

HIGH TOUGHNESS AND HIGH TENSILE STRENGTH THICK STEEL
PLATE WITH EXCELLENT MATERIAL HOMOGENEITY AND
PRODUCTION METHOD FOR SAME

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TECHNICAL FIELD

[0001] This disclosure relates to a thick steel plate with excellent strength, elongation, and toughness, and excellent material homogeneity in a plate thickness direction, that is suitable for use in steel structures such as buildings, bridges, ships, marine structures, construction machinery, tanks, and penstocks, and also relates to a production method for this thick steel plate.

In particular, this disclosure relates to a high toughness and high tensile strength thick steel plate having a plate thickness of 100 mm or more, in which the yield strength of a mid-thickness part is 500 MPa or more, the reduction of area in the mid-thickness part by tension in a plate thickness direction is 40 % or more, and the low-temperature toughness at -60 °C of the mid-thickness part is 70 J or more.

Herein, the phrase “excellent material homogeneity” is used with the meaning that hardness difference in the plate thickness direction is small.

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BACKGROUND

[0002] When a steel material is to be used in any of various fields such as buildings, bridges, ships, marine structures, construction machinery, tanks, and penstocks, the steel material is made into a desired shape by welding in accordance with the shape of a steel structure for which the steel material is to be used. Recent years have seen the development of increasing large steel structures and the use of stronger and thicker steel materials at a remarkable rate.

[0003] A thick steel plate having a plate thickness of 100 mm or more is typically produced by blooming a large steel ingot produced by ingot casting and then hot rolling the obtained slab. In this ingot casting and blooming process, however, a concentrated segregation area of a hot top portion or a negative segregation area of a steel ingot bottom portion needs to be discarded. This hinders yield improvement, and leads to higher production cost and longer construction time.

[0004] On the other hand, in the case of producing a thick steel plate having a plate thickness of 100 mm or more by a process that uses a continuously-cast slab as a raw material, the aforementioned concern does not exist, but there is little working reduction to the product thickness because the continuously-cast slab is thin compared to a slab produced by ingot casting. Moreover, the general tendency to require stronger and thicker steel materials in recent years has increased the amount of alloying element added to ensure necessary properties. This causes new problems such as center porosity caused by center segregation and deterioration of inner quality due to upsizing.

[0005] To solve these problems, the following techniques have been proposed for use in a process of producing an ultra-thick steel plate from a continuously-cast slab, with the aim of compressing center porosity to improve the properties of the center segregation area in the steel plate.

[0006] For example, Non-Patent Literature (NPL) 1 describes a technique of compressing center porosity by increasing the rolling shape ratio in hot rolling of a continuously-cast slab.

[0007] JP S55-114404 A (PTL 1) and JP S61-273201 A (PTL 2) describe techniques of compressing center porosity in a continuously-cast slab by, in production of the continuously-cast slab, working the material using rolls or flat dies in a continuous casting machine.

[0008] JP 3333619 B (PTL 3) describes a technique of compressing center porosity by performing forging before hot rolling in production of a thick steel plate from a continuously-cast slab with a cumulative working reduction of 70 % or less.

[0009] JP 2002-194431 A (PTL 4) describes a technique of not only eliminating center porosity but also reducing the center segregation zone to improve the resistance to temper embrittlement by, in production of an ultra-thick steel plate from a continuously-cast slab through forging and thick plate rolling with a total working reduction of 35 % to 67 %, holding a mid-thickness part of the raw material at a temperature of 1200 °C or higher for 20 hours or more before forging, and setting the working reduction of the forging to 16 % or more.

[0010] JP 2000-263103 A (PTL 5) describes a technique of remedying center

porosity and center segregation by cross-forging a continuously-cast slab and then hot rolling the slab.

[0011] JP 2006-111918 A (PTL 6) describes a production method for a thick steel plate having a tensile strength of 588 MPa or more, with center porosity
5 being eliminated and the center segregation zone being reduced. In the production method, a continuously-cast slab is held at a temperature of 1200 °C or higher for 20 hours or more, the working reduction of forging is set to 17 % or more, thick plate rolling is performed such that the total working reduction including the forging is in the range of 23 % to 50 %, and quenching
10 is implemented twice after the thick plate rolling.

[0012] JP 2010-106298 A (PTL 7) describes a production method for a thick steel plate having excellent weldability and plate thickness direction ductility. In the production method, a continuously-cast slab having a specific chemical composition is reheated to at least 1100 °C and no higher than 1350 °C, and is
15 then hot worked at 1000 °C or higher with a strain rate of 0.05/s to 3/s and a cumulative working reduction of 15 % or more.

CITATION LIST

Patent Literature

20 **[0013]** PTL 1: JP S55-114404 A
PTL 2: JP S61-273201 A
PTL 3: JP 3333619 B
PTL 4: JP 2002-194431 A
PTL 5: JP 2000-263103 A
25 PTL 6: JP 2006-111918 A
PTL 7: JP 2010-106298 A

Non-Patent Literature

[0014] NPL 1: Transactions of the Iron and Steel Institute of Japan, 66 (1980), pp. 201-210
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SUMMARY

(Technical Problem)

[0015] However, the technique described in NPL 1 requires repeated rolling with a high rolling shape ratio to obtain a steel plate having good inner quality.

This poses a problem in production due to exceeding the upper limit of the equipment specifications of a mill. If a typical method is used for rolling, the mid-thickness part cannot be worked sufficiently and, as a result, center porosity may remain and inner quality may not be improved.

5 **[0016]** The techniques described in PTL 1 and 2 require a larger continuous casting line to produce a thick steel plate having a plate thickness of 100 mm or more, and thus require significant capital investment.

10 **[0017]** The techniques described in PTL 3 to 7 are effective in center porosity reduction and center segregation zone improvement. However, when these techniques are adopted in the production of a thick steel plate with a plate thickness of 100 mm or more, a yield strength of 500 MPa or more, and a large addition amount of alloying element, the following problem may arise. Specifically, it is difficult to ensure toughness of the mid-thickness part at -60 °C using conventional rolling and forging methods since an increase in
15 strength and thickness of the material is accompanied by a trade-off in terms of deterioration of toughness.

20 **[0018]** To solve the problems described above, it would be helpful if even in the case of a high strength thick steel plate in which an increase in the added amount of alloying element is required, a high tensile strength thick steel plate having excellent strength, elongation, and toughness in a mid-thickness part could be provided along with a production method for this thick steel plate.

(Solution to Problem)

25 **[0019]** The inventors aimed to solve the problems described above by conducting diligent research in which they investigated the controlling factors of microstructure within a steel plate in relation to strength, elongation, and toughness of a mid-thickness part, particularly focusing on thick steel plates having a plate thickness of 100 mm or more. Through their research, the inventors reached the following findings.

30 **[0020]** (A) To achieve good strength and toughness in the mid-thickness part of a steel plate, which has a significantly slower cooling rate than the surface of the steel plate, it is important to appropriately select the chemical composition of the steel such that the microstructure becomes a martensite and/or bainite structure even at a slow cooling rate.

[0021] (B) To ensure good ductility in the mid-thickness part of a thick steel plate, which tends to have lower ductility due to strengthening and higher defect sensitivity with respect to ductility, it is important to manage the die shape, total working reduction, and strain rate in hot forging to compress center porosity and render it harmless.

[0022] This disclosure is based on these findings and further investigation conducted by the inventors. The primary features of this disclosure are as follows.

