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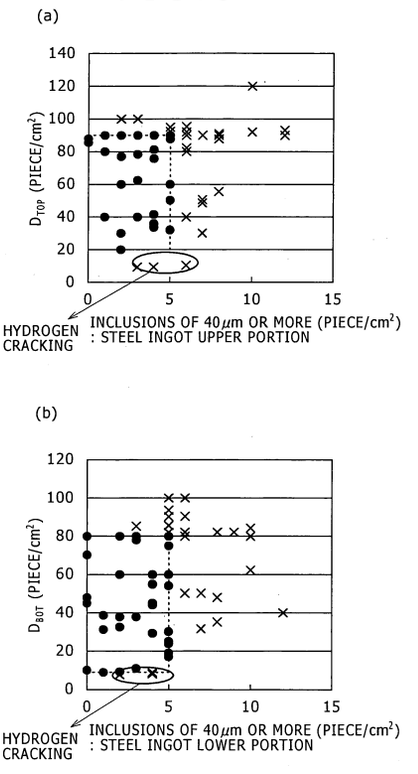
(54) STEEL INGOT FOR FORGING AND INTEGRAL CRANKSHAFT

(57) The present invention provides a forging steel ingot and a solid type crankshaft excellent in both fatigue properties and hydrogen cracking resistance.

A forging steel ingot cast with a mold is produced wherein: the number density (D_{BOT}) of inclusions 5 to 10 μm in longest diameter observed on a steel cross-section is 10 to 80 pieces/cm^2 at the steel ingot lower portion; the number density (D_{TOP}) of inclusions 5 to 10. μm in longest diameter observed on a steel cross-section is 20 to 90 pieces/cm^2 at the steel ingot upper portion; the number density of inclusions 40 μm or more in longesf diameter observed on a steel cross-section is 5 pieces/cm^2 or less at both the steel ingot lower portion and the steel ingot upper portion; and the expression (D_{TOP}) /(D_{BOT}) ≥ [S (ppm)]/18 is satisfied. A solid type crankshaft is produced by hot-forging the forging steel ingot.

FIG. 8



EP 2 141 254 A1

Description

Technical Field

[0001] The present invention relates to a forging steel ingot and a solid type crankshaft produced from the forging steel ingot. The forging steel ingot and solid type crankshaft according to the present invention: are used widely and effectively in the industrial areas of machines, ships, electrical generators, and others; and are suitable particularly for parts requiring high fatigue strength such as rotational movement parts.

Background Art

[0002] Patent Document 1 (JP-A No. 336092/2006) describes a forging steel ingot wherein, with the aim of improving the hydrogen cracking resistance of a crankshaft for a ship: the average of roundness (hereunder referred to as an average roundness) of the inclusions contained in steel having a maximum chord length of 1 μm or more is 0.5 or more; the number of inclusions having a maximum chord length of 20 μm or more is less than 40 pieces per 100 mm^2 and the average roundness thereof is 0.25 or more; and the number of inclusions having a maximum chord length of 1 to 10 μm is 100 pieces or more per 100 mm^2

[0003] Patent Document 2 (JP-ANo. 194502/2002) describes a steel, with the aim of improving the machinability and wear resistance of a crankshaft: comprising C: 0.62 to 0.80%, Si: 0.60% or less, Mn: 0.30 to 1.80%, S: 0.04 to 0.35%, Cr: 0.05 to 0.50%, Al: less than 0.005%, and O: 0.0020% or less, with the remainder composed of Fe and unavoidable impurities; after hot forging, being mainly composed of pearlite having a pro-eutectoid ferrite fraction of 3% or less; and containing sulfide-type inclusions 20 μm or less in thickness.

Disclosure of the Invention

[0004] Recent problems of parts for ships are hydrogen cracking caused by hydrogenous defects and the deterioration of fatigue strength caused by inclusion-type defects. By the aforementioned conventional technologies however, even though a forging steel ingot excellent in machinability and wear resistance can be produced, a forging steel ingot having a fatigue strength enough to hardly fracture even under a harsh usage environment and a sufficiently good hydrogen cracking resistance has not been produced. The present invention has been established in view of the above circumstances and an object of the present invention is to provide a forging steel ingot and a solid type crankshaft excellent in both fatigue properties and hydrogen cracking resistance.

