

DESCRIPTION

Title of Invention: THICK, TOUGH, HIGH TENSILE STRENGTH
STEEL PLATE AND PRODUCTION METHOD THEREFOR

Technical Field

[0001]

The present invention relates to thick high-toughness high-strength steel plates with excellent strength, toughness and weldability that are used for steel structures such as buildings, bridges, marine vessels, marine structures, construction and industrial machineries, tanks and penstocks, and to methods for manufacturing such steel plates. Preferably, the invention relates to steel plates having a plate thickness of 100 mm or more and a yield strength of 620 MPa or more.

Background Art

[0002]

In recent years, significant upsizing of steel structures has led to a marked increase in the strength and the thickness of steel that is used. Thick steel plates having a plate thickness of 100 mm or more are usually manufactured by slabbing a large steel ingot produced by an ingot making method, and hot rolling the resultant slab. In this ingot making-slabbing process, densely segregated areas in hot tops and negatively segregated areas in ingot bottoms have to be discarded. This causes low yields, high

production costs and long work periods.

[0003]

In contrast, a process using a continuously cast slab as the material steel is free from such concerns. However, the fact that the thickness of a continuously cast slab is smaller than that of an ingot slab causes the rolling reduction to the product thickness to be small. In the production of thick steel plates having increased strength, alloying elements are added in large amounts to ensure desired characteristics. This results in the occurrence of center porosities ascribed to center segregation, and the upsizing of steels consequently encounters the problematic deterioration of internal quality.

[0004]

To solve this problem, the following techniques are proposed in the art for the purpose of improving the characteristics of center segregation areas by compressing center porosities during the process in which continuously cast slabs are worked into ultrathick steel plates.

[0005]

Non Patent Literature 1 describes a technique in which center porosities are compressed by increasing the rolling shape factor during the hot rolling of a continuously cast slab. Patent Literatures 1 and 2 describe techniques in which center porosities in a continuously cast slab are

compressed by working the continuously cast slab with rolls or anvils during its production in the continuous casting machine.

[0006]

Patent Literature 3 describes a technique in which a continuously cast slab is worked into a thick steel plate with a cumulative reduction of not more than 70% in such a manner that the slab is forged before hot rolling so as to compress center porosities. Patent Literature 4 describes a technique in which a continuously cast slab is worked into an ultrathick steel plate by forging and thick plate rolling with a total working reduction of 35 to 67%. In this process, the central area through the plate thickness of the steel is held at a temperature of 1200°C or above for at least 20 hours before forging and the steel is forged with a reduction of not less than 16% so as to eliminate center porosities and also to decrease or remedy the center segregation zone, thereby improving temper brittleness resistance characteristics.

[0007]

Patent Literature 5 describes a technique in which a continuously cast slab is cross forged and then hot rolled to remedy center porosities and center segregation. Patent Literature 6 describes a technique related to a method for manufacturing thick steel plates with a tensile strength of

not less than 588 MPa in which a continuously cast slab is held at a temperature of 1200°C or above for at least 20 hours, forged with a reduction of not less than 17%, subjected to thick plate rolling with a total reduction including the forging reduction in the range of 23 to 50%, and quench hardened two times after the thick plate rolling, thereby eliminating center porosities and also decreasing or remedying the center segregation zone.

[0008]

Patent Literature 7 describes a technique related to a method for manufacturing thick steel plates with excellent weldability and ductility in the plate thickness direction wherein a continuously cast slab having a prescribed chemical composition is reheated to 1100°C to 1350°C and is thereafter worked at not less than 1000°C with a strain rate of 0.05 to 3/s and a cumulative working reduction of not less than 15%.

Citation List

Patent Literature

[0009]

PTL 1: Japanese Unexamined Patent Application
Publication No. 55-114404

PTL 2: Japanese Unexamined Patent Application
Publication No. 61-273201

PTL 3: Japanese Patent No. 3333619

PTL 4: Japanese Unexamined Patent Application
Publication No. 2002-194431

PTL 5: Japanese Unexamined Patent Application
Publication No. 2000-263103

PTL 6: Japanese Unexamined Patent Application
Publication No. 2006-111918

PTL 7: Japanese Unexamined Patent Application
Publication No. 2010-106298

Non Patent Literature

[0010]

NPL 1: Tetsu to Hagane (Iron and Steel), Vol. 66 (1980),
No. 2, pp. 201-210

Summary of Invention

Technical Problem

[0011]

The technique described in Non Patent Literature 1 requires that steel plates be rolled with a high rolling shape factor repeatedly in order to achieve good internal quality. However, such rolling is beyond the upper limit of equipment specifications of rolling machines, and consequently manufacturing constraints are encountered.

[0012]

The techniques of Patent Literatures 1 and 2 have a problem in that large capital investments are necessary for the adaptation of continuous casting facilities, and also

have uncertainty about the strength of steel plates obtained in Examples. The techniques of Patent Literatures 3 to 7 are effective for remedying center porosities and for improving center segregation zones. However, the yield strength of steel plates obtained in Examples of these literatures is less than 620 MPa. Thick steel plates with a yield strength of 620 MPa or above decrease their toughness due to the increase in strength. Further, thick steel plates are cooled at a lower rate in the central area through the plate thickness than in the other areas. In order to ensure strength in such central regions, it is necessary to increase the amounts of alloying elements that are added. Such thick steel plates containing large amounts of alloying elements increase their deformation resistance, and consequently center porosities are not sufficiently compressed and tend to remain after the working. Thus, there is a concern that the steel plates will exhibit insufficient elongation and toughness in the central area through the plate thickness. As discussed above, there are no established techniques which realize thick high-toughness high-strength steel plates having a yield strength of 620 MPa or above, and methods for manufacturing such steel plates with existing facilities.

[0013]

It is therefore an object of the invention to provide

thick high-toughness high-strength steel plates with a yield strength of 620 MPa or above that contain large amounts of alloying elements and still have excellent strength and toughness in the central area through the plate thickness, as well as to provide methods for manufacturing such steel plates. The plate thickness of interest is 100 mm or more.