1. A high toughness and high tensile strength thick steel plate having a plate thickness of 100 mm or more with excellent material homogeneity, having a chemical composition containing (consisting of), in mass%,

C: 0.08 % to 0.20 %,

Si: 0.40 % or less,

Mn: 0.5 % to 5.0 %,

P: 0.015 % or less,

S: 0.0050 % or less,

Ni: 5.0 % or less,

Ti: 0.005 % to 0.020 %,

Al: 0.080 % or less,

N: 0.0070 % or less,

B: 0.0030 % or less, and

one or more selected from

Cu: 0.50 % or less,

Cr: 3.0 % or less,

Mo: 1.50 % or less,

V: 0.200 % or less, and

Nb: 0.100 % or less,

the balance being Fe and incidental impurities, wherein

a value Ceq^{IIW} defined by formula (1) below is 0.55 to 0.80:

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

where each element symbol indicates content, in mass %, of a corresponding element in the chemical composition and is taken to be 0 when the corresponding element is not contained,

a mid-thickness part of the steel plate has a yield strength of 500 MPa

or more,

reduction of area in the mid-thickness part by tension in a plate thickness direction is 40 % or more, and

the mid-thickness part has a low-temperature toughness at $-60\text{ }^{\circ}\text{C}$ of
5 70 J or more.

[0023] 2. The high toughness and high tensile strength thick steel plate with excellent material homogeneity of the foregoing section 1, wherein

the chemical composition further contains, in mass%, one or more selected from

10 Mg: 0.0005 % to 0.0100 %,
Ta: 0.01 % to 0.20 %,
Zr: 0.005 % to 0.1 %,
Y: 0.001 % to 0.01 %,
Ca: 0.0005 % to 0.0050 %, and
15 REM: 0.0005 % to 0.0200 %.

[0024] 3. The high toughness and high tensile strength thick steel plate with excellent material homogeneity of the foregoing section 1 or 2, wherein

in a hardness distribution in the plate thickness direction, a difference ΔHV between average hardness of a plate thickness surface (HVS) and
20 average hardness of the mid-thickness part (HVC), where $\Delta\text{HV} = \text{HVS} - \text{HVC}$, is 30 or less.

[0025] 4. A production method for the high toughness and high tensile strength thick steel plate with excellent material homogeneity of any one of the foregoing sections 1 to 3, comprising

25 heating a continuously-cast slab having the chemical composition in the foregoing section 1 or 2 to at least $1200\text{ }^{\circ}\text{C}$ and no higher than $1350\text{ }^{\circ}\text{C}$,

then hot forging the continuously-cast slab under conditions of a temperature of $1000\text{ }^{\circ}\text{C}$ or higher, a strain rate of 3/s or less, and a cumulative working reduction of 15 % or more using opposing dies having respective
30 short sides differing such that when a short side length of a die having a shorter one of the short sides is taken to be 1, a short side length of a die having a longer one of the short sides is 1.1 to 3.0,

then allowing cooling to obtain a steel raw material,

then reheating the steel raw material to at least an Ac_3 temperature and

no higher than 1250 °C,

then performing hot rolling of the steel raw material including at least two passes carried out with a rolling reduction of 4 % or more per pass,

then allowing cooling to obtain a thick steel plate,

5 then reheating the thick steel plate to at least the Ac_3 temperature and no higher than 1050 °C,

then rapidly cooling the thick steel plate to 350 °C or lower, and

then tempering the thick steel plate at at least 550 °C and no higher 700 °C.

10 **[0026]** 5. The production method of the foregoing section 4, wherein

a working reduction ratio from the continuously-cast slab prior to working to the thick steel plate obtained after the hot rolling in production of the high toughness and high tensile strength thick steel plate is 3 or less.

(Advantageous Effect)

15 **[0027]** Through the disclosed techniques, it is possible to obtain a thick steel plate having a plate thickness of 100 mm or more, with excellent material homogeneity and excellent base metal strength, elongation, and toughness. Moreover, the disclosed techniques significantly contribute to increasing steel structure size, improving steel structure safety, improving yield, and
20 shortening construction time, and are, therefore, industrially very useful. In particular, the disclosed techniques enable good properties to be obtained in the mid-thickness part without the need for measures such as increasing the scale of a continuous casting line, even in a situation in which the working reduction ratio from the pre-working slab is 3 or less. Note that
25 conventionally, it has not been possible to achieve adequate properties in the mid-thickness part in this situation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] In the accompanying drawings:

30 FIG. 1 illustrates the main points of forging a slab using asymmetrical dies according to this disclosure; and

FIG. 2 compares equivalent plastic strain in a raw material (steel plate) when conventional symmetrical dies (dies having upper/lower symmetry) are used and when asymmetrical dies (dies not having upper/lower

symmetry) according to this disclosure are used.

DETAILED DESCRIPTION

5 [0029] The following provides a detailed description of the disclosed techniques.

First, suitable ranges for the steel plate composition will be described. The contents of elements in the steel plate composition, shown in %, are all mass% values.

[0030] C: 0.08 % to 0.20 %

10 C is an element that is useful for obtaining the strength required for structural-use steel at low-cost. Addition of C in an amount of 0.08 % or more is required to obtain this effect. On the other hand, an upper limit of 0.20 % is set for the C content because C content exceeding 0.20 % causes significant deterioration of base metal toughness and weld toughness. The C content is
15 more preferably 0.08 % or more. The C content is more preferably 0.14 % or less.

[0031] Si: 0.40 % or less

Si is added for deoxidation. However, addition of Si in excess of 0.40 % causes significant deterioration of base metal toughness and
20 heat-affected zone toughness. Therefore, the Si content is set as 0.40 % or less. The Si content is more preferably 0.05 % or more. The Si content is more preferably 0.30 % or less. The Si content is even more preferably 0.1 % or more and 0.30 % or less.

[0032] Mn: 0.5 % to 5.0 %

25 Mn is added to ensure base metal strength. However, this effect is not sufficiently obtained if less than 0.5 % of Mn is added. On the other hand, an upper limit of 5.0 % is set for the Mn content because addition of Mn in excess of 5.0 % not only causes deterioration of base metal toughness, but also promotes central segregation and increases the scale of slab porosity. The
30 Mn content is more preferably 0.6 % or more. The Mn content is more preferably 2.0 % or less. The Mn content is even more preferably 0.6 % or more and 1.6 % or less.

[0033] P: 0.015 % or less

The P content is limited to 0.015 % or less because P content

exceeding 0.015 % significantly reduces base metal toughness and heat-affected zone toughness. The P content does not have a specific lower limit and may be 0 %.

[0034] S: 0.0050 % or less

5 The S content is limited to 0.0050 % or less because S content exceeding 0.0050 % significantly reduces base metal toughness and heat-affected zone toughness. The S content does not have a specific lower limit and may be 0 %.

[0035] Ni: 5.0 % or less

10 Ni is a useful element for improving steel strength and heat-affected zone toughness. However, an upper limit of 5.0 % is set for the Ni content because addition of Ni in excess of 5.0 % has a significant negative economical impact. The Ni content is more preferably 0.5 % or more. The Ni content is more preferably 4.0 % or less.

15 **[0036]** Ti: 0.005 % to 0.020 %

 Ti forms TiN during heating, effectively inhibits coarsening of austenite, and improves base metal toughness and heat-affected zone toughness. Therefore, the Ti content is 0.005 % or more. However, addition of Ti in excess of 0.020 % causes coarsening of Ti nitrides and reduces base
20 metal toughness. Therefore, the Ti content is set in a range of 0.005 % to 0.020 %. The Ti content is more preferably 0.008 % or more. The Ti content is more preferably 0.015 % or less.

