L - C)/C_L \times 100 \geq 30 \quad (2)$$

As described later, the present invention provides a steel plate having desirable characteristics even when the steel plate is manufactured from steel casted under conditions where the cooling rate of a slab surface during solidification is 1°C/s or less. In the present invention, microsegregation needs to be reduced to achieve high toughness ($\text{vE-40} \geq 70 \text{ J}$) of the surface of a thick-walled high-toughness high-strength steel plate having a thickness of 100 mm or more, particularly manufactured from steel casted under conditions where the cooling rate of a slab surface during solidification is 1°C/s or less. To this end, primary crystals during solidification need to form a δ phase, and the percentage $((C_L - C)/C_L \times 100)$ of the δ phase at the beginning of the formation of a γ phase needs to be 30% or more.

$$C_L = 0.2 - (-0.1 \times (0.2 - \text{Si}) - 0.03 \times (1.1 - \text{Mn}) - 0.12 \times (0.2 - \text{Cu}) - 0.11 \times (3 - \text{Ni}) + 0.025 \times (1.2 - \text{Cr}) + 0.1 \times (0.5 - \text{Mo}) + 0.2 \times (0.04 - \text{V}) - 0.05 \times (0.06 - \text{Al})) \quad (3)$$

In the formula (3), the element symbols denote the respective alloy component contents (% by mass), and in the absence of an element, the element symbol is denoted by 0.

[0054]

In order to form a δ phase, the C content needs to be specified depending on each component other than C, such as Si or Mn. The effects of an alloying element on the C solid

solubility limit (C_L) of the δ phase were calculated using thermodynamic calculation software "Thermo-Calc". The result was used to determine the factor. For example, the factor "-0.1" for "Si" means that 1% Si decreases the C solid solubility limit of the δ phase by 0.1%, and the C content of the base metal needs to be decreased to achieve the required percentage of the δ phase. In the present invention, the calculation of C_L was based on the component of C: 0.12%, Si: 0.2%, Mn: 1.1%, Cu: 0.2%, Cr: 1.2%, Ni: 3%, Mo: 0.5%, V: 0.04% and Al: 0.06%, and the factors for the calculation of C_L were determined by calculating a variation from the dissolved C content caused by a variation in each alloying element content. When the percentage $(C_L - C)/C_L \times 100$ of C to be added relative to the C solid solubility limit in the δ phase thus calculated is 30% or more, the percentage of the δ phase at the beginning of the formation of the γ phase can be 30% or more.

[0055]

In the present invention, in order to ensure the safety of steel during use, the reduction of area in the thickness direction at half the thickness of the plate is preferably 40% or more when measured by a method described in the example.

[0056]

<Method for Manufacturing Thick-Walled High-Toughness High-

Strength Steel Plate>

The manufacturing conditions in the present invention will be described below. In the description, the temperature "°C" refers to the temperature in the half-thickness portion except for the quenching temperature in the case of quenching without leaving to cool after rolling. The quenching temperature in the case of quenching without leaving to cool after rolling is the surface temperature of the steel plate. This is because the temperature distribution of the steel plate in the thickness direction increases during rolling, and a decrease in the surface temperature of the steel plate needs to be considered. The temperature of the half-thickness portion is determined, for example, by simulation calculation from the thickness, surface temperature, and cooling conditions. For example, the temperature of the half-thickness portion is determined by calculating the temperature distribution in the thickness direction using finite difference methods.

[0057]

Steel

A molten steel having the composition described above is produced by a conventional method, such as with a converter, an electric furnace, or a vacuum melting furnace, and is formed into a piece of steel, such as a slab or billet, by a conventional casting method, such as a

continuous casting process or an ingot casting process. The cooling rate during solidification is determined by direct measurement with a thermocouple or by simulation calculation, such as heat-transfer calculation. As described above, in the present invention, steel manufactured under conditions where the cooling rate of a surface during solidification is 1°C/s or less can preferably be used.

[0058]

When the loads of a forging machine and a rolling mill and so on are restricted, the thickness of the material may be reduced by slabbing.