Solution to Problem

[0014]

To achieve the above object, the present inventors have carried out extensive studies with respect to thick steel plates having a yield strength of not less than 620 MPa and a plate thickness of not less than 100 mm so as to find a relationship between the microstructure and the strength and toughness in the central area through the plate thickness, as well as to identify the manufacturing conditions that provide such a microstructure. The present invention has been completed based on the obtained findings and further studies. That is, some aspects of the present invention reside in the following.

1. A thick high-toughness high-strength steel plate having a plate thickness of not less than 100 mm, the steel plate including a microstructure having, throughout an entire region in the plate thickness direction, an average prior austenite grain size of not more than 50 μm and a martensite and/or bainite phase area fraction of not less

than 80%.

2. The thick high-toughness high-strength steel plate described in 1, wherein the yield strength is not less than 620 MPa.

3. The thick high-toughness high-strength steel plate described in 1 or 2, wherein the reduction of area after fracture in a tensile test in the direction of the plate thickness of the steel plate is not less than 25%.

4. A method for manufacturing a thick high-toughness high-strength steel plate having a plate thickness of not less than 100 mm, the steel plate including a microstructure having, throughout an entire region in the plate thickness direction, an average prior austenite grain size of not more than 50 μm and a martensite and/or bainite phase area fraction of not less than 80%, the method including heating a continuously cast slab to 1200°C to 1350°C, hot working the slab at not less than 1000°C with a strain rate of not more than 3/s and a cumulative working reduction of not less than 15%, and thereafter hot rolling, quench hardening and tempering the steel, the continuously cast slab including, by mass%, C: 0.08 to 0.20%, Si: not more than 0.40%, Mn: 0.5 to 5.0%, P: not more than 0.015%, S: not more than 0.0050%, Cr: not more than 3.0%, Ni: not more than 5.0%, Ti: 0.005% to 0.020%, Al: 0.010 to 0.080%, N: not more than 0.0070% and B: 0.0003 to 0.0030%, the balance being Fe and inevitable

impurities, the continuously cast slab satisfying the relationship represented by Expression (1):

$$Ceq^{IIW} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5 \geq 0.57 \dots (1)$$
 wherein the alloying element symbols indicate the respective contents (mass%) and are 0 when absent.

5. The method for manufacturing a thick high-toughness high-strength steel plate described in 4, wherein the yield strength is not less than 620 MPa.

6. The method for manufacturing a thick high-toughness high-strength steel plate described in 4 or 5, wherein the slab further includes, by mass%, one, or two or more of Cu: not more than 0.50%, Mo: not more than 1.00% and V: not more than 0.200%.

7. The method for manufacturing a thick high-toughness high-strength steel plate described in any one of 4 to 6, wherein the slab further includes, by mass%, one or both of Ca: 0.0005 to 0.0050% and REM: 0.0005 to 0.0050%.

8. The method for manufacturing a thick high-toughness high-strength steel plate described in any one of 4 to 7, wherein the continuously cast slab is heated to 1200°C to 1350°C, hot worked at not less than 1000°C with a strain rate of not more than 3/s and a cumulative working reduction of not less than 15%, allowed to cool naturally, heated again to Ac3 point to 1200°C, subjected to hot rolling including at least two or more passes with a rolling

reduction per pass of not less than 4%, allowed to cool naturally, heated to Ac3 point to 1050°C, quenched to 350°C or below and tempered at 450°C to 700°C.

9. The method for manufacturing a thick high-toughness high-strength steel plate described in 8, wherein the continuously cast slab is worked to reduce the width by not less than 100 mm before hot working and is thereafter hot worked with a strain rate of not more than 3/s and a cumulative working reduction of not less than 15%.

Advantageous Effects of Invention

[0015]

According to the present invention, thick steel plates with a plate thickness of not less than 100 mm achieve excellent internal quality in the central area through the plate thickness. Specifically, the thick steel plates exhibit a yield strength of not less than 620 MPa and have excellent toughness. The inventive manufacturing methods can produce such steel plates. The invention has marked effects in industry by making great contributions to the upsizing of steel structures, improving the safety of steel structures, enhancing the yields, and reducing the production work periods.

Description of Embodiments

[0016]

Embodiments of the invention will be described in

detail below.

[Microstructure]

In order to ensure that thick steel plates having a plate thickness of not less than 100 mm exhibit a yield strength of not less than 620 MPa and excellent toughness, the invention requires that the microstructure have an average prior austenite grain size of not more than 50 μm and a martensite and/or bainite phase area fraction of not less than 80% throughout an entire region in the plate thickness direction. Phases other than the martensite and/or bainite phases are not particularly limited. In the invention, the average prior austenite grain size is the average grain size of prior austenite at the center through the plate thickness.

[Chemical composition]

In the description, the contents of the respective elements are all in mass%.

C: 0.080 to 0.200%

Carbon is an element useful for obtaining the strength required for structural steel at low cost. In order to obtain this effect, the addition of 0.080% or more carbon is necessary. If, on the other hand, more than 0.200% carbon is added, the toughness of base steel and welds is markedly decreased. Thus, the upper limit is limited to 0.200%. The C content is preferably 0.080% to 0.140%.

[0017]

Si: not more than 0.40%

Silicon is added for the purpose of deoxidation.

However, the addition of more than 0.40% silicon results in a marked decrease in the toughness of base steel and weld heat affected zones. Thus, the Si content is limited to not more than 0.40%. The Si content is preferably in the range of 0.05% to 0.30%, and more preferably in the range of 0.10% to 0.30%.

[0018]

Mn: 0.5 to 5.0%

Manganese is added to ensure the strength of base steel. However, the effect is insufficient when the amount added is less than 0.5%. Adding more than 5.0% manganese not only decreases the toughness of base steel but also facilitates the occurrence of center segregation and increases the size of center porosities in the slabs. Thus, the upper limit is limited to 5.0%. The Mn content is preferably in the range of 0.6 to 2.0%, and more preferably in the range of 0.6 to 1.6%.