[0037] Al: 0.080 % or less

 Al is added to sufficiently deoxidize molten steel. However, addition
25 of Al in excess of 0.080 % causes a large amount of Al to dissolve in the base metal, leading to a decrease in base metal toughness. Therefore, the Al content is set as 0.080 % or less. The Al content is more preferably 0.030 % or more and 0.080 % or less. The Al content is even more preferably 0.030 % or more. The Al content is even more preferably 0.060 % or less.

30 **[0038]** N: 0.0070 % or less

 N has an effect of refining structure through formation of nitrides with Ti and the like, and thereby improving base metal toughness and heat-affected zone toughness. However, addition of N in excess of 0.0070 % increases the amount of N dissolved in the base metal, leading to a significant decrease in

base metal toughness, and also causes formation of coarse nitrides in the heat-affected zone, leading to a decrease in heat-affected zone toughness. Therefore, the N content is set as 0.0070 % or less. The N content is more preferably 0.0050 % or less. The N content is even more preferably 0.0040 % or less. The N content does not have a specific lower limit and may be 0 %.

[0039] B: 0.0030 % or less

B has an effect of inhibiting ferrite transformation at austenite grain boundaries by segregating at the grain boundaries, and thereby improving quench hardenability. However, addition of B in excess of 0.0030 % causes precipitation of B as a carbonitride, leading to poorer quench hardenability and reduced toughness. Therefore, the B content is set as 0.0030 % or less. The B content is more preferably 0.0003 % or more. The B content is more preferably 0.0030 % or less. The B content is even more preferably 0.0005 % or more. The B content is even more preferably 0.0020 % or less. The B content does not have a specific lower limit and may be 0 %.

[0040] In addition to the elements described above, one or more selected from Cu, Cr, Mo, V, and Nb are contained in the steel plate composition to further increase strength and/or toughness.

Cu: 0.50 % or less

Cu can improve the strength of steel without loss of toughness. However, addition of Cu in excess of 0.50 % causes cracking of the surface of the steel plate during hot working. Therefore, the Cu content is set as 0.50 % or less. The Cu content does not have a specific lower limit and may be 0 %.

[0041] Cr: 3.0 % or less

Cr is an effective element for strengthening the base metal. However, the Cr content is set as 3.0 % or less because addition of a large amount of Cr reduces weldability. The Cr content is more preferably 0.1 % or more. The Cr content is more preferably 2.0 % or less from a viewpoint of production cost.

[0042] Mo: 1.50 % or less

Mo is an effective element for strengthening the base metal. However, an upper limit of 1.50 % is set for the Mo content because addition of Mo in excess of 1.50 % causes precipitation of a hard alloy carbide, leading to an increase in strength and a decrease in toughness. The Mo content is more preferably 0.02 % or more. The Mo content is more preferably 0.80 % or less.

[0043] V: 0.200 % or less

V has an effect of improving base metal strength and/or toughness and effectively reduces the amount of solute N through precipitation as VN. However, addition of V in excess of 0.200 % reduces toughness of the steel due to precipitation of hard VC. Therefore, the V content is set as 0.200 % or less. The V content is more preferably 0.005 % or more. The V content is more preferably 0.100 % or less.

[0044] Nb: 0.100 % or less

Nb is useful due to an effect of strengthening the base metal. However, an upper limit of 0.100 % is set for the Nb content because addition of Nb in excess of 0.100 % significantly reduces base metal toughness. The Nb content is more preferably 0.025 % or less.

[0045] In addition to the basic components described above, one or more selected from Mg, Ta, Zr, Y, Ca, and REM may be contained in the steel plate composition to further enhance material quality.

Mg: 0.0005 % to 0.0100 %

Mg forms a stable oxide at high temperature and effectively inhibits coarsening of prior γ (austenite) grains in a heat-affected zone, and is thus an effective element for improving weld toughness. Therefore, the Mg content is preferably 0.0005 % or more. However, addition of Mg in excess of 0.0100 % increases the amount of inclusions and reduces toughness. Therefore, in a situation in which Mg is added, the Mg content is preferably 0.0100 % or less. The Mg content is more preferably 0.0005 % or more and 0.0050 % or less.

[0046] Ta: 0.01 % to 0.20 %

Ta effectively improves strength when added in an appropriate amount. However, no clear effect is obtained when less than 0.01 % of Ta is added. Therefore, the Ta content is preferably 0.01 % or more. On the other hand, addition of Ta in excess of 0.20 % reduces toughness due to precipitate formation. Therefore, the Ta content is preferably 0.20 % or less.

[0047] Zr: 0.005 % to 0.1 %

Zr is an effective element for increasing strength. However, no clear effect is obtained when less than 0.005 % of Zr is added. Therefore, the Zr content is preferably 0.005 % or more. On the other hand, addition of Zr in excess of 0.1 % reduces toughness due to formation of a coarse precipitate.

Therefore, the Zr content is preferably 0.1 % or less.

[0048] Y: 0.001 % to 0.01 %

Y forms a stable oxide at high temperature and effectively inhibits coarsening of prior γ grains in a heat-affected zone, and is thus an effective element for improving weld toughness. However, these effects are not obtained if less than 0.001 % of Y is added. Therefore, the Y content is preferably 0.001 % or more. On the other hand, addition of Y in excess of 0.01 % increases the amount of inclusions and reduces toughness. Therefore, the Y content is preferably 0.01 % or less.

[0049] Ca: 0.0005 % to 0.0050 %

Ca is a useful element for morphological control of sulfide inclusions. In a situation in which Ca is added, the Ca content is preferably 0.0005 % or more in order to display this effect. However, addition of Ca in excess of 0.0050 % leads to a decrease in the cleanliness factor and causes deterioration of toughness. Therefore, in a situation in which Ca is added, the Ca content is preferably 0.0050 % or less. The Ca content is more preferably 0.0005 % or more and 0.0025 % or less.

[0050] REM: 0.0005 % to 0.0200 %

REM (rare earth metal) has an effect of improving material quality by forming oxides and sulfides in the steel in the same way as Ca. However, this effect is not obtained unless the REM content is 0.0005 % or more. Moreover, this effect reaches saturation when REM is added in excess of 0.0200 %. Therefore, in a situation in which REM is added, the REM content is preferably 0.0200 % or less. The REM content is more preferably 0.0005 % or more. The REM content is more preferably 0.0100 % or less.

[0051] The basic components and selectable components of the steel plate composition have been described through the above. In addition, it is important that the equivalent carbon content, indicated by Ceq^{IIW} , is in an appropriate range.

Ceq^{IIW} (%): 0.55 to 0.80

In the presently disclosed techniques, it is required that appropriate components are added to ensure that the mid-thickness part has a yield strength of 500 MPa or more and good low-temperature toughness at $-60\text{ }^{\circ}\text{C}$. It is also required that the composition is adjusted such that Ceq^{IIW} (%),

defined by the following formula (1), is 0.55 to 0.80.

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

Each element symbol indicates the content, in mass%, of the corresponding element.

5 **[0052]** By adopting the forging process described below with respect to a thick steel plate having a plate thickness of 100 mm or more and having the chemical composition described above, center porosity in a mid-thickness part of the thick steel plate can be compressed and thus rendered substantially harmless.

10 Moreover, by subsequently adopting the hot working process described below, strength, ductility, and toughness of the mid-thickness part of the steel plate can be improved, and thus a yield strength in the mid-thickness part of 500 MPa or more, a reduction of area in the mid-thickness part by tension in a plate thickness direction of 40 % or more,
15 and a low-temperature toughness at $-60\text{ }^{\circ}\text{C}$ in the mid-thickness part of 70 J or more can be achieved.