[0005] As a usual measure for preventing hydrogen cracking, MnS-type inclusions to trap hydrogen in a steel are distributed in the steel. The MnS-type inclusions however deteriorate the fatigue strength of the steel although they improve hydrogen cracking resistance. Consequently, it is very difficult to simultaneously improve both the hydrogen cracking resistance and fatigue strength having the relationship of tradeoff.

[0006] Under such circumstances, the present inventors have found that the content of hydrogen in steel causing hydrogen cracking is higher at the upper portion than at the lower portion in a steel ingot. As a result of additional studies, the present inventors: have ascertained that the hydrogen cracking of a forging steel ingot can be prevented without deteriorating the fatigue strength of the steel ingot when the ratio of a number density of inclusions at a steel ingot upper portion to a number density of inclusions at a steel ingot lower portion and the content of S (sulfur) closely related to the forming of inclusions satisfy a certain relationship; and have established the present invention.

[0007] A forging steel ingot according to the present invention that attains the aforementioned object is a forging steel ingot cast with a mold wherein: the number density D_{BOT} of inclusions 5 to 10 μm in longest diameter observed on a steel cross-section is 10 to 80 pieces/cm^2 at the steel ingot lower portion ranging from the bottom end of the steel ingot to the bottom 20% of the total height of the steel ingot in the direction of the gravity; the number density D_{TOP} of inclusions 5 to 10 μm in longest diameter observed on the steel cross-section is 20 to 90 pieces/cm^2 at the steel ingot upper portion ranging from the top end of the steel ingot to the top 20% of the total height of the steel ingot; the number density of inclusions 40 μm or more in longest diameter observed on the steel cross-section is 5 pieces/cm^2 or less at both the steel ingot lower portion and the steel ingot upper portion; and the following expression (1) is satisfied.

[0008]

[Expression 1]

$$(D_{TOP})/(D_{BOT}) \geq [S]/18 \qquad (1),$$

here, [S] represents the content (in mass ppm) of S in steel.

[0009] It is recommended that the above forging steel ingot comprises
C: 0.2 to 0.6% (in mass %, the same is applied hereunder),
Si: 0.05 to 0.5%,
Mn: 0.2 to 1.2%,
Ni: 0.1 to 3.5%,
Cr: 0.9 to 2.5%,
Mo: 0.1 to 0.7%,
V: 0.005 to 0.2%,
Al: 0.01 to 0.1%,
S: 0.005% or less,
Ti: 0.005% or less, and
O: 0.0015% or less,
with the remainder composed of iron and unavoidable impurities.

[0010] A solid type crankshaft according to the present invention that attains the aforementioned object is produced by hot-forging the aforementioned forging steel ingot.

[0011] The present inventionmakes it possible to produce a forging steel ingot excellent in fatigue properties and hydrogen cracking resistance by: adjusting the number density of fine inclusions at a steel ingot lower portion, the number density of fine inclusions at a steel ingot upper portion, and the number density of coarse inclusions at both the steel ingot lower portion and the steel ingot upper portion; and satisfying the ratio of the number density of inclusions between the steel ingot upper portion and the steel ingot lower portion and an S content in steel with a certain relationship. Then, by hot-forging the forging steel ingot, it is possible to produce a solid type crankshaft excellent in fatigue properties and hydrogen cracking resistance.

[0012] For example, although a current crankshaft is supposed to undergo a load corresponding to an output of 2,000 kW per a cylinder, a future crankshaft for a large vessel is required to have fatigue properties withstanding the downsizing and weight reduction of an engine aiming at the improvement of fuel efficiency. An endurance limit ratio (fatigue strength/tensile strength) of 0.45 or more is required in order to meet with the above requirements regardless of the size of the crankshaft. The present invention makes it possible to provide a crankshaft satisfying the above requirements.

Brief Description of the Drawings

[0013]

Fig. 1 is a view showing the state of the solidification of a steel ingot produced by an ingot-making method.
Fig. 2 is a view showing a steel ingot produced by an ingot-making method.
Fig. 3 is an SEM photograph of a steel cross-section observed at a magnification of 2,000.
Fig. 4 is an SEM photograph of a steel cross-section observed at a magnification of 200.
Fig. 5 is an SEM photograph of a steel cross-section observed at a magnification of 200.
Fig. 6 is a graph showing hydrogen contents at steel ingot upper portions and steel ingot lower portions.
Fig. 7 is a graph showing the evaluation results on the hydrogen cracking and endurance limit ratios of steel ingots; the ratio of fine inclusions between a steel ingot upper portion and a steel ingot lower portion is shown along the vertical axis, and an S content in steel is shown along the horizontal axis.
Figs. 8 comprise graphs showing the evaluation of the endurance limit ratios of steel ingots and the occurrence of hydrogen cracking;
Fig. 8(a) shows the results at steel ingot upper portions and Fig. 8(b) shows the results at steel ingot lower portions.