[0019]

P: not more than 0.015%

If more than 0.015% phosphorus is added, the toughness of base steel and weld heat affected zones is markedly lowered. Thus, the P content is limited to not more than

0.015%.

[0020]

S: not more than 0.0050%

If more than 0.0050% sulfur is added, the toughness of base steel and weld heat affected zones is markedly lowered. Thus, the S content is limited to not more than 0.0050%.

[0021]

Cr: not more than 3.0%

Chromium is an element effective for increasing the strength of base steel. However, the addition of an excessively large amount results in a decrease in weldability. Thus, the Cr content is limited to not more than 3.0%. The Cr content is preferably 0.1% to 2.0%.

[0022]

Ni: not more than 5.0%

Nickel is a useful element that increases the strength of steel and the toughness of weld heat affected zones. However, adding more than 5.0% nickel causes a significant decrease in economic efficiency. Thus, the upper limit of the Ni content is preferably 5.0% or less. The Ni content is more preferably 0.5% to 4.0%.

[0023]

Ti: 0.005% to 0.020%

Titanium forms TiN during heating to effectively suppress the coarsening of austenite and to enhance the

toughness of base steel and weld heat affected zones. In order to obtain this effect, 0.005% or more titanium is added. However, the addition of more than 0.020% titanium results in the coarsening of titanium nitride and consequently the toughness of base steel is lowered. Thus, the Ti content is limited to the range of 0.005% to 0.020%. The Ti content is preferably in the range of 0.008% to 0.015%.

[0024]

Al: 0.010 to 0.080%

Aluminum is added to deoxidize molten steel. However, the deoxidation effect is insufficient if the amount added is less than 0.010%. If more than 0.080% aluminum is added, the amount of aluminum dissolved in the base steel is so increased that the toughness of base steel is lowered. Thus, the Al content is limited to the range of 0.010 to 0.080%. The Al content is preferably in the range of 0.030 to 0.080%, and more preferably in the range of 0.030 to 0.060%.

[0025]

N: not more than 0.0070%

Nitrogen has an effect of reducing the size of the microstructure by forming nitrides with elements such as titanium, and thereby enhances the toughness of base steel and weld heat affected zones. If, however, more than 0.0070% nitrogen is added, the amount of nitrogen dissolved

in the base steel is so increased that the toughness of base steel is significantly lowered and further the toughness of weld heat affected zones is decreased due to the formation of coarse carbonitride. Thus, the N content is limited to not more than 0.0070%. The N content is preferably not more than 0.0050%, and more preferably not more than 0.0040%.

[0026]

B: 0.0003 to 0.0030%

Boron is segregated in austenite grain boundaries and suppresses ferrite transformation from the grain boundaries, thereby exerting an effect of enhancing hardenability. To ensure that this effect is produced sufficiently, 0.0003% or more boron is added. If the amount added is more than 0.0030%, boron is precipitated as carbonitride to cause a decrease in hardenability and a decrease in toughness. Thus, the B content is limited to the range of 0.0003% to 0.0030%. The B content is preferably in the range of 0.0005 to 0.0020%.

[0027]

$Ceq^{IIW} \geq 0.57\%$

In the invention, it is necessary to design the microstructure so that the central area through the plate thickness exhibits both a yield strength of not less than 620 MPa and excellent toughness. In order to ensure that the martensite and/or bainite phase area fraction will be

80% or more even in spite of the conditions in which the plate thickness is 100 mm or more and the central area through the plate thickness is cooled at a lower rate than the other areas, it is necessary that the components be added in such amounts that Ceq^{IIW} defined by Expression (1) below satisfies the relationship: $Ceq^{IIW} \geq 0.57\%$.

$Ceq^{IIW} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5 \geq 0.57 \dots (1)$ wherein the element symbols indicate the contents (mass%) of the respective elements and are 0 when absent.

[0028]

The aforementioned components constitute the basic chemical composition of the present invention, and the balance is iron and inevitable impurities. The chemical composition may further include one, or two or more of copper, molybdenum and vanadium in order to enhance strength and toughness.

[0029]

Cu: not more than 0.50%

Copper increases the strength of steel without causing a decrease in toughness. However, adding more than 0.50% copper results in the occurrence of cracks on the steel plate surface during hot working. Thus, the content of copper, when added, is limited to not more than 0.50%.

[0030]

Mo: not more than 1.00%

Molybdenum is an element effective for increasing the strength of base steel. If, however, more than 1.00% molybdenum is added, hardness is increased by the precipitation of alloy carbide and consequently toughness is decreased. Thus, the upper limit of molybdenum, when added, is limited to 1.00%. The Mo content is preferably in the range of 0.20% to 0.80%.

[0031]

V: not more than 0.200%

Vanadium is effective for increasing the strength and the toughness of base steel, and also effectively decreases the amount of solute nitrogen by being precipitated as VN. However, adding more than 0.200% vanadium results in a decrease in toughness due to the precipitation of hard VC. Thus, the content of vanadium, when added, is limited to not more than 0.200%. The V content is preferably in the range of 0.010 to 0.100%.

[0032]

Further, one, or two or more of calcium and rare earth metals may be added to increase strength and toughness.

[0033]

Ca: 0.0005 to 0.0050%

Calcium is an element useful for controlling the morphology of sulfide inclusions. To obtain its effect,

0.0005% or more calcium needs to be added. If, however, the amount added exceeds 0.0050%, cleanliness is lowered and toughness is decreased. Thus, the content of calcium, when added, is limited to 0.0005 to 0.0050%. The Ca content is preferably in the range of 0.0005% to 0.0025%.

[0034]

REM: 0.0005 to 0.0050%

Similarly to calcium, rare earth metals have an effect of improving quality through the formation of oxides and sulfides in steel. To obtain this effect, 0.0005% or more rare earth metals need to be added. The effect is saturated after the amount added exceeds 0.0050%. Thus, the content of rare earth metals, when added, is limited to 0.0005 to 0.0050%. The REM content is preferably in the range of 0.0005 to 0.0025%.