[0053] In the case of a thick steel plate having a plate thickness of 100 mm or more and a yield strength of 500 MPa or more, a hardness distribution in the plate thickness direction of the steel plate is typically high at the surface of
20 the steel plate and falls toward a mid-thickness part of the steel plate. If the composition of the steel plate is inappropriate and quench hardenability is insufficient, a structure of mainly ferrite and upper bainite forms, leading to greater variation in the hardness distribution in the plate thickness direction (i.e., a greater difference between hardness near the surface and hardness of
25 the mid-thickness part), and thus poorer material homogeneity.

Herein, appropriate adjustment of the steel plate composition as described above ensures quench hardenability, resulting in a microstructure that is a martensite and/or bainite structure.

In particular, material homogeneity can be further improved when, in
30 the plate thickness direction hardness distribution, the difference ΔHV between the average hardness of the plate thickness surface (HVS) and the average hardness of the mid-thickness part (HVC), where $\Delta HV = HVS - HVC$, is 30 or less.

The average hardness of the plate thickness surface (HVS) and the

average hardness of the mid-thickness part (HVC) can be determined, for example, from a cross-section parallel to a longitudinal direction of the steel plate by measuring the hardness at a number of points at a position 2 mm inward from the steel plate surface and a number of points at a mid-thickness position in the cross-section, and then determining an average value for each of these positions.

[0054] The following describes production conditions in the presently disclosed techniques.

In the following description, temperatures given in “°C” refer to the temperature of the mid-thickness part. The presently disclosed production method for a steel plate requires, in particular, that a steel raw material be hot forged under the following conditions to render harmless casting defects such as center porosity in the steel raw material.

[0055] I. Hot forging conditions of steel raw material

Heating temperature: 1200 °C to 1350 °C

A steel raw material for a cast steel or slab having the aforementioned composition is subjected to steelmaking and continuous casting by a typically known method, such as using a converter, an electric heating furnace, or a vacuum melting furnace, and is then reheated to at least 1200 °C and no higher than 1350 °C. If the reheating temperature is lower than 1200 °C, a predetermined cumulative working reduction and temperature lower limit cannot be ensured in hot forging and deformation resistance during the hot forging is high, making it impossible to ensure a sufficient per-pass working reduction. As a result, a larger number of passes are needed, which not only reduces production efficiency, but also makes it impossible to compress casting defects such as center porosity in the steel raw material to render them harmless. Therefore, the slab reheating temperature is set as 1200 °C or higher. An upper limit of 1350 °C is set for the reheating temperature because reheating to a temperature higher than 1350 °C consumes excessive energy and facilitates formation of surface defects due to scale during heating, leading to an increased mending load after hot forging.

[0056] Hot forging according to this disclosure is performed using a pair of opposing dies whose long sides lie in the width direction of the continuously-cast slab and whose short sides lie in the traveling direction of

the continuously-cast slab. A feature of the hot forging according to this disclosure is that the respective short sides of the opposing dies have different lengths, as illustrated in FIG. 1.

In FIG. 1, reference sign 1 indicates an upper die, reference sign 2 indicates a lower die, and reference sign 3 indicates a slab.

[0057] Among the opposing upper and lower dies, when the short side length of the die having a shorter one of the short sides (i.e., the upper die in FIG. 1) is taken to be 1, the short side length of the opposing die having a longer one of the short sides (i.e., the lower die in FIG. 1) is set such as to be from 1.1 times to 3.0 times the short side length of the die having the shorter one of the short sides. As a result, not only can an asymmetrical strain distribution be obtained within the steel material, but also a position of minimum strain application during forging can be set so as not to coincide with a position at which center porosity of the continuously-cast slab occurs. This makes it possible to ensure that the center porosity is rendered harmless.

[0058] If the ratio of the longer one of the short sides to the shorter one of the short sides is less than 1.1, the effect of rendering center porosity harmless is not sufficiently achieved. On the other hand, if the ratio of the longer one of the short sides to the shorter one of the short sides exceeds 3.0, the efficiency of hot forging drops significantly. Accordingly, it is important that, with regards to the respective short side lengths of the pair of opposing dies used in the hot forging according to this disclosure, when the shorter one of the short side lengths is taken to be 1, the longer one of the short side lengths is set as 1.1 to 3.0. It should be noted that so long as the respective short side lengths of the opposing dies satisfy the ratio described above, it does not matter whether the die having the shorter one of the short side lengths is located above or below the continuously-cast slab. In other words, the lower die in FIG. 1 may alternatively be the die having the shorter one of the short side lengths.

[0059] FIG. 2 compares the equivalent plastic strain in a slab, calculated in a thickness direction of the slab, when hot forging was performed using dies for which the respective short side lengths of the upper and lower dies are the same (conventional dies indicated by white circles in FIG. 2) and when hot forging was performed using dies for which the ratio of short side lengths of a

die having a shorter short side and a die having a longer short side is 2.5 (dies according to this disclosure indicated by black circles in FIG. 2). With the exception of the die shape, the hot forging was performed with both pairs of dies under the same conditions of a heating temperature of 1250 °C, a working
5 start temperature of 1215 °C, a working end temperature of 1050 °C, a cumulative working reduction of 16 %, a strain rate of 0.1/s, and a maximum working reduction per pass of 8 %, and without width direction working.

FIG. 2 clearly illustrates that hot forging using the dies according to this disclosure was more successful in imparting sufficient strain to the center
10 of the slab.

[0060] Hot forging temperature: 1000 °C or higher

A forging temperature of lower than 1000 °C in the hot forging raises deformation resistance during the hot forging and thus increases the load on the forging machine, making it impossible to ensure that center porosity is
15 rendered harmless. Therefore, the forging temperature is set as 1000 °C or higher. The forging temperature does not have a specific upper limit but is preferably no higher than approximately 1350 °C in view of production costs.

[0061] Cumulative working reduction of hot forging: 15 % or more

If the cumulative working reduction of the hot forging is less than
20 15 %, casting defects such as center porosity in the steel raw material cannot be compressed and rendered harmless. Therefore, the cumulative working reduction is set as 15 % or more. Although casting defects can be more effectively rendered harmless with increasing cumulative working reduction, an upper limit of approximately 30% is set for the cumulative working
25 reduction in view of manufacturability. In a situation in which the thickness is increased through hot forging in the width direction of the continuously-cast slab, the cumulative working reduction is measured from the increased thickness.

Particularly in production of a thick steel plate having a plate
30 thickness of 120 mm or more, it is preferable to ensure that at least one pass is performed with a working reduction of 5 % or more per pass in the hot forging to ensure that center porosity is rendered harmless. The working reduction per pass is more preferably 7 % or more.

[0062] Strain rate of hot forging: 3/s or less

A strain rate exceeding 3/s in the hot forging raises deformation resistance during the hot forging and thus increases the load on the forging machine, making it impossible to ensure that center porosity is rendered harmless. Therefore, the strain rate is set as 3/s or less.

5 On the other hand, a strain rate of less than 0.01/s lengthens the hot forging time, leading to lower productivity. Therefore, the strain rate is preferably 0.01/s or more. The strain rate is more preferably 0.05/s or more. The strain rate is more preferably 1/s or less.

[0063] In the disclosed techniques, the hot forging is followed by hot working
10 to obtain a steel plate of a desired plate thickness and improve strength and toughness of the mid-thickness part.