Best Mode for Carrying Out the Invention

[0014] In a steel ingot produced by an ingot-making method, the number density of inclusions increases at a steel ingot lower portion that is a precipitation crystal zone and at a steel ingot upper portion that is a final solidification site as shown in Fig. 1. Consequently, the steel ingot lower portion and the steel ingot upper portion: are the portions that markedly affect the hydrogen cracking resistance and fatigue properties of a steel ingot; and are suitable as the portions for specifying the characteristics of the steel ingot.

[0015] Here in the present invention, as shown in Fig. 2: a steel ingot lower portion is defined as the portion ranging from the bottom end of a steel ingot to the bottom 20% of the total height of the steel ingot in the direction of the gravity (when a precipitation crystal zone appears, inclusions existing at the precipitation crystal zone are also taken into consideration in the above portion); and a steel ingot upper portion is defined as the portion ranging from the top end of the steel ingot to the top 20% of the total height of the steel ingot, respectively.

[0016] (Number density of fine inclusions at a steel ingot lower portion (D_{BOT}): 10 to 80 pieces/cm^2)
It is possible to improve hydrogen cracking resistance by dispersing fine inclusions in steel as stated above but, in order to exhibit the effect effectively, it is necessary to control the fine inclusions (5 to 10 μm in longest diameter) observed on a steel cross-section at a steel ingot lower portion to not less than 10 pieces/cm^2 (preferably not less than 20 pieces/cm^2, and yet preferably not less than 30 pieces/cm^2) . In contrast, even fine inclusions, if they are contained excessively, as shown in the scanning electron micrographs in Figs. 3 to 5, inclusion clusters are formed and act as the origins of fatigue fracture in the same way as coarse inclusions. Consequently, it is necessary to control the fine inclusions observed on the steel cross-section to not more than 80 pieces/cm^2 (preferably not more than 70 pieces/cm^2, and yet preferably not more than 60 pieces/cm^2).

[0017] In fact, inclusions of less than 5 μm also have hydrogen cracking resistance and hence the inclusions of less than 5 μm may be counted as fine inclusions. Since the inclusions of less than 5 μm have nearly the same distribution characteristic as the inclusions of 5 to 10 μm however, it is enough to count the number of inclusions of 5 to 10 μm in order to evaluate hydrogen cracking resistance. Consequently, the inclusions of less than 5 μm are excluded from an object of the count and thereby the convenience of additional tests is improved.

(Number density of fine inclusions at a steel ingot upper portion (D_{TOP}): 20 to 90 pieces/cm^2)

[0018] At a steel ingot upper portion, it is necessary to control the fine inclusions (5 to 10 μm in longest diameter) observed on a steel cross-section to not less than 20 pieces/cm^2 (preferably not less than 30 pieces/cm^2, and yet preferably not less than 40 pieces/cm^2). In contrast as stated above, even fine inclusions, if they are contained excessively, inclusion clusters are formed and act as the origins of fatigue fracture in the same way as coarse inclusions. Consequently, it is necessary to control the fine inclusions observed on the steel cross-section to not more than 90 pieces/cm^2 (preferably not more than 80 pieces/cm^2, and yet preferably not more than 70 pieces/cm^2).

(Number density of coarse inclusions: 5 pieces/cm^2 or less)

[0019] Coarse inclusions act as origins of fatigue fracture and hence it is necessary to control the coarse inclusions (not less than 40 μm in longest diameter) observed on a steel cross-section to not more than 5 pieces/cm^2 (preferably not more than 4 pieces/cm^2, and yet preferably not more than 3 pieces/cm^2) at both the steel ingot upper portion and the steel ingot lower portion.