[0035]

[Manufacturing conditions]

In the description, the temperature "°C" refers to the temperature in the central area through the plate thickness of the slab or the steel plate. In the method for manufacturing thick steel plates of the invention, casting defects such as center porosities in the steel are eliminated by subjecting the steel to hot working and, after air cooling and reheating or directly without cooling, subjecting the hot-worked steel to hot rolling so as to

obtain a desired plate thickness. The temperature of the central area through the plate thickness may be obtained by a method such as simulation calculation using data such as plate thickness, surface temperature and cooling conditions. For example, the temperature in the center through the plate thickness may be obtained by calculating the temperature distribution in the plate thickness direction using a difference method.

[0036]

Conditions for hot working of steel

Heating temperature: 1200°C to 1350°C

Steel having the aforementioned chemical composition is smelted by a usual known method in a furnace such as a converter furnace, an electric furnace or a vacuum melting furnace, and is continuously cast and rolled into a slab (a steel slab), which is reheated to 1200°C to 1350°C. If the reheating temperature is less than 1200°C, hot working cannot ensure a prescribed cumulative working reduction and further the steel exhibits high deformation resistance during hot working and fails to ensure a sufficient working reduction per pass.

[0037]

As a result, the number of passes is increased to cause a decrease in production efficiency. Further, the compression cannot remedy casting defects such as center

porosities in the steel. For these reasons, the reheating temperature is limited to not less than 1200°C.

[0038]

On the other hand, reheating at a temperature exceeding 1350°C consumes excessively large amounts of energy, and scales formed during the heating raise the probability of surface defects, thus increasing the load in maintenance after the hot working. Thus, the upper limit is limited to 1350°C. Preferably, the hot working described below is performed after the continuously cast slab is worked in the width direction at least until an increase in slab thickness is obtained. This allows center porosities to be compressed more reliably.

[0039]

Width reduction before hot working: not less than 100 mm

Preferably, the slab is worked in the width direction before the hot working and thereby the slab thickness is increased to ensure a margin for working. When this working is performed, the reduction of width is preferably 100 mm or more because working by 100 mm or more gives rise to a thickness increase in an area that is distant from both ends of the slab width by 1/4 of the slab width. This makes it possible to effectively compress the center porosities of the slab that frequently occur in this area. The width

reduction that is 100 mm or more is the total of the width reduction at both ends of the slab width.

[0040]

Working temperature in hot working: not less than 1000°C

If the working temperature during the hot working is less than 1000°C, the hot working encounters high deformation resistance. Consequently, the load on the hot working machine is increased, and the reliable compression of center porosities fails. Thus, the working temperature is limited to not less than 1000°C. The working temperature is preferably 1100°C or more.

[0041]

Cumulative working reduction during hot working: not less than 15%

If the cumulative working reduction during the hot working is less than 15%, the compression fails to remedy casting defects such as center porosities in the steel. Thus, the cumulative working reduction is limited to not less than 15%. In the case where the plate thickness (the thickness) of the slab has been increased by hot working of the continuously cast slab in the width direction, the cumulative working reduction is the reduction from the increased thickness.

[0042]

In the production of thick steel plates having a plate thickness of 120 mm or more, it is preferable that the hot working include one or more passes in which the working reduction per pass is 7% or more in order to reliably compress the center porosities. More preferably, the working reduction per pass is in the range of 10% and above.

[0043]

Strain rate during hot working: not more than 3/s

If the strain rate during the hot working exceeds 3/s, the hot working encounters high deformation resistance. Consequently, the load on the hot working machine is increased, and the compression of center porosities fails. Thus, the strain rate is limited to not more than 3/s.

[0044]

At a strain rate of less than 0.01/s, the hot working requires an extended time to cause a decrease in productivity. Thus, the strain rate is preferably not less than 0.01/s. More preferably, the strain rate is in the range of 0.05/s to 1/s. The hot working may be performed by a known method such as hot forging or hot rolling. Hot forging is preferable from the viewpoints of economic efficiency and high degree of freedom.

[0045]

By performing the hot working under the aforementioned conditions, the central area through the plate thickness

achieves stable enhancement in elongation in a tensile test.

[0046]

Air cooling after hot working

The hot-worked steel is subjected to hot rolling so as to obtain a desired plate thickness. The hot rolling is performed after air cooling and reheating or is carried out directly without cooling.

[0047]

Hot rolling conditions

In the invention, the hot-worked steel is hot rolled into a steel plate having a desired plate thickness. The steel plate is then subjected to quench hardening and tempering in order to ensure that a yield strength of not less than 620 MPa and good toughness are exhibited even in the central area through the plate thickness of the resultant steel plate.

[0048]

Temperature of reheating of hot-worked steel: Ac3 point to 1200°C

To obtain an austenite single phase, the hot-worked steel is heated to or above the Ac3 transformation point. At above 1200°C, the austenite structure is coarsened to cause a decrease in toughness. Thus, the reheating temperature is limited to the Ac3 point to 1200°C. The Ac3 transformation point is a value calculated using Expression

(2) below.

$$\begin{aligned} \text{Ac3} = & 937.2 - 476.5C + 56Si - 19.7Mn - 16.3Cu - 26.6Ni \\ & - 4.9Cr + 38.1Mo + 124.8V + 136.3Ti + 198.4Al + 3315B \dots \end{aligned}$$

(2)

In Expression (2), the element symbols indicate the contents (mass%) of the respective alloying elements.

[0049]

Rolling reduction per pass: two or more passes with 4% or more reduction

Rolling with a reduction per pass of 4% or more ensures that the recrystallization of austenite is promoted over the entire region through the plate thickness. By performing such rolling two or more times, the austenite grains attain small and regular sizes. As a result, fine prior austenite grains are formed by quench hardening and tempering, and consequently toughness may be enhanced. More preferably, the rolling reduction per pass is 6% or more.