[0064] II. Conditions of hot working after forging

Reheating temperature of steel raw material after forging: Ac_3 temperature to 1250 °C

15 The steel raw material is reheated to the Ac_3 transformation temperature or higher after the hot forging to homogenize the steel as a single austenite phase. The reheating temperature is required to be at least the Ac_3 temperature and no higher than 1250 °C.

Herein, the Ac_3 transformation temperature is taken to be a value
20 calculated according to formula (2), shown below.

$$Ac_3 \text{ (}^\circ\text{C)} = 937.2 - 476.5C + 56Si - 19.7Mn - 16.3Cu - 26.6Ni - 4.9Cr + 38.1Mo + 124.8V + 136.3Ti + 198.4Al + 3315B \quad (2)$$

Each element symbol in formula (2) indicates the content, in mass%, of the corresponding alloying element in the steel.

25 [0065] Performance of hot rolling including at least two passes carried out with a rolling reduction of 4 % or more per pass

In the presently disclosed techniques, the reheating to at least the Ac_3 temperature and no higher than 1250 °C is followed by hot rolling including at least two passes carried out with a rolling reduction of 4 % or more per pass.
30 Such rolling allows sufficient working of the mid-thickness part. This can refine structure by promoting recrystallization and can contribute to improving mechanical properties. The number of passes carried out in the hot rolling is preferably 10 or less because mechanical properties improve as the number of passes is reduced.

[0066] Conditions of heat treatment after hot rolling

In the presently disclosed techniques, the steel is allowed to cool after the hot rolling, is then reheated again to at least the Ac_3 temperature and no higher than $1050\text{ }^{\circ}\text{C}$, and is subsequently rapidly cooled from the Ar_3 temperature or higher to $350\text{ }^{\circ}\text{C}$ or lower to improve strength and toughness of the mid-thickness part. The reheating temperature is set as $1050\text{ }^{\circ}\text{C}$ or lower because reheating to a high temperature exceeding $1050\text{ }^{\circ}\text{C}$ significantly reduces base metal toughness due to austenite grain coarsening.

Herein, the Ar_3 transformation temperature is taken to be a value calculated according to formula (3), shown below.

$$Ar_3\text{ (}^{\circ}\text{C)} = 910 - 310C - 80Mn - 20Cu - 15Cr - 55Ni - 80Mo \quad (3)$$

Each element symbol in formula (3) indicates the content, in mass %, of the corresponding alloying element in the steel.

[0067] The temperature of the mid-thickness part is determined by simulation calculation or the like based on the plate thickness, surface temperature, cooling conditions, and so forth. For example, the temperature of the mid-thickness part may be determined by calculating a temperature distribution in the plate thickness direction by the finite difference method.

In industry, the method of rapid cooling is normally water cooling. However, a cooling method other than water cooling, such as gas cooling or the like, may be adopted because the cooling rate is preferably as fast as possible.

[0068] Tempering temperature: $550\text{ }^{\circ}\text{C}$ to $700\text{ }^{\circ}\text{C}$

The rapid cooling is followed by tempering at at least $550\text{ }^{\circ}\text{C}$ and no higher than $700\text{ }^{\circ}\text{C}$. The reason for this is that a tempering temperature of lower than $550\text{ }^{\circ}\text{C}$ does not effectively remove residual stress, whereas a tempering temperature exceeding $700\text{ }^{\circ}\text{C}$ causes precipitation of various carbides and coarsens the structure of the base metal, leading to a significant decrease in strength and toughness. In particular, tempering at a temperature of $600\text{ }^{\circ}\text{C}$ or higher is preferable for adjusting yield strength and improving low-temperature toughness in the tempering step. Tempering at a temperature of $650\text{ }^{\circ}\text{C}$ or higher is more preferable.

[0069] In industry, there are instances in which steel is quenched repeatedly to make the steel tougher. While quenching may be performed repeatedly in

the disclosed techniques, the final quenching is required to involve heating to at least the Ac_3 temperature and no higher than 1050 °C, subsequent rapid cooling to 350 °C or lower, and subsequent tempering at at least 550 °C and no higher than 700 °C.

- 5 **[0070]** Conventional techniques struggle to achieve the excellent properties described above in a situation in which the working reduction ratio from the slab prior to working is 3 or less. However, according to the presently disclosed techniques, the desired properties can be achieved even in this situation.
- 10 **[0071]** By performing quenching and tempering as described above in production of a steel plate according to this disclosure, a steel plate having excellent strength and toughness can be produced.

EXAMPLES

- 15 **[0072]** Steels 1-32 shown in Table 1 were produced by steel making to obtain continuously-cast slabs that were then subjected to hot forging and hot rolling under the conditions shown in Table 2. The number of passes of hot rolling was 10 or less. The plate thickness after the hot rolling was in a range of 100 mm to 240 mm. After the hot rolling, quenching and tempering were
- 20 performed under the conditions shown in Table 3 to produce steel plates indicated as samples 1-44 in Tables 2 and 3. The produced steel plates were tested as follows.

[0073] (1) Tensile test

- 25 A round bar tensile test piece (Φ : 12.5 mm, GL: 50 mm) was sampled from a mid-thickness part of each of the steel plates in a direction perpendicular to the rolling direction and was used to measure yield strength (YS) and tensile strength (TS).

[0074] (2) Plate thickness direction tensile test

- 30 Three round bar tensile test pieces (ϕ 10 mm) were collected from each of the steel plates in the plate thickness direction, the reduction of area after fracture was measured, and evaluation was conducted using the smallest value of the three test pieces.

[0075] (3) Charpy impact test

Three 2 mm V notch Charpy test pieces having a longitudinal direction

corresponding to the rolling direction were collected from the mid-thickness part of each of the steel plates, absorbed energy (vE_{-60}) was measured for each test piece by a Charpy impact test at $-60\text{ }^{\circ}\text{C}$, and the average of the three test pieces was calculated.

5 **[0076]** (4) Hardness measurement

Test pieces for hardness measurement were collected from the surface and the mid-thickness part of each of the steel plates such that hardness of a cross-section parallel to the longitudinal direction of the steel plate could be measured. Each of the test pieces was embedded and polished. Thereafter, a
10 Vickers hardness meter was used to measure the hardness of three points at a surface position (position 2 mm inward from the surface) and three points at a mid-thickness position (middle position) using a load of 98 N (10 kgf). An average value for each set of three points was calculated as the average hardness of the corresponding position. The hardness difference ΔHV was
15 calculated according to: $\Delta\text{HV} = \text{average hardness of plate thickness surface} - \text{average hardness of mid-thickness part}$.

Results of the tests described above are shown in Table 3.