[0020]

$$((D_{TOP})/(D_{BOT}) \geq [S]/18)$$

The present inventors investigated the hydrogen content in a steel ingot and found that the hydrogen content was higher at the steel ingot upper portion than at the steel ingot lower portion as shown in Fig. 6. Further, the hydrogen cracking resistance and the endurance limit ratio at the steel ingot upper portion were also investigated. The results are shown in Fig. 7. In Fig. 7, (D_{TOP}) / (D_{BOT}) is shown along the vertical axis and [S] is shown along the horizontal axis, and a case where a hydrogen cracking resistance and an endurance limit ratio satisfy certain criteria is rated as the symbol "•" and a case where they do not satisfy the certain criteria is rated as the symbol "×", and the cases are shown in the figure. The criteria for the judgment are the same as the judgment criteria of the "comprehensive evaluation" in Tables 1 to 3 described later.

[0021] [S] represents the content (mass ppm) of S in steel. It is understood from Fig. 7 that, interposing the straight line defined by the expression (D_{TOP})/(D_{BOT}) = [S]/18 in between, the cases of the symbol "•" appear on the upper side of the straight line and the cases of the symbol "×" appear on the lower side of the straight line, respectively.

[0022] Fig. 7 shows that, in the region where an S content in steel is high, when a value (D_{TOP}) / (D_{BOT}) increases, namely when a fine inclusion content increases at a steel ingot upper portion in comparison with at a steel ingot lower portion, hydrogen cracking occurs at the steel ingot upper portion. It is noteworthy however that, in the region where an S content in steel is low, the hydrogen cracking does not occur even when a value (D_{TOP})/(D_{BOT}) is not' high. For example, the hydrogen cracking does not occur even when the value (D_{TOP})/(D_{BOT}) is less than one.

[0023] For example, whereas the allowable value of hydrogen in steel is 1.5 ppm in the case where an S content in the steel is 0.003%, the allowable hydrogen value is as very low as 1.0 ppm in the case where an S content is 0.001%. Generally, when one crankshaft is produced from one steel ingot, the range of hydrogen value is roughly from 0.5 to 1.8 ppm.

[0024] As it will be stated later, the present inventors have made it possible to control the hydrogen value to not more than 1.2 ppm and hence it is possible to produce a forging steel ingot without causing hydrogen cracking even when

the S content is 0.003% or less. As a result, there arises room for further reducing the S content.

[0025] Generally hydrogen cracking tends to occur when the S content is reduced in order to improve fatigue properties but, from Fig. 7, the hydrogen cracking resistance and the fatigue properties can be maintained even when the S content is reduced as long as the condition $(D_{TOP})/(D_{BOT}) \geq [S]/18$ is satisfied. Thereby, it is estimated that the balance between the fatigue properties and the hydrogen cracking resistance in a steel ingot can be improved better than ever.

(Hot forging)

[0026] A forging steel ingot obtained through the above ingot-making process is successively formed into a shape of an intermediate product such as a round bar by hot forging. After the forming, intermediate inspections on compositions, defects, cleanliness, and others are carried out and thereafter, by applying hot forging again, the intermediate product is formed into the shape of a large product such as a solid type crankshaft, a journal, or the like. Successively, after heat treatment is applied in accordance with required product properties, finishing treatment is applied by machining and a final product is produced.

[0027] The following processes are quoted as a concrete procedure for producing a solid type crankshaft from the above forging steel ingot. That is, a completely solidified steel ingot is taken out from a mold and, as preparation for applyinghot forging, heated to preferably 1,150˚C or higher, yet preferably 1,180˚C or higher, and yet still preferably 1,200˚C or higher. Successively, the steel ingot is hot-forged into a round bar or a stepped shape at a forging ratio of 3 or more. On the occasion of the steel ingot forging, the steel ingot may be upset in the direction of the steel ingot height and thereafter subjected to extend forging to a prescribed length in order to compress internal defects. After hot forging, the intermediate product is processed into the shape of a solid type crankshaft. Here, in the event of the forging for forming of the solid type crankshaft, either throws may be formed one by one or a plurality of throws may be formed simultaneously by blocking the whole body. After the forging forming, a solid type crankshaft of a prescribed size is produced by machining for finishing. Otherwise a solid type crankshaft may be produced by forming into a stepped shape through hot forging and thereafter applying machining. Still otherwise the solid type crankshaft maybe structured so as to have a flange on one end of the crankshaft or flanges on both the ends thereof. The number of throws is 3 to 12 for example.