[0050]

Conditions for heat treatment after hot rolling

To obtain strength and toughness in the central area through the plate thickness, quench hardening and tempering are performed in the invention. In the quench hardening, the hot-rolled plate is allowed to cool naturally, reheated to the Ac3 point to 1050°C, and quenched from a temperature of not less than the Ar3 point to 350°C or below. The

reheating temperature is limited to 1050°C or below because reheating at a high temperature exceeding 1050°C causes the austenite grains to be coarsened and thus results in a marked decrease in the toughness of base steel. The Ar3 transformation point is a value calculated using Expression (3) below.

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

(3)

In Expression (3), the element symbols indicate the contents (mass%) of the respective alloying elements.

[0051]

A general quenching method in industry is water cooling. However, because the cooling rate is desirably as high as possible, any cooling methods other than water cooling may be adopted. Exemplary methods include gas cooling.

[0052]

The tempering temperature is 450°C to 700°C. Tempering at less than 450°C produces a small effect in removing residual stress. If, on the other hand, the temperature exceeds 700°C, various carbides are precipitated and the microstructure of the base steel is coarsened to cause a marked decrease in strength and toughness. Thus, the tempering temperature is limited to 450°C to 700°C.

[0053]

In the case where quench hardening is performed a

plurality of times for the purpose of increasing the strength and the toughness of steel, it is necessary that the final quench hardening be performed in such a manner that the steel is heated to the Ac3 point to 1050°C, quenched to 350°C or below and tempered at 450°C to 700°C.

EXAMPLES

[0054]

Steels Nos. 1 to 29 shown in Table 1 were smelted and shaped into slabs (continuously cast slabs) having a slab thickness of 310 mm. The slabs were then hot worked and hot rolled under various conditions, thereby forming steel plates with a plate thickness of 100 mm to 240 mm. Thereafter, the steel plates were quench hardened and tempered to give product specimens Nos. 1 to 39, which were subjected to the following tests.

[0055]

Microstructure evaluation

Samples having a 10 × 10 (mm) observation area were obtained from the surface and the center through the plate thickness of an L cross section of the steel as quenched. The microstructure was exposed with a Nital etching solution. Five fields of view were observed with a ×200 optical microscope, and the images were analyzed to measure fractions in the microstructure. To determine the average prior austenite grain size, L cross sectional observation

samples were etched with picric acid to expose the prior γ grain boundaries, and the images were analyzed to measure the circular equivalent diameters of the prior γ grains, the results being averaged.

[0056]

Evaluation of porosities

A sample 12.5 in thickness and 50 in length (mm) was obtained from the central area through the plate thickness. The sample was inspected for 100 μm or larger porosities with an optical microscope.

[0057]

Tensile test

Round bars as tensile test pieces (diameter 12.5 mm, GL 50 mm) were obtained from the central area through the plate thickness of each of the steel plates, along a direction perpendicular to the rolling direction. The test pieces were tested to measure the yield strength (YS), the tensile strength (TS) and the total elongation (t. El).

[0058]

Charpy impact test

Three Charpy test pieces with a 2 mm V notch were obtained from the central area through the plate thickness of each of the steel plates in such a manner that the rolling direction was the longitudinal direction. Each of the test pieces was subjected to a Charpy impact test at -

40°C to measure the absorbed energy (vE_{-40}), and the results were averaged.

[0059]

Tensile test in plate thickness direction

Three round bars as tensile test pieces (diameter 10 mm) were obtained along the direction of the plate thickness of each steel plate. The reduction of area after fracture was measured, and the results were averaged.

[0060]

Tables 2 to 5 describe the manufacturing conditions and the results of the above tests. From the tables, the steel plates of the steels Nos. 1 to 16 (the specimens Nos. 1 to 16) which satisfied the chemical composition of steel according to the present invention achieved YS of not less than 620 MPa, TS of not less than 720 MPa, t. El of not less than 16%, base steel toughness (vE_{-40}) of not less than 70 J, and a reduction of area of not less than 25%. Thus, the base steels exhibited excellent strength and toughness.

[0061]

In the steel plates of Comparative Examples (the specimens Nos. 17 to 28) which were produced from the steels Nos. 17 to 28 having a chemical composition outside the scope of the invention, the characteristics of base steel were inferior and corresponded to one or more of YS of less than 620 MPa, TS of less than 720 MPa, t. El of less than

16% and toughness (vE_{-40}) of less than 70 J. In particular, the steel No. 28 failed to satisfy the Ceq requirement, and consequently the martensite and/or bainite fraction in the central area through the plate thickness was less than 80% to cause a decrease in yield strength. Thus, the corresponding steel plate did not achieve the target strength.

[0062]

Further, as demonstrated by the specimens Nos. 29 to 39, even the steel plates satisfying the chemical composition of steel according to the invention were unsatisfactory in one or more characteristics of YS, TS, t. El and toughness (vE_{-40}) when the manufacturing conditions were outside the scope of the invention. In particular, the specimen No. 39 had undergone an insufficient number of rolling passes with 4% or more reduction per pass. Consequently, it was impossible to control the average prior austenite grain size throughout the plate thickness to 50 μm or less, and the base steel exhibited poor toughness.

[0063]

[Table 1]