[0059]

Hot-Forging Conditions for Steel

A cast bloom or steel bloom having the composition described above is heated to a temperature in the range of 1200°C to 1350°C . A reheating temperature of less than 1200°C results in not only an insufficient rolling reduction due to an increased load to achieve a predetermined cumulative rolling reduction in hot working but also low production efficiency due to additional heating as required during working. Thus, the reheating temperature is 1200°C or more. A large amount of additive alloying element as steel having a carbon equivalent of 0.65% or more according to the present invention results in a casting defect such as a center porosity or porous shrinkage cavity, having a much

increased size in steel. In order to make them harmless by pressure bonding, the cumulative rolling reduction needs to be 25% or more. On the other hand, a reheating temperature of more than 1350°C results in excessive energy consumption, increased likelihood of occurrence of surface flaws due to scales during heating, and increased repair load after hot forging. Thus, the upper limit is 1350°C.

[0060]

Slabbing Conditions for Steel

A cast bloom or steel bloom having the composition described above is heated to a temperature in the range of 1200°C to 1350°C. A reheating temperature of less than 1200°C results in not only an insufficient rolling reduction due to an increased load to achieve a predetermined cumulative rolling reduction in hot working but also low production efficiency due to additional heating as required during working. Thus, the reheating temperature is 1200°C or more. In order to make casting defects harmless by pressure bonding and to provide the advantages of the present invention, the cumulative rolling reduction is 30% or more, preferably 40% or more in terms of good reduction of area (RA). On the other hand, a reheating temperature of more than 1350°C results in excessive energy consumption, increased likelihood of surface flaws due to scales during heating, and increased repair load after hot forging. Thus,

the upper limit is 1350°C.

[0061]

Reheating of Steel after Forging or after Slabbing

Steel after forging is heated to an Ac3 transformation temperature or more and 1200°C or less in order that the steel may have a uniform austenite structure alone. The heating temperature preferably ranges from 1000°C to 1200°C.

The Ac3 transformation temperature is calculated using the following formula (4).

$$\text{Ac3} = 937.2 - 476.5C + 56Si - 19.7Mn - 16.3Cu - 26.6Ni - 4.9Cr + 38.1Mo + 124.8V + 136.3Ti + 198.4Al + 3315B \quad (4)$$

The element symbols in the formula (4) denote the respective alloy component contents (% by mass).

[0062]

Hot Rolling Conditions

Steel is hot-rolled to form a plate having a desired thickness. In order to ensure desirable mechanical properties of a half-thickness portion of a thick-walled steel plate having a thickness of 100 mm or more, it is necessary to adjust the steel in the rolling step in order to sufficiently elicit an effect of adjusting and refining of the prior γ grain size. More specifically, rolling at a cumulative rolling reduction of 40% or more can adjust the grain size in the rolling step even in the half-thickness portion in which recrystallization rarely occurs in

processing.

[0063]

Heat-Treatment Conditions

In order to achieve high strength and toughness of a half-thickness portion, in the present invention, a steel plate is left to cool (for example, air cooling) after hot rolling or is rapidly cooled from the Ar3 temperature or more to 350°C or less without leaving to cool after hot rolling. When the steel plate is left to cool, the steel plate is reheated to the Ac3 temperature to 1050°C and is rapidly cooled from the Ac3 temperature or more to 350°C or less. The reason for the reheating temperature of 1050°C or less is that reheating at a high temperature of more than 1050°C results in coarsening of austenite grains and significantly deteriorates toughness of the base metal in a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding. The reheating temperature is the Ac3 temperature or more in order that the steel plate may entirely have an austenite structure. The quenching temperature is the Ac3 temperature or more because the desirable characteristics are not obtained at a temperature below the Ac3 temperature due to the formation of a nonuniform structure composed of ferrite and austenite. In the case of rapid cooling without leaving to cool, the quenching temperature is the Ar3 temperature or

more for quenching from the austenite single phase region. The rapid cooling stop temperature is a lower temperature selected from 350°C or less and the Ar3 temperature or less in order to ensure that the steel plate entirely has a transformed structure. The stop temperature should be the Ar3 temperature or less and 350°C or less.

The Ar3 transformation temperature is calculated using the following formula (5).

$$\text{Ar3} = 910 - 310\text{C} - 80\text{Mn} - 20\text{Cu} - 15\text{Cr} - 55\text{Ni} - 80\text{Mo} \quad (5)$$

The element symbols in the formula (5) denote the respective alloy component contents (% by mass).