[0077] [Table 1]

Table 1

Steel no.		Chemical composition (mass%)																					Ac ₃	Ar ₃	Remarks	
		C	Si	Mn	P	S	Ni	Ti	Al	N	B	Cu	Cr	Mo	V	Nb	Mg	Ta	Zr	Y	Ca	REM	Ceq ^{1W}	°C		°C
1		0.081	0.15	1.6	0.008	0.0009	0.6	0.010	0.043	0.0035	0.0012	0.26	0.8	0.25	0.020	-	-	-	-	-	0.0020	-	0.62	877	687	Conforming steel
2		0.087	0.10	1.3	0.004	0.0011	0.9	0.009	0.049	0.0030	0.0011	0.22	1.0	0.31	0.025	-	-	-	-	-	-	0.0110	0.65	873	685	Conforming steel
3		0.105	0.15	1.1	0.007	0.001	1.0	0.007	0.045	0.0033	0.0011	0.24	0.7	0.43	0.041	-	-	-	-	-	0.0014	-	0.60	875	686	Conforming steel
4		0.115	0.21	1.2	0.006	0.0007	1.5	0.010	0.035	0.0029	0.0010	0.11	0.9	0.35	0.034	-	-	-	-	-	0.0015	-	0.68	854	652	Conforming steel
5		0.119	0.17	1.2	0.005	0.0009	1.9	0.012	0.041	0.0030	0.0012	0.20	1.0	0.48	0.025	0.012	-	-	-	-	0.0021	-	0.75	843	616	Conforming steel
6		0.123	0.21	1.1	0.005	0.0007	2.1	0.010	0.045	0.0027	0.0010	0.19	0.8	0.44	0.042	-	-	-	-	-	0.0013	-	0.72	841	617	Conforming steel
7		0.120	0.16	1.1	0.004	0.0006	3.4	0.005	0.066	0.0042	0.0012	0.20	0.4	0.45	0.021	-	-	-	-	-	0.0022	-	0.72	809	552	Conforming steel
8		0.122	0.19	1.2	0.003	0.0004	2.2	0.011	0.044	0.0031	0.0012	0.15	0.9	0.46	0.035	-	-	-	-	-	0.0019	-	0.75	838	606	Conforming steel
9		0.125	0.20	1.2	0.005	0.0006	2.1	0.012	0.060	0.0040	0.0010	-	1.0	0.55	0.045	-	-	-	-	-	0.0017	-	0.78	849	605	Conforming steel
10		0.115	0.17	1.1	0.005	0.0006	2.4	0.010	0.055	0.0032	0.0012	0.20	0.8	0.50	0.040	-	-	-	-	-	-	0.0051	0.74	840	598	Conforming steel
11		0.160	0.23	1.5	0.004	0.0005	2.0	0.008	0.048	0.0029	0.0009	0.20	0.8	-	-	-	-	-	-	-	0.0023	-	0.72	798	614	Conforming steel
12		0.179	0.11	0.6	0.003	0.0003	4.2	0.009	0.053	0.0025	0.0008	-	-	0.50	-	-	-	-	-	-	-	-	0.66	768	536	Conforming steel
13		0.193	0.21	0.9	0.004	0.0009	2.2	0.011	0.050	0.0028	0.0012	-	1.0	-	0.015	-	-	-	-	0.0018	-	-	0.69	793	642	Conforming steel
14		0.125	0.22	1.2	0.006	0.0005	2.0	0.009	0.045	0.0024	-	0.15	0.7	0.42	0.043	-	-	-	-	0.0016	-	-	0.69	839	619	Conforming steel
15		0.119	0.24	1.1	0.005	0.0008	1.9	0.012	0.005	0.0025	0.0011	0.21	0.9	0.50	0.045	-	-	-	-	0.0015	-	-	0.73	845	623	Conforming steel
16		0.120	0.04	0.6	0.003	0.0006	0.1	0.010	0.027	0.0039	0.0009	-	1.8	0.87	0.090	-	-	-	-	-	-	-	0.78	913	723	Conforming steel

Values for Ceq^{1W}, Ac₃, and Ar₃ were calculated according to formulae (1) to (3) in the specification
Underlining indicates deviation from the scope of this disclosure

Table 1 (cont'd)

Table 1 (cont'd)																										
Steel		Chemical composition (mass%)																				Ac ₃	Remarks			
no.	C	Si	Mn	P	S	Ni	Ti	Al	N	B	Cu	Cr	Mo	V	Nb	Mg	Ta	Zr	Y	Ca	REM	Ceq ^{IIW}	°C	°C		
17	0.123	0.13	1.1	0.003	0.0004	1.8	0.011	0.035	0.0028	0.0012	0.20	0.9	0.50	0.045	-	0.0020	-	-	-	0.0017	-	0.73	846	627	Conforming steel	
18	0.129	0.24	1.2	0.005	0.0012	0.9	0.008	0.004	0.0022	0.0006	0.25	1.0	0.45	-	-	-	0.055	-	-	0.0013	-	0.70	854	669	Conforming steel	
19	0.139	0.17	1.3	0.006	0.0009	1.5	0.009	0.004	0.0028	0.0009	0.30	0.6	0.50	0.004	-	-	-	0.007	-	0.0020	-	0.70	832	625	Conforming steel	
20	0.110	0.28	1.1	0.006	0.001	0.5	0.010	0.040	0.0030	0.0010	0.21	0.7	0.44	0.150	-	-	-	-	0.004	0.0010	-	0.60	907	711	Conforming steel	
21	0.122	0.21	0.7	0.005	0.0008	1.0	0.009	0.035	0.0028	0.0006	0.25	0.9	0.45	0.060	0.009	-	-	-	-	-	-	0.60	877	707	Conforming steel	
22	<u>0.228</u>	0.25	1.3	0.005	0.0009	0.6	0.009	0.043	0.0030	0.0012	0.35	1.1	0.44	0.038	-	-	-	-	-	-	-	<u>0.82</u>	825	644	Comparative steel	
23	0.152	<u>0.56</u>	1.0	0.006	0.0006	0.9	0.010	0.044	0.0032	0.0015	0.17	0.9	0.52	-	-	-	-	-	-	-	-	0.67	880	675	Comparative steel	
24	0.105	0.40	<u>0.3</u>	0.009	0.0015	1.1	0.009	0.050	0.0030	0.0012	0.22	1.3	0.58	0.035	-	-	-	-	-	0.0021	-	0.63	906	723	Comparative steel	
25	0.136	0.35	1.2	<u>0.019</u>	0.0012	0.5	0.011	0.045	0.0038	0.0009	0.26	1.0	0.52	0.045	-	-	-	-	-	-	0.0097	0.70	885	683	Comparative steel	
26	0.144	0.15	1.3	0.011	<u>0.007</u>	1.2	0.011	0.025	0.0055	0.0006	0.13	1.1	0.44	0.039	-	-	-	-	-	0.0011	-	0.77	842	641	Comparative steel	
27	0.082	0.26	1.6	0.006	0.0005	1.6	<u>0.003</u>	0.050	0.0040	0.0005	-	0.6	0.35	-	-	-	-	-	-	0.0023	-	0.65	861	632	Comparative steel	
28	0.093	0.29	1.0	0.005	0.0007	1.5	<u>0.024</u>	0.035	0.0041	0.0008	-	0.9	0.41	0.010	-	-	-	-	-	-	-	0.62	875	672	Comparative steel	
29	0.122	0.26	1.1	0.006	0.0009	1.5	0.011	<u>0.095</u>	0.0039	0.0006	0.44	1.0	0.44	-	-	-	-	-	-	0.0023	-	0.72	859	643	Comparative steel	
30	0.120	0.26	1.1	0.007	0.001	2.0	0.006	0.040	<u>0.0085</u>	0.0005	0.33	0.7	0.60	-	-	-	-	-	-	-	-	0.72	844	610	Comparative steel	
31	0.130	0.26	1.1	0.008	0.0011	2.1	0.008	0.044	0.0030	<u>0.0040</u>	0.26	0.8	0.50	-	-	-	-	-	-	0.0023	-	0.73	846	609	Comparative steel	
32	0.105	0.17	0.8	0.014	0.0015	1.2	0.012	0.035	0.0030	0.0009	0.17	0.5	0.35	0.020	-	-	-	-	-	0.0016	-	0.50	871	709	Comparative steel	