Table 1

Categories	Steel No.	Chemical composition (mass%)																	Ac3 (°C)	Ar3 (°C)
		C	Si	Mn	P	S	Cr	Ni	Ti	Al	N	B	Cu	Mo	V	Ca	REM	Ceq ^{IIV}		
Inv. Steels	1	0.083	0.15	1.4	0.006	0.0010	0.8	0.5	0.010	0.045	0.0032	0.0009	0.25	0.30	0.020	0.0015		0.59	884	704
	2	0.088	0.08	1.5	0.005	0.0011	0.6	0.9	0.008	0.048	0.0029	0.0011	0.20	0.30	0.045		0.0018	0.60	871	676
	3	0.085	0.20	4.0	0.004	0.0009	0.2	1.5	0.010	0.045	0.0030	0.0012	0.10	0.15	0.040			0.93	812	465
	4	0.096	0.26	1.3	0.005	0.0004	1.2	2.0	0.009	0.050	0.0026	0.0009		0.25				0.74	845	628
	5	0.102	0.18	0.9	0.006	0.0015	2.5	1.5	0.008	0.040	0.0032	0.0010	0.10	0.15	0.040			0.90	850	672
	6	0.108	0.20	1.0	0.006	0.0010	0.7	0.9	0.009	0.050	0.0030	0.0012	0.25	0.45	0.040	0.0016		0.58	883	696
	7	0.118	0.22	1.1	0.005	0.0008	0.9	2.0	0.010	0.045	0.0028	0.0010	0.20	0.48	0.041	0.0018		0.73	848	620
	8	0.122	0.24	1.1	0.004	0.0006	0.8	2.6	0.011	0.038	0.0030	0.0011	0.19	0.50	0.039	0.0016		0.76	831	585
	9	0.124	0.13	1.0	0.003	0.0005	0.8	3.8	0.008	0.055	0.0030	0.0013		0.56	0.040	0.0015		0.82	803	526
	10	0.130	0.23	1.0	0.005	0.0006	0.9	3.6	0.012	0.060	0.0040	0.0010	0.22	0.65	0.045	0.0018		0.87	812	522
	11	0.135	0.19	1.3	0.005	0.0006	0.6	1.9	0.010	0.055	0.0032	0.0012					0.0016	0.60	821	651
	12	0.158	0.22	1.2	0.004	0.0005	0.5	1.0	0.008	0.048	0.0029	0.0009		0.50		0.0018		0.62	854	663
	13	0.175	0.26	0.8	0.003	0.0003	0.8	4.5	0.009	0.053	0.0025	0.0008		0.50	0.040			0.88	767	492
	14	0.195	0.20	0.6	0.006	0.0009	0.8	2.2	0.011	0.050	0.0028	0.0012		0.65		0.0016		0.73	821	617
	15	0.116	0.25	1.5	0.006	0.0005		3.0	0.011	0.040	0.0032	0.0010	0.15	0.45	0.045			0.68	820	550
	16	0.122	0.10	1.5	0.003	0.0004	0.9		0.009	0.045	0.0028	0.0009	0.20	0.20	0.035	0.0020		0.61	873	719
Comp. Steels	17	<u>0.242</u>	0.26	1.3	0.004	0.0008	1.0	0.6	0.012	0.040	0.0032	0.0009	0.20	0.45	0.038	0.0019		0.81	821	643
	18	0.140	<u>0.55</u>	1.1	0.006	0.0007	0.8	1.0	0.009	0.045	0.0028	0.0015	0.15	0.50				0.66	881	669
	19	0.085	<u>0.35</u>	<u>0.3</u>	0.007	0.0009	1.2	0.9	0.009	0.050	0.0032	0.0012	0.22	0.60	0.039	0.0025		0.58	920	740
	20	0.125	0.25	1.0	<u>0.020</u>	0.0012	1.0	0.9	0.009	0.043	0.0029	0.0010	0.20	0.55	0.045		0.0018	0.68	879	679
	21	0.122	0.29	1.1	0.006	0.0005	0.8	2.0	<u>0.003</u>	0.050	0.0040	0.0011				0.0019		0.60	830	662
	22	0.125	0.33	1.0	0.005	0.0006	1.0	1.9	<u>0.024</u>	0.035	0.0045	0.0008		0.60	0.020			0.74	859	624
	23	0.132	0.28	1.2	0.005	0.0009	1.1	2.0	0.009	<u>0.003</u>	0.0035	0.0012		0.35				0.76	827	619
	24	0.120	0.26	1.0	0.005	0.0009	0.9	1.9	0.011	<u>0.095</u>	0.0045	0.0006	0.45	0.45		0.0022		0.71	852	630
	25	0.123	0.18	1.1	0.009	0.0006	0.8	2.0	0.010	0.040	<u>0.0075</u>	0.0009	0.30	0.60				0.74	840	608
	26	0.135	0.26	1.2	0.009	0.0008	0.8	1.9	0.008	0.050	0.0030	<u>0.0001</u>	0.25	0.48		0.0018		0.73	835	612
	27	0.133	0.26	1.1	0.010	0.0010	0.8	2.0	0.008	0.050	0.0030	<u>0.0040</u>	0.25	0.49		0.0022		0.72	848	615
	28	0.120	0.15	0.7	0.010	0.0015	0.6	1.0	0.012	0.035	0.0030	0.0009	0.25	0.45	0.040	0.0015		<u>0.54</u>	875	712

Note 1: Underlined values are outside the inventive ranges.

Note 2: The values of Ceq^{IIV}, Ac3 and Ar3 were calculated using Expressions (1) to (3), respectively.

[0064]

[Table 2]

Table 2

Categories	Specimen No.	Steel No.	Hot working								Treatment after hot working
			Working method	Heating temp. (°C)	Working start temp. (°C)	Working finish temp. (°C)	Cumulative working reduction (%)	Strain rate (/s)	Maximum reduction per pass (%)	Draft in width direction (mm)	
Inv. Steels	1	1	Forging	1200	1185	1050	15	0.1	10	200	Air cooling
	2	2	Rolling	1250	1230	1120	20	2.5	7	0	Hot rolling without cooling
	3	3	Forging	1250	1230	1060	20	0.1	8	0	Air cooling
	4	4	Forging	1200	1190	1030	15	0.1	5	0	Hot rolling without cooling
	5	5	Rolling	1250	1220	1080	15	2	10	0	Air cooling
	6	6	Rolling	1200	1150	1050	15	2	5	0	Air cooling
	7	7	Forging	1270	1265	1100	20	0.1	10	100	Air cooling
	8	8	Forging	1270	1265	1100	20	0.1	10	300	Air cooling
	9	9	Forging	1270	1265	1100	20	0.1	10	200	Air cooling
	10	10	Forging	1270	1265	1080	25	0.1	10	200	Hot rolling without cooling
	11	11	Rolling	1250	1230	1120	20	2.5	7	0	Air cooling
	12	12	Forging	1250	1245	1150	15	1	7	0	Air cooling
	13	13	Forging	1270	1265	1100	20	0.1	10	300	Air cooling
	14	14	Forging	1300	1290	1150	20	0.1	10	200	Air cooling
	15	15	Forging	1250	1235	1100	20	0.1	10	200	Air cooling
	16	16	Forging	1230	1190	1050	15	0.1	10	200	Air cooling
Comp. Steels	17	17	Forging	1200	1190	1030	15	0.1	5	0	Air cooling
	18	18	Forging	1200	1185	1050	15	0.1	10	100	Air cooling
	19	19	Forging	1200	1185	1050	15	0.1	10	200	Air cooling
	20	20	Forging	1270	1265	1100	20	0.1	10	200	Air cooling
	21	21	Forging	1270	1265	1100	20	0.1	10	200	Air cooling