[0064]

In general, the rapid cooling method is industrially water cooling. It is desirable that the cooling rate be as high as possible. Thus, the cooling method is not necessarily water cooling and may be gas cooling, for example.

[0065]

Tempering Conditions

The reason for tempering at a temperature in the range of 450°C to 700°C after rapid cooling is described below. Residual stress is not effectively relieved at less than 450°C. On the other hand, a temperature of more than 700°C results in precipitation of various carbides and coarsens the structure of the base metal and deteriorates strength

and toughness of the base metal in a steel structure manufactured from a thick-walled high-toughness high-strength steel plate by welding.

[0066]

Industrially, quenching is sometimes repeated to strengthen steel. Although quenching may be repeated also in the present invention, final quenching requires rapid cooling to 350°C or less after heating to the Ac3 temperature to 1050°C and requires subsequent tempering at 450°C to 700°C.

EXAMPLES

[0067]

Steel plate samples No. 1 to No. 38 were manufactured by melting and casting steel No. 1 to No. 30 listed in Table 1 under the conditions listed in Table 2, performing hot forging (except for the samples No. 5, No. 6, and No. 41) or slabbing (the samples No. 5, No. 6, and No. 41), hot-rolling the steel to form a steel plate having a thickness listed in Table 2, and subjecting the steel plate to water quenching and tempering. The steel plate samples No. 1 to No. 38 were subjected to the following tests. In reheating and quenching in this example, the reheating temperature corresponds to the quenching temperature.

[0068]

The percentage of the δ phase is calculated using the

formula (2) from C_L calculated using the formula (3) with each base metal component and the C content of the base metal.

[0069]

The cooling rate during solidification in the manufacture of steel is determined by heat-transfer calculation from the mold surface temperature data measured with a radiation thermometer.

[0070]

Tensile Test

A round bar tensile test piece ($\phi 12.5$ mm, GL 50 mm) was taken from the half-thickness portion of each steel plate in the direction perpendicular to the rolling direction and was measured in terms of yield strength (YS) and tensile strength (TS).

[0071]

Charpy Impact Test

Three 2-mm V-notched Charpy impact test specimens were taken from each surface and half-thickness portion of the steel plates. The rolling direction was the longitudinal direction. The absorbed energies of the test specimens were measured at a test temperature of -40°C in a Charpy impact test and were averaged (the average value for the test specimens taken from the half-thickness portion and the average value for the test specimens taken from the surface).

[0072]

Tensile Test in Thickness Direction

A round bar tensile test piece ($\phi 10$ mm) was taken from a region including the half-thickness portion of each steel plate in the thickness direction and was measured in terms of reduction of area (RA). The reduction of area is the percentage of the difference between the minimum cross-sectional area after the test specimen was broken and the original cross-sectional area relative to the original cross-sectional area.

[0073]

Table 2 shows the test results. The results showed that the steel plates of the examples having a steel composition according to the present invention (samples No. 1 to No. 21 and No. 41) had YS of 620 MPa or more, TS of 720 MPa or more, and toughness (vE-40) of 70 J or more at -40°C in the surface and half-thickness portion of the base metal, showing high strength and toughness of the base metal. A comparison between Nos. 5 and 6 and No. 41 showed that reduction of area (RA) was also satisfactory under particular slabbing conditions.

[0074]

In contrast, in the steel plates according to comparative examples having a composition outside the scope of the present invention (samples No. 22 to No. 32), the

base metal had at least one of YS of less than 620 MPa, TS of less than 720 MPa, and toughness (vE-40) of less than 70 J, thus deteriorating characteristics.

[0075]

As in samples No. 33 to No. 40, even if steel plates had a steel composition according to the present invention, steel plates manufactured under the conditions outside the scope of the present invention had at least one deterioration in YS, TS, and toughness (vE-40) (No. 41, which had a cumulative rolling reduction of 30% and satisfied the minimum conditions required to provide the advantages of the present invention, is not outside the scope of the present invention).