Values for Ceq^{IIW}, Ac₃, and Ar₃ were calculated according to formulae (1) to (3) in the specification
Underlining indicates deviation from the scope of this disclosure

[0078] [Table 2]

Table 2

Sample no.	Steel no.	Slab thickness (mm)	Hot forging								Hot rolling		Rolling conditions (*1)	Plate thickness (mm)	Working reduction ratio from slab
			Heating temperature (°C)	Working start temperature (°C)	Working end temperature (°C)	Cumulative working reduction (%)	Strain rate (/s)	Maximum working reduction per pass (%)	Width direction working	Die shape ratio	Reheating temperature (°C)	Rolling reduction (%)			
1	1	250	1200	1155	1020	20	0.1	10	Yes	1.1	1150	55	Conforming	100	2.5
2	2	250	1270	1160	1120	15	0.1	7	No	1.1	1150	39	Conforming	130	1.9
3	3	310	1200	1170	1020	15	0.1	5	No	1.5	1100	51	Conforming	130	2.4
4	4	450	1250	1235	1060	15	0.1	10	Yes	1.5	1200	45	Conforming	210	2.1
5	5	310	1270	1245	1120	20	0.1	10	Yes	1.5	1130	45	Conforming	150	2.1
6	6	310	1270	1240	1120	20	0.1	10	Yes	1.5	1130	32	Conforming	180	1.7
7	7	310	1270	1245	1100	20	0.1	10	Yes	1.5	1170	20	Conforming	210	1.5
8	8	310	1200	1165	1050	20	0.1	5	No	1.5	1130	27	Conforming	180	1.7
9	9	450	1270	1250	1080	15	0.1	10	Yes	2.5	1200	42	Conforming	240	1.9
10	10	310	1250	1220	1120	20	0.1	7	No	1.5	1150	27	Conforming	180	1.7
11	11	310	1250	1215	1150	20	0.1	7	No	1.5	1150	40	Conforming	150	2.1
12	12	310	1270	1245	1100	20	0.1	10	Yes	2.0	1200	32	Conforming	180	1.7
13	13	310	1300	1270	1150	20	0.1	10	Yes	2.0	1200	45	Conforming	150	2.1
14	14	250	1200	1160	1050	15	0.1	5	No	1.5	1130	53	Conforming	100	2.5
15	15	310	1270	1235	1100	20	0.1	10	Yes	1.5	1170	45	Conforming	150	2.1
16	16	450	1270	1255	1050	15	0.1	10	Yes	1.5	1200	50	Conforming	210	2.1
17	17	310	1200	1165	1050	20	0.1	5	No	1.5	1130	40	Conforming	150	2.1
18	18	310	1270	1235	1050	15	0.1	10	Yes	1.5	1170	56	Conforming	130	2.4
19	19	310	1270	1245	1100	20	0.1	10	Yes	1.5	1200	53	Conforming	130	2.4
20	20	250	1200	1135	1050	15	0.1	5	No	1.5	1130	53	Conforming	100	2.5
21	21	250	1270	1150	1050	20	0.1	10	No	1.5	1130	50	Conforming	100	2.5
22	22	310	1200	1165	1030	15	0.1	5	No	1.5	1100	32	Conforming	180	1.7

(*1) "Conforming" indicates that at least two passes were carried out with a rolling reduction of 4% or more per pass
Underlining indicates deviation from the scope of this disclosure

Table 2 (cont'd)

Sample no.	Steel no.	Slab thickness (mm)	Hot forging						Hot rolling		Rolling conditions (*1)	Plate thickness (mm)	Working reduction ratio from slab
			Heating temperature (°C)	Working start temperature (°C)	Working end temperature (°C)	Cumulative working reduction (%)	Strain rate (/s)	Maximum working reduction per pass (%)	Width direction working	Die shape ratio	Reheating temperature (°C)	Rolling reduction (%)	
23	23	250	1200	1145	1050	15	0.1	10	Yes	1.1	1150	58	Conforming
24	24	250	1200	1150	1050	15	0.1	10	Yes	1.1	1150	58	Conforming
25	25	310	1270	1235	1100	20	0.1	10	Yes	1.5	1200	45	Conforming
26	26	310	1270	1240	1100	20	0.1	10	Yes	1.5	1170	45	Conforming
27	27	310	1270	1250	1100	20	0.1	10	Yes	1.5	1200	45	Conforming
28	28	310	1270	1250	1100	20	0.1	10	Yes	1.5	1130	45	Conforming
29	29	310	1270	1245	1100	20	0.1	10	Yes	1.5	1170	45	Conforming
30	30	310	1270	1235	1100	20	0.1	10	Yes	1.5	1200	45	Conforming
31	31	310	1270	1235	1100	20	0.1	10	Yes	1.5	1200	32	Conforming
32	32	310	1270	1250	1100	20	0.1	10	Yes	1.5	1200	32	Conforming
33	5	310	1050	1005	850	15	0.1	3	No	1.5	1150	43	Conforming
34	5	310	1200	1165	900	15	0.1	4	Yes	1.5	1150	48	Conforming
35	5	310	1200	1165	1050	7	0.1	4	No	1.5	1150	48	Conforming
36	5	310	1200	1170	1050	15	10	8	No	1.5	1100	43	Conforming
37	6	310	1250	1215	1050	15	0.1	8	Yes	1.5	800	48	Conforming
38	6	310	1270	1250	1050	20	0.1	10	Yes	1.5	1150	32	Conforming
39	6	310	1270	1235	1050	20	0.1	5	Yes	1.5	1150	32	Conforming
40	6	310	1270	1260	1050	20	0.1	5	Yes	1.5	1100	32	Conforming
41	6	310	1270	1245	1050	20	0.1	10	Yes	1.5	1100	32	Conforming
42	6	310	1270	1240	1050	20	0.1	5	Yes	1.5	1100	32	Conforming
43	6	310	1270	1235	1050	20	0.1	10	No	1.0	1100	27	Conforming
44	6	310	1270	1245	1050	20	0.1	10	Yes	1.5	1150	32	<u>Non-conforming</u>

(*1) "Conforming" indicates that at least two passes were carried out with a rolling reduction of 4% or more per pass
Underlining indicates deviation from the scope of this disclosure

[0079] [Table 3]

Table 3

Sample no.	Steel no.	Heat treatment conditions of final heat treatment					Base metal properties					Remarks
		Reheating temperature (°C)	Holding time (min)	Cooling end temperature (°C)	Tempering temperature (°C)	Tempering time (min)	YS (MPa)	TS (MPa)	v_{E-60} (J)	Plate thickness direction tension reduction of area (%)	Hardness difference ΔHV (-)	
1	1	1000	10	150	670	30	517	738	126	60	25	Example
2	2	900	30	100	670	40	539	653	164	70	21	Example
3	3	900	30	100	645	90	542	634	155	75	23	Example
4	4	900	30	100	660	30	535	654	136	65	24	Example
5	5	900	30	150	645	80	547	670	167	70	25	Example
6	6	900	30	100	670	40	613	694	168	70	26	Example
7	7	900	30	100	655	50	608	669	154	60	24	Example
8	8	850	30	100	660	50	567	697	133	60	26	Example
9	9	900	60	100	660	60	576	657	126	70	27	Example
10	10	900	30	200	660	50	571	664	146	75	28	Example
11	11	900	30	100	650	60	556	697	156	60	26	Example
12	12	900	30	100	660	60	568	664	136	75	24	Example
13	13	900	30	150	660	60	550	710	135	65	26	Example
14	14	900	10	100	670	40	572	694	178	65	26	Example
15	15	900	30	150	670	40	565	633	163	65	25	Example
16	16	950	60	100	670	30	590	655	145	55	26	Example
17	17	900	30	150	670	30	525	625	167	55	27	Example
18	18	900	30	100	650	60	568	663	142	60	21	Example
19	19	950	30	100	650	60	557	669	146	65	24	Example
20	20	900	30	150	650	60	552	662	156	60	23	Example
21	21	900	30	100	650	60	614	684	146	65	21	Example
22	22	900	30	100	660	50	621	765	37	45	29	Comparative Example