Note: re outside the inventive ranges.

[0065]

[Table 3]

Table 3

Categories	Specimen No.	Steel No.	Hot working								Treatment after hot working
			Working method	Heating temp. (°C)	Working start (°C)	Working finish (°C)	Cumulative working reduction (%)	Strain rate (/s)	Maximum reduction per pass (%)	Draft in width direction (mm)	
Comp. Steels	22	22	Forging	1270	1265	1100	20	0.1	10	300	Air cooling
	23	23	Forging	1270	1265	1100	20	0.1	10	100	Air cooling
	24	24	Forging	1270	1265	1100	20	0.1	10	200	Air cooling
	25	25	Forging	1270	1265	1100	20	0.1	10	200	Air cooling
	26	26	Forging	1270	1265	1100	20	0.1	10	200	Air cooling
	27	27	Forging	1270	1265	1100	20	0.1	10	200	Air cooling
	28	28	Forging	1270	1265	1100	20	0.1	10	100	Air cooling
	29	7	Forging	<u>1050</u>	<u>1045</u>	<u>850</u>	15	0.1	<u>3</u>	0	Air cooling
	30	7	Forging	1200	1185	<u>900</u>	15	0.1	4	100	Air cooling
	31	7	Forging	1200	1190	1050	<u>7</u>	0.2	4	0	Air cooling
	32	7	Rolling	1200	1170	1050	15	<u>10</u>	8	0	Air cooling
	33	7	Forging	1250	1245	1150	15	0.1	8	200	Air cooling
	34	9	Forging	1270	1265	1050	20	0.1	7	200	Air cooling
	35	9	Forging	1270	1265	1050	20	0.1	8	200	Air cooling
	36	9	Forging	1270	1260	1045	20	0.1	7	200	Air cooling
	37	9	Forging	1250	1245	1050	20	0.1	8	100	Air cooling
	38	9	Forging	1250	1240	1050	20	0.1	8	100	Air cooling
	39	9	Forging	1270	1235	1045	20	0.1	8	100	Air cooling

Note: Underlined values are outside the inventive ranges.

[0066]

[Table 4]

Categories	Specimen No.	Steel No.	Hot rolling				Final heat treatment conditions				Base steel characteristics					Porosities	Average prior austenite grain size (μm)	Fraction in microstructure (%) (Note 1)	
			Heating temp. (°C)	Rolling reduction (%)	Number of passes with 4% or more reduction per pass (times)	Plate thickness (mm)	Reheating temp. (°C)	Holding time (min.)	Cooling finish temp. (°C)	Tempering temp. (°C)	YS (MPa)	TS (MPa)	t.El (%)	vE-40 (J)	Reduction of area by tension in plate thickness direction (%)			Steel plate surface	Central area through plate thickness
Inv. Steels	1	1	1150	65	5	100	900	10	150	660	711	795	18.6	138	37	Absent	40	≥80	≥80
	2	2	—	48	5	130	900	30	100	630	723	803	16.1	141	28	Absent	38	≥80	≥80
	3	3	1200	48	4	130	900	30	100	630	721	806	17.2	123	32	Absent	40	≥80	≥80
	4	4	—	20	3	210	1000	30	100	600	703	795	16.5	116	30	Absent	43	≥80	≥80
	5	5	1150	43	4	150	1000	30	100	630	728	804	16.8	135	29	Absent	46	≥80	≥80
	6	6	1100	51	4	130	930	30	100	630	739	812	16.2	132	28	Absent	36	≥80	≥80
	7	7	1200	42	3	150	930	30	150	630	769	845	19.2	151	39	Absent	41	≥80	≥80
	8	8	1200	37	3	180	900	30	100	630	745	809	18.1	216	38	Absent	39	≥80	≥80
	9	9	1200	23	3	210	900	30	100	600	759	832	17.5	225	36	Absent	43	≥80	≥80
	10	10	—	10	3	240	900	60	100	550	801	865	18.8	193	35	Absent	46	≥80	≥80
	11	11	1150	60	5	100	900	10	200	630	739	801	16.6	163	28	Absent	33	≥80	≥80
	12	12	1150	32	3	180	900	30	100	630	665	748	21.5	186	35	Absent	30	≥80	≥80
	13	13	1200	37	4	180	900	30	100	500	798	859	20.2	198	36	Absent	36	≥80	≥80
	14	14	1200	45	4	150	900	30	150	630	812	883	18.5	128	37	Absent	44	≥80	≥80
	15	15	1200	45	4	150	900	30	100	630	721	806	17.3	203	36	Absent	32	≥80	≥80
	16	16	1150	65	5	100	930	10	100	600	768	845	18.3	115	38	Absent	29	≥80	≥80
Comp. Steels	17	17	1100	20	3	210	900	30	100	600	805	883	16.0	49	28	Absent	45	≥80	≥80
	18	18	1150	64	5	100	900	30	150	660	769	835	17.8	55	36	Absent	30	≥80	≥80
	19	19	1150	65	5	100	900	10	150	660	652	722	18.2	36	39	Absent	29	≥80	≥80
	20	20	1200	45	4	150	900	30	150	630	775	848	17.3	22	35	Absent	36	≥80	≥80
	21	21	1200	45	5	150	900	30	150	630	738	801	17.3	32	36	Absent	39	≥80	≥80