[0076]

[Table 1]

Category	Steel ingot No.	Chemical composition (mass%)																							Ac3 °C	Ar3 °C	δ fraction %	
		C	Si	Mn	P	S	Cr	Ni	Ti	Al	N	B	Cu	Mo	V	O	Nb	Mg	Ta	Zr	Y	Ca	REM	Ceq ^{III}				
Example	1	0.085	0.18	1.61	0.006	0.0012	0.66	0.88		0.063	0.0041	0.0013	0.25	0.45	0.035	0.0021						0.0017		0.658	883	656	78	
	2	0.095	0.22	1.15	0.005	0.0006	1.80	1.95		0.045	0.0022				0.0015										0.777	830	654	68
	3	0.128	0.21	0.98	0.005	0.0011	0.81	1.01	0.010	0.045	0.0040	0.0011	0.28	0.54	0.045	0.0018						0.0019	0.0021	0.656	873	675	69	
	4	0.120	0.22	1.14	0.006	0.0006	0.94	1.94		0.062	0.0049	0.0011	0.18	0.49	0.039	0.0016						0.0017		0.745	850	618	61	
	5	0.126	0.20	1.15	0.003	0.0008	0.95	2.05	0.010	0.043	0.0028	0.0009	0.22	0.51	0.042	0.0018						0.0015		0.769	840	607	58	
	6	0.123	0.20	1.18	0.004	0.0007	0.87	2.44		0.066	0.0050	0.0012	0.19	0.52	0.041	0.0019						0.0020		0.781	836	585	52	
	7	0.109	0.17	0.85	0.003	0.0004	1.13	3.56		0.071	0.0049	0.0010	0.08	0.53	0.040	0.0022						0.0012		0.833	819	551	34	
	8	0.121	0.22	0.88	0.006	0.0011	1.49	2.93		0.068	0.0046	0.0008	0.21	0.55	0.038	0.0021						0.0019		0.893	828	570	46	
	9	0.142	0.21	0.69	0.006	0.0009	1.51	2.87		0.071	0.0038	0.0013	0.20	0.50	0.037	0.0019						0.0018		0.871	823	586	39	
	10	0.113	0.11	0.81	0.006	0.0005	1.53	3.61		0.069	0.0052	0.0010	0.02	0.56	0.040	0.0023						0.0016		0.916	813	543	39	
	11	0.178	0.09	0.60	0.006	0.0006	1.14	2.84		0.078	0.0054	0.0009	0.11	0.55	0.041	0.0024								0.821	807	587	31	
	12	0.196	0.06	0.53	0.009	0.0007	1.35	3.65		0.062	0.0046			1.43	0.059	0.0021								1.095	807	471	31	
Comparative example	13	0.095	0.23	2.21	0.006	0.0004		0.74		0.035	0.0039	0.0011	0.20	0.65		0.0022						0.0022		0.656	874	607	76	
	14	0.118	0.21	1.13	0.006	0.0008	1.44	3.49		0.065	0.0045		0.12	0.57	0.045	0.0021						0.0013		0.958	809	521	30	
	15	0.142	0.05	0.57	0.009	0.0012	2.41	0.15	0.009	0.026	0.0050	0.0009	0.14	1.07	0.328	0.0022	0.031							1.018	934	688	80	
	16	0.161	0.22	1.03	0.005	0.0013	1.55	0.98	0.011	0.045	0.0033	0.0011	0.32		0.043	0.0009		0.0013						0.738	833	694	56	
	17	0.103	0.20	0.98	0.006	0.0018	0.56	2.21		0.049	0.0063	0.0013	0.18	0.55	0.036	0.0022			0.048					0.655	855	622	63	
	18	0.132	0.13	1.01	0.005	0.0006	0.86	1.44	0.012	0.065	0.0041	0.0009	0.22	0.44	0.028	0.0019				0.015				0.677	853	657	64	
	19	0.162	0.16	0.59	0.006	0.0019	1.41	3.98		0.063	0.0038	0.0018	0.16	1.47	0.115	0.0018					0.005			1.135	831	452	31	
	20	0.113	0.22	1.14	0.006	0.0006	0.81	3.57		0.070	0.0050	0.0012	0.20	0.51	0.040	0.0020								0.826	813	530	9	
	21	0.083	0.16	1.45	0.007	0.0011	0.67	0.45		0.006	0.0043	0.0014	0.21	0.45	0.038	0.0022								0.600	887	693	82	
	22	0.221	0.55	1.02	0.006	0.0006	0.91	0.89	0.010	0.044	0.0028	0.0011	0.12	0.46		0.0013								0.732	844	658	43	
	23	0.058	0.39	1.41	0.010	0.0018	1.23	1.96		0.045	0.0056	0.0012	0.23	0.41	0.041	0.0018						0.0023		0.775	875	616	79	
	24	0.129	0.63	1.33	0.009	0.0009	0.98	0.65		0.058	0.0049	0.0009	0.21	0.55	0.039	0.0021							0.0016	0.722	900	665	68	
	25	0.153	0.18	6.11	0.009	0.0009	1.04	1.21		0.066	0.0051	0.0009	0.21	0.44	0.041	0.0016							0.0014	1.570	751	252	36	
	26	0.124	0.22	1.41	0.018	0.0007	0.91	2.11		0.056	0.0048	0.0007	0.19	0.38		0.0026							0.0016	0.770	827	595	52	
	27	0.135	0.21	1.14	0.005	0.0069	1.21	1.48		0.065	0.0044	0.0009		0.48	0.026	0.0019								0.767	854	639	65	
	28	0.124	0.26	0.65	0.005	0.0006	4.10	1.38		0.056	0.0038	0.0007		0.25		0.0016								1.194	846	662	72	
	29	0.131	0.24	1.15	0.009	0.0008	1.05	1.95	0.006	0.098	0.0069	0.0009	0.29	0.48		0.0016							0.0026	0.778	845	610	54	
	30	0.133	0.26	1.13	0.009	0.0018	0.96	1.99		0.063	0.0123	0.0008	0.22	0.43		0.0022							0.0018	0.747	836	616	53	