(Chemical compositions in steel ingot)

[0028] Although the present invention is characterized by controlling the size and number density of inclusions existing in a steel as explained above and the basic composition of the steel is not particularly limited, in order to satisfy strength, toughness, and moreover fatigue properties required of a crankshaft for example, it is desirable to satisfy the following basic composition in consideration of the general technological level on steel.

(C: 0.2 to 0.6%)

[0029] C is an element contributing to the improvement of strength and, in order to give sufficient strength to a crankshaft, C may be contained, for example, by: 0.2% or more; preferably 0.25% or more; and yet preferably 0.3% or more. If the C content is excessive however, the toughness of the crankshaft deteriorates, and hence C is controlled, for example, to: 0.6% or less; preferably 0.55% or less; and yet preferably 0.5% or less.

(Si: 0.05 to 0.5%)

[0030] Si functions as a strength improving element and, in order to give sufficient strength to a crankshaft, Si may be contained, for example, by: 0.05% or more; preferably 0.1% or more; and yet preferably 0.15% or more. If Si is excessive however, inverted-V-shaped segregation becomes marked and a clean steel ingot is hardly obtained, and hence Si is controlled, for example, to: 0.5% or less; preferably 0.45% or less; and yet preferably 0.4% or less.

(Mn: 0.2 to 1.2%)

[0031] Mn is an element enhancing hardenability and also contributing to the improvement of strength and, in order to secure both sufficient strength and hardenability, Mn is desirably contained, for example, by: 0.2% or more; preferably 0.5% or more; and yet preferably 0.8% or more. If Mn is excessive however, inverted-V-shaped segregation may be furthered in some cases, and hence Mn is controlled, for example, to: 1.2% or less; preferably 1.1% or less; and yet preferably 1% or less.

(Ni: 0.1 to 3.5%)

[0032] Ni is useful as a toughness improving element and it is recommended to contain Ni, for example, by: 0.1% or more; and preferably 0.2% or more. If the Ni amount is excessive however, the cost increases, and hence Ni is controlled to: 3.5% or less; and preferably 3% or less.

(Cr: 0.9 to 2.5%).

[0033] Cr is an element effective in enhancing hardenability and improving toughness and, in order to exhibit such functions, Cr is contained, for example, by: 0.9% or more; preferably 1.1% or more; and yet preferably 1.3% or more. If Cr is excessive however, inverted-V-shaped segregation may be furthered and a high cleanliness steel is hardly produced in some cases, and hence Cr is controlled, for example, to: 2.5% or less; preferably 2.3% or less; andyetpreferably 2.1% or less.

(Mo: 0.1 to 0.7%)

[0034] Mo is an element effectively functioning for the improvement of hardenability, strength, and toughness and, in order to exhibit such functions effectively, Mo is contained, for example, by: 0.1% or more; preferably 0.2% or more; and yet preferably 0.25% or more. Mo has a small equilibrium distribution coefficient and is likely to form microsegregation (normal segregation) however, and hence Mo is controlled, for example, to: 0.7% or less; preferably 0.6% or less; and yet preferably 0.5% or less.

(V: 0.005 to 0.2%)

[0035] V has the effects of precipitation hardening and structure fractionation and is an element useful for enhancing the strength of steel. In order to exhibit such functions effectively, it is recommendedto containV, for example, by: 0.005% or more; and preferably 0.01% or more. When V is contained excessively however, the above effects are saturated and that is inefficient economically, and hence V is controlled to: 0.2% or less; and preferably 0.15% or less.

(Al: 0.01 to 0.1%)

[0036] Al is effective as a deoxidizing element in a steel making process and also effective for the cracking resistance of steel. Consequently, it is recommended to contain Al, for example, by: 0.01% or more; and preferably 0.015% or more. In contrast, Al fixes N in the form of AlN or the like, hinders the strengthening function of steel by the blend of N, V, and others, combines with various other elements, yields nonmetallic inclusions and intermetallic compounds, and deteriorates the toughness of steel in some cases, and hence Al is controlled, for example, to: 0.1% or less; and preferably 0.08% or less.

(S: 0.005% or less)

[0037] S is likely to form coarse inclusions in a forging steel and hence may deteriorate the fatigue strength of a forging steel ingot or a crankshaft in some cases. Consequently, the S content in steel is controlled, for example, to: 0.005% or less; preferably 0.0045% or less; yet preferably 0.004% or less; and yet still preferably 0.0035% or less.