Note 1 Martensite and/or bainite area fraction

[0067]

[Table 5]

Categories	Specimen No.	Steel No.	Hot rolling				Final heat treatment conditions				Base steel characteristics					Porosities	Average prior austenite grain size (μ m)	Fraction in microstructure (%) (Note 2)	
			Heating temp. (°C)	Rolling reduction (%)	Number of passes with 4% or more reduction per pass (times)	Plate thickness (mm)	Reheating temp. (°C)	Holding time (min.)	Cooling finish temp. (°C)	Tempering temp. (°C)	YS (MPa)	TS (MPa)	t. El (%)	vE-40 (J)	Reduction of area by tension in plate thickness direction (%)			Steel plate surface	Central area through plate thickness
Comp. Steels	22	22	1200	48	4	150	900	30	150	630	768	830	17.0	29	35	Absent	46	≥80	≥80
	23	23	1200	42	5	150	900	30	150	630	649	726	17.4	24	36	Absent	43	≥80	≥80
	24	24	1200	45	4	150	900	30	150	630	750	803	18.2	41	35	Absent	45	≥80	≥80
	25	25	1200	45	4	150	900	30	150	630	682	733	17.1	39	36	Absent	40	≥80	≥80
	26	26	1200	34	4	180	900	30	100	630	<u>539</u>	634	19.1	19	35	Absent	42	≥80	50
	27	27	1200	34	3	180	900	30	100	630	789	869	18.3	52	38	Absent	41	≥80	≥80
	28	28	1200	31	3	180	900	30	100	630	<u>563</u>	685	21.2	26	36	Absent	44	≥80	45
	29	7	1150	43	4	150	900	30	150	630	763	829	10.5	103	16	Present	33	≥80	≥80
	30	7	1150	46	4	150	900	30	150	630	748	816	8.6	86	15	Present	39	≥80	≥80
	31	7	1150	48	3	150	900	30	100	630	785	863	6.9	92	18	Present	41	≥80	≥80
	32	7	1100	43	3	150	900	30	150	630	761	831	5.3	115	8	Present	39	≥80	≥80
	33	7	<u>800</u>	48	4	150	900	30	100	630	735	819	16.1	48	36	Absent	112	≥80	25
	34	9	1150	23	3	210	<u>1100</u>	10	150	600	762	841	16.0	35	30	Absent	74	≥80	≥80
	35	9	1150	23	3	210	<u>750</u>	30	100	600	<u>610</u>	682	16.4	215	33	Absent	105	≥80	≥80
	36	9	1100	23	3	210	900	30	<u>450</u>	600	<u>593</u>	645	16.3	39	32	Absent	43	≥80	30
	37	9	1100	19	2	210	900	30	150	<u>730</u>	<u>576</u>	633	16.2	221	35	Absent	45	≥80	≥80
	38	9	1100	19	3	210	900	30	150	<u>380</u>	871	1025	16.5	16	36	Absent	41	≥80	≥80
	39	9	1100	19	1	210	900	30	150	630	769	858	16.3	32	29	Absent	85	≥80	≥80

Note 1 Underlined values are outside the inventive ranges.

Note 2 Martensite and/or bainite area fraction

CLAIMS

[Claim 1]

A thick high-toughness high-strength steel plate having a plate thickness of not less than 100 mm, the steel plate comprising:

by mass%, C: 0.08 to 0.20%, Si: not more than 0.40%,

Mn: 0.5 to 5.0%, P: not more than 0.015%,

S: not more than 0.0050%, Cr: not more than 3.0%,

Ni: not more than 5.0%, Ti: 0.005% to 0.020%,

Al: 0.010 to 0.080%, N: not more than 0.0070% and

B: 0.0003 to 0.0030%, the balance being Fe and

inevitable impurities; and

a microstructure having, throughout an entire region in the plate thickness direction, an average prior austenite grain size of not more than 50 μm and a martensite and/or bainite phase area fraction of not less than 80%, wherein

the yield strength is not less than 620 MPa;

the reduction of area after fracture in a tensile test in the direction of the plate thickness of the steel plate is not less than 25%;

base steel toughness ($\sqrt{E_{-40}}$) of Charpy impact test at -40°C is not less than 70 J; and

the thick high-toughness high-strength steel plate satisfies the relationship represented by Expression (1):

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

0.57 ... (1)

where the alloying element symbols indicate the respective contents (mass%) and are 0 when absent.

[Claim 2]

The thick high-toughness high-strength steel plate according to claim 1, further comprising:

by mass%, one, or two or more of Cu: not more than 0.50%, Mo: not more than 1.00% and V: not more than 0.200%.

[Claim 3]

The thick high-toughness high-strength steel plate according to claim 1 or 2, further comprising:

by mass%, one or both of Ca: 0.0005 to 0.0050% and REM: 0.0005 to 0.0050%.

[Claim 4]

A method for manufacturing a thick high-toughness high-strength steel plate according to any one of claims 1-3, the method comprising steps of:

heating a continuously cast slab to 1200°C to 1350°C;

hot working the slab at not less than 1000°C with a strain rate of not more than 3/s and a cumulative working reduction of not less than 15%;

thereafter air cooling the slab;

heating the slab again to Ac3 point to 1200°C;

thereafter, performing hot rolling with the slab to form a plate, the hot rolling including at least two or more

passes with a rolling reduction per pass of not less than 4%;

thereafter, air cooling the plate;

heating the plate to Ac3 point to 1050°C;

thereafter, quenching the plate to 350°C or below; and
performing tempering at 450°C to 700°C with the plate.

[Claim 5]

The method for manufacturing a thick high-toughness high-strength steel plate according to claim 4,

wherein the continuously cast slab is worked to reduce the width by not less than 100 mm before hot working and is thereafter hot worked with a strain rate of not more than 3/s and a cumulative working reduction of not less than 15%.