Underlining indicates deviation from the scope of this disclosure

Table 3 (cont'd)

Sample no.	Steel no.	Heat treatment conditions of final heat treatment					Base metal properties					Remarks
		Reheating temperature (°C)	Holding time (min)	Cooling end temperature (°C)	Tempering temperature (°C)	Tempering time (min)	YS (MPa)	TS (MPa)	σ_{E-60} (J)	Plate thickness direction tension reduction of area (%)	Hardness difference Δ HV (-)	
23	<u>23</u>	900	30	150	650	60	602	669	<u>36</u>	75	24	Comparative Example
24	<u>24</u>	900	10	150	670	30	462	607	<u>36</u>	70	23	Comparative Example
25	<u>25</u>	900	30	150	670	30	527	633	<u>35</u>	65	24	Comparative Example
26	<u>26</u>	900	30	150	670	30	561	680	<u>25</u>	70	26	Comparative Example
27	<u>27</u>	900	30	150	670	30	536	681	<u>26</u>	65	34	Comparative Example
28	<u>28</u>	900	30	150	670	30	555	689	<u>24</u>	65	36	Comparative Example
29	<u>29</u>	900	30	150	650	60	539	704	<u>25</u>	65	24	Comparative Example
30	<u>30</u>	900	30	150	660	60	532	694	<u>32</u>	65	26	Comparative Example
31	<u>31</u>	900	30	100	660	50	526	661	<u>33</u>	60	24	Comparative Example
32	<u>32</u>	900	30	100	660	60	454	542	<u>45</u>	65	45	Comparative Example
33	5	900	30	150	650	60	517	679	105	20	26	Comparative Example
34	5	900	30	150	650	60	539	621	88	<u>15</u>	25	Comparative Example
35	5	900	30	100	660	50	552	681	83	<u>25</u>	24	Comparative Example
36	5	900	30	150	660	50	572	695	91	<u>20</u>	24	Comparative Example
37	6	900	30	100	670	30	579	616	<u>22</u>	45	26	Comparative Example
38	6	<u>1100</u>	10	150	650	60	625	722	<u>32</u>	65	24	Comparative Example
39	6	<u>750</u>	30	100	650	60	463	533	146	60	20	Comparative Example
40	6	900	30	<u>480</u>	650	60	<u>378</u>	576	<u>28</u>	55	24	Comparative Example
41	6	900	30	150	<u>730</u>	30	<u>462</u>	560	170	60	26	Comparative Example
42	6	900	30	150	400	60	596	759	<u>65</u>	55	35	Comparative Example
43	6	900	30	150	650	60	537	702	175	<u>25</u>	26	Comparative Example
44	6	900	30	150	660	60	512	636	<u>26</u>	45	28	Comparative Example

Underlining indicates deviation from the scope of this disclosure

[0080] It can be seen from Table 3 that for each steel plate obtained in accordance with this disclosure (samples 1-21), YS was 500 MPa or more, TS was 610 MPa or more, base metal toughness ($\sqrt{E_{-60}}$) was 70 J or more, reduction of area in the plate thickness direction tensile test was 40 % or more, and the hardness difference ΔHV was 30 or less. Accordingly, each of these steel plates had excellent base metal strength, toughness, plate thickness direction tensile properties, and material homogeneity.

In contrast, it can be seen that at least one of these properties was poor in each of samples 22-44 having a chemical composition or production conditions outside of the suitable ranges.

REFERENCE SIGNS LIST

[0081]	1	upper die
	2	lower die
15	3	slab

CLAIMS

1. A high toughness and high tensile strength thick steel plate having a plate thickness of 100 mm or more with excellent material homogeneity,
- 5 having a chemical composition containing, in mass%,
- C: 0.08 % to 0.20 %,
Si: 0.40 % or less,
Mn: 0.5 % to 5.0 %,
P: 0.015 % or less,
- 10 S: 0.0050 % or less,
Ni: 5.0 % or less,
Ti: 0.005 % to 0.020 %,
Al: 0.080 % or less,
N: 0.0070 % or less,
- 15 B: 0.0030 % or less, and
one or more selected from
- Cu: 0.50 % or less,
Cr: 3.0 % or less,
Mo: 1.50 % or less,
- 20 V: 0.200 % or less, and
Nb: 0.100 % or less,
- the balance being Fe and incidental impurities, wherein
a value Ceq^{IIW} defined by formula (1) below is 0.55 to 0.80:
- $$Ceq^{IIW} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5 \quad (1)$$
- 25 where each element symbol indicates content, in mass %, of a corresponding element in the chemical composition and is taken to be 0 when the corresponding element is not contained,
- a mid-thickness part of the steel plate has a yield strength of 500 MPa or more,
- 30 reduction of area in the mid-thickness part by tension in a plate thickness direction is 40 % or more, and
- the mid-thickness part has a low-temperature toughness at -60°C of 70 J or more.

2. The high toughness and high tensile strength thick steel plate with excellent material homogeneity of claim 1, wherein

the chemical composition further contains, in mass%, one or more selected from

- 5 Mg: 0.0005 % to 0.0100 %,
 Ta: 0.01 % to 0.20 %,
 Zr: 0.005 % to 0.1 %,
 Y: 0.001 % to 0.01 %,
 Ca: 0.0005 % to 0.0050 %, and
10 REM: 0.0005 % to 0.0200 %.

3. The high toughness and high tensile strength thick steel plate with excellent material homogeneity of claim 1 or 2, wherein

 in a hardness distribution in the plate thickness direction, a difference
15 Δ HV between average hardness of a plate thickness surface (HVS) and average hardness of the mid-thickness part (HVC), where Δ HV = HVS – HVC, is 30 or less.

4. A production method for the high toughness and high tensile
20 strength thick steel plate with excellent material homogeneity of any one of claims 1 to 3, comprising

 heating a continuously-cast slab having the chemical composition in claim 1 or 2 to at least 1200 °C and no higher than 1350 °C,

 then hot forging the continuously-cast slab under conditions of a
25 temperature of 1000 °C or higher, a strain rate of 3/s or less, and a cumulative working reduction of 15 % or more using opposing dies having respective short sides differing such that when a short side length of a die having a shorter one of the short sides is taken to be 1, a short side length of a die having a longer one of the short sides is 1.1 to 3.0,

30 then allowing cooling to obtain a steel raw material,

 then reheating the steel raw material to at least an A_{c3} temperature and no higher than 1250 °C,

 then performing hot rolling of the steel raw material including at least two passes carried out with a rolling reduction of 4 % or more per pass,

then allowing cooling to obtain a thick steel plate,
then reheating the thick steel plate to at least the Ac_3 temperature and
no higher than 1050 °C,
then rapidly cooling the thick steel plate to 350 °C or lower, and
5 then tempering the thick steel plate at at least 550 °C and no higher
700 °C.

5. The production method of claim 4, wherein
a working reduction ratio from the continuously-cast slab prior to
10 working to the thick steel plate obtained after the hot rolling in production of
the high toughness and high tensile strength thick steel plate is 3 or less.