Ceq^{III}, Ac3, Ar3, and δ fraction were calculated using the formulae (1), (2), (4), and (5), respectively.

[Table 2]

Category	Sample No.	Steel ingot No.	Thickness of material (mm)	Cooling rate during solidification °C/s	Hot forging or slabbing		Hot rolling		Thickness of product (mm)	Type of heat treatment	Final heat treatment conditions			Mechanical properties of base metal (1/2t)				Toughness of base metal (surface)
					Heating (°C)	Cumulative rolling reduction (%)	Heating (°C)	Cumulative rolling reduction (%)			Quenching temperature (°C)	Cooling stop (°C)	Tempering (°C)	YS (MPa)	TS (MPa)	vE-40 (J)	Tensile RA in thickness direction RA (%)	
Example	1	1	1000	0.32	1270	80	1130	43	100	Direct quenching	850	150	630	695	786	108	73	98
	2	2	500	0.64	1230	65	1130	43	100	Reheating quenching	930	100	650	698	795	167	63	105
	3	3	300	0.90	1200	30	1130	50	100	Reheating quenching	930	100	630	725	793	102	70	116
	4	4	1000	0.33	1270	70	1160	43	150	Reheating quenching	900	100	630	785	856	205	65	221
	5	4	1000	0.33	1320	55	1200	53	210	Reheating quenching	900	100	630	743	829	145	71	124
	6	4	1000	0.33	1300	55	1180	67	150	Direct quenching	860	100	630	751	832	126	58	159
	7	5	500	0.61	1270	45	1160	43	150	Reheating quenching	900	100	630	725	821	153	63	205
	8	6	1000	0.32	1270	55	1130	53	180	Reheating quenching	880	100	630	705	816	238	61	211
	9	7	1000	0.31	1270	55	1130	53	210	Reheating quenching	880	100	650	756	864	216	63	163
	10	8	1000	0.31	1300	55	1130	53	210	Reheating quenching	880	100	650	741	836	193	60	121
	11	9	1000	0.30	1270	55	1130	53	210	Reheating quenching	880	100	650	759	857	186	62	101
	12	10	1200	0.25	1270	55	1160	50	250	Reheating quenching	900	100	630	748	852	221	59	146
	13	11	1000	0.29	1270	70	1160	43	150	Reheating quenching	880	100	630	728	839	169	71	101
	14	12	1300	0.19	1270	60	1160	50	250	Reheating quenching	880	100	660	793	912	221	68	145
	15	13	1200	0.32	1270	85	1130	43	100	Reheating quenching	930	100	650	665	756	103	73	126
	16	14	1000	0.31	1270	55	1160	53	210	Reheating quenching	880	100	660	723	814	203	69	163
	17	15	1000	0.32	1270	55	1160	53	210	Reheating quenching	1050	150	670	641	738	145	70	101
	18	16	500	0.64	1230	65	1130	43	100	Reheating quenching	930	100	650	732	841	167	77	83
	19	17	500	0.65	1230	65	1160	43	100	Reheating quenching	880	100	650	703	789	196	73	113
Comparative example	20	18	300	0.91	1200	40	1160	43	100	Direct quenching	880	100	650	752	846	138	65	106
	21	19	1000	0.29	1350	50	1160	50	250	Reheating quenching	900	100	650	746	863	231	62	93
	22	20	1000	0.29	1270	55	1160	53	210	Reheating quenching	880	100	640	716	815	196	61	43
	23	21	300	0.92	1200	40	1160	43	100	Reheating quenching	930	100	650	589	695	22	69	121
	24	22	1000	0.31	1270	70	1160	43	150	Reheating quenching	900	100	630	845	956	19	62	96
	25	23	1000	0.29	1270	70	1160	43	150	Reheating quenching	930	100	630	547	663	21	68	124
	26	24	1000	0.29	1270	55	1130	53	210	Reheating quenching	930	100	650	728	823	41	64	39
	27	25	1200	0.24	1270	55	1160	50	250	Reheating quenching	880	100	630	802	915	23	51	96
	28	26	1000	0.28	1270	70	1160	43	150	Reheating quenching	880	100	630	731	829	32	57	23
	29	27	1000	0.31	1270	55	1130	53	210	Reheating quenching	900	100	650	741	854	35	63	31
	30	28	1000	0.29	1270	55	1130	53	210	Reheating quenching	900	100	650	796	921	43	61	89
	31	29	1000	0.32	1270	55	1130	53	210	Reheating quenching	900	100	650	732	816	48	72	56
	32	30	1000	0.31	1270	70	1160	43	150	Reheating quenching	900	100	630	698	784	61	70	52
	33	3	300	0.91	1200	15	1130	60	100	Reheating quenching	930	100	630	716	804	43	23	115
	34	3	300	0.89	1200	55	1130	20	100	Reheating quenching	930	100	630	722	816	45	35	96
	35	3	300	0.90	1200	30	1130	50	100	Reheating quenching	1100	100	630	735	824	36	53	49
	36	3	300	0.92	1200	30	1130	50	100	Reheating quenching	840	100	630	536	646	46	49	52
	37	3	300	0.90	1200	30	1130	50	100	Direct quenching	623	100	630	596	683	52	51	61
	38	3	300	0.91	1200	30	1130	50	100	Reheating quenching	930	400	630	641	732	32	64	103
Example	39	3	300	0.90	1200	30	1130	50	100	Reheating quenching	930	100	720	569	657	153	68	146
	40	3	300	0.91	1200	30	1130	50	100	Reheating quenching	930	100	400	793	902	41	63	53
	41	5	500	0.61	1300	30	1180	40	210	Reheating quenching	900	100	600	683	766	105	29	192

CLAIMS

[Claim 1]

A thick-walled high-toughness high-strength steel plate having a thickness of 100 mm or more, comprising, on a mass percent basis,

C: 0.08% to 0.20%,

Si: 0.40% or less,

Mn: 0.5% to 5.0%,

P: 0.010% or less,

S: 0.0050% or less,

Cr: 3.0% or less,

Ni: 0.1% to 5.0%,

Al: 0.010% to 0.080%,

N: 0.0070% or less, and

O: 0.0025% or less,

following formulae (1) and (2) being satisfied, a remainder being Fe and incidental impurities, and

a surface of the steel plate having a toughness (vE-40) of 70 J or more.

$$\text{Ceq}^{\text{IIW}} = \text{C} + \text{Mn}/6 + (\text{Cu} + \text{Ni})/15 + (\text{Cr} + \text{Mo} + \text{V})/5 \geq 0.65 \quad (1)$$

$$(\text{C}_L - \text{C})/\text{C}_L \times 100 \geq 30 \quad (2)$$

wherein C_L is defined by the following formula:

$$\text{C}_L = 0.2 - (-0.1 \times (0.2 - \text{Si}) - 0.03 \times (1.1 - \text{Mn}) - 0.12 \times (0.2 - \text{Cu}) - 0.11 \times (3 - \text{Ni}) + 0.025 \times (1.2 - \text{Cr}) + 0.1 \times$$

$$(0.5 - Mo) + 0.2 \times (0.04 - V) - 0.05 \times (0.06 - Al)) \quad (3)$$

wherein element symbols in the formulae denote the respective alloy component contents (% by mass), and in the absence of an element the element symbol is denoted by 0.

[Claim 2]

The thick-walled high-toughness high-strength steel plate according to Claim 1, further comprising, on a mass percent basis, one or two or more of

Cu: 0.50% or less,

Mo: 1.50% or less,

V: 0.400% or less,

Nb: 0.100% or less, and

Ti: 0.005% to 0.020%.

[Claim 3]

The thick-walled high-toughness high-strength steel plate according to Claim 1 or 2, further comprising, on a mass percent basis, one or two of

Mg: 0.0001% to 0.0050%,

Ta: 0.01% to 0.20%,

Zr: 0.005% to 0.1%,

Y: 0.001% to 0.01%,

B: 0.0030% or less,

Ca: 0.0005% to 0.0050%, and

REM: 0.0005% to 0.0100%.

[Claim 4]

The thick-walled high-toughness high-strength steel plate having a yield strength of 620 MPa or more according to any one of Claims 1 to 3.

[Claim 5]

The thick-walled high-toughness high-strength steel plate according to any one of Claims 1 to 4, wherein a reduction of area in a thickness direction at half the thickness of the plate is 40% or more.

[Claim 6]

A method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of Claims 1 to 5, comprising:

heating steel to 1200°C to 1350°C,

hot-forging the steel at a cumulative rolling reduction of 25% or more,

heating the steel to an Ac3 temperature or more and 1200°C or less,

hot-rolling the steel at a cumulative rolling reduction of 40% or more,

leaving the steel to cool,

reheating the steel to the Ac3 temperature or more and 1050°C or less,

rapidly cooling the steel from the Ac3 temperature or more to a lower temperature selected from 350°C or less and an Ar3 temperature or less, and

tempering the steel at a temperature in the range of 450°C to 700°C.

[Claim 7]

A method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of Claims 1 to 5, comprising:

heating steel to 1200°C to 1350°C,

hot-forging the steel at a cumulative rolling reduction of 25% or more,

heating the steel to an Ac3 temperature or more and 1200°C or less,

hot-rolling the steel at a cumulative rolling reduction of 40% or more,

rapidly cooling the steel from the Ar3 temperature or more to a lower temperature selected from 350°C or less and an Ar3 temperature or less, and

tempering the steel at a temperature in the range of 450°C to 700°C.

[Claim 8]

A method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of Claims 1 to 5, comprising:

heating steel to 1200°C to 1350°C,

slabbing the steel at a cumulative rolling reduction of 40% or more,

heating the steel to an Ac3 temperature or more and 1200°C or less,

hot-rolling the steel at a cumulative rolling reduction of 40% or more, leaving the steel to cool,

reheating the steel to the Ac3 temperature or more and 1050°C or less,

rapidly cooling the steel from the Ac3 temperature or more to a lower temperature selected from 350°C or less and an Ar3 temperature or less, and

tempering the steel at a temperature in the range of 450°C to 700°C.

[Claim 9]

A method for manufacturing the thick-walled high-toughness high-strength steel plate according to any one of Claims 1 to 5, comprising:

heating steel to 1200°C to 1350°C,

slabbing the steel at a cumulative rolling reduction of 40% or more,

heating the steel to an Ac3 temperature or more and 1200°C or less,

hot-rolling the steel at a cumulative rolling reduction of 40% or more,

rapidly cooling the steel from the Ar3 temperature or more to a lower temperature selected from 350°C or less and an Ar3 temperature or less, and

tempering the steel at a temperature in the range of 450°C to 700°C.