[0038] Meanwhile, when fine S-type inclusions are contained by a certain number density or more in a forging steel, many stress fields are formed in the steel, and thus the fine S-type inclusions are likely to trap excessive hydrogen exceeding a solid solubility limit in the steel and have the effect of improving the hydrogen cracking resistance of the steel.

[0039] In order to secure such S-type inclusions, the S content in steel is controlled to: 0.0002% or more; preferably 0.0004% or more; yet preferably 0.0006% or more; and yet still preferably 0.0008% or more.

[0040] An S content can be adjusted by controlling the composition of slag during melt refining. More specifically, the S content in steel can be reduced by raising the ratio of a CaO content to an SiO_2 content (CaO/SiO_2, hereunder referred to as "C/S" occasionally) in slag. Further, as a complimentary means, the S content in steel can be reduced by raising the ratio of a CaO content to an Al_2O_3 content (CaO/Al_2O_3, hereunder referred to as "C/A" occasionally). Inversely, when the S content is wanted to be increased, the slag composition is adjusted so that C/S and/or C/A may be reduced.

(Ti: 0.005% or less)

[0041] Ti forms coarse nitrides in steel and deteriorates the fatigue strength of a forging steel ingot or a crankshaft in some cases. Consequently, the Ti content in steel is controlled, for example: to 0.005% or less; preferably 0.004% or

less; and yet preferably 0.003% or less. Here, Ti makes fine inclusions such as TiN, TiC, and $Ti_4C_2S_2$, disperses in steel, occludes and traps excessive hydrogen exceeding a solid solubility limit in the steel, and has the effect of improving the hydrogen cracking resistance of the steel. When such Ti-type inclusions are secured, the Ti content in steel is controlled, for example, to: 0.0002% or more; preferably 0.0004% or more; and yet preferably 0.0006% or more.

[0042] A Ti content can be adjusted by regulating the ratio between a used amount of an alloy having a high impurity Ti content (a low grade alloy) and a used amount of an alloy having a low impurity Ti content (a high grade alloy) in auxiliary materials.

(O: 0.0015% or less)

[0043] O (oxygen) is an element that forms oxides such as SiO_2, Al_2O_3, MgO, CaO, and others, turns into inclusions, and deteriorates the fatigue strength of a steel ingot. Consequently, it is desirable to reduce O to the utmost and the total oxygen amount is controlled to: 0.0015% or less; and preferably 0.001% or less.

[0044] The basic compositions of a forging steel used in the present invention are preferably as stated above and the remainder comprises Fe substantially but unavoidable impurities may be contained in the steel. As the unavoidable impurities, for example P and N are quoted and for example the content of P is: preferably 0.03% or less; and yet preferably 0.02% or less. Further, it is also possible to use a forging steel further containing another element intentionally within the range not adversely affecting the aforementioned functions of the present invention.

[0045] The examples of another element that can be added intentionally are B having a hardenability improving effect, and W, Nb, Ta, Cu, Ce, Zr, Te, and others that are solid solution strengthening elements or precipitation strengthening elements. The elements can be added independently or in combination of two or more kinds. A desirable addition amount of the elements is, for example, about 0.1% or less in total.

Examples

[0046] The present invention is hereunder explained more concretely with examples. However, the present invention is substantially not limited to the examples and may be modified appropriately within the range conforming to the aforementioned and after-mentioned gists, and all of those modifications are included in the technological scope of the present invention.

[0047] It is recommended to refine steel by the method explained below in order to: increase the cleanliness of molten steel poured into a mold; thereby control the number density (D_{BOT}) of inclusions 5 to 10 μm in longest diameter observed on a steel cross-section to about 10 to 80 pieces/cm^2 at a steel ingot lower portion, the number density (D_{TOP}) of inclusions 5 to 10 μm in longest diameter observed on a steel cross-section to about 20 to 90 pieces/cm^2 at a steel ingot upper portion, and the number density of inclusions 40 μm or more in longest diameter to about 5 pieces/cm^2 or less; and satisfy the expression (1).

[0048] The refining method is a method for producing high cleanliness steel by:applying first secondary-refining to molten steel tapped from a converter or an electric furnace; applying degassing treatment to the molten steel after subjected to the first secondary-refining; and applying second secondary-refining to the molten steel after subjected to the degassing treatment.

[0049] That is, in order to produce high cleanliness steel having a small amount of inclusions caused by slag inclusion and a high cleanliness, it is effective to apply secondary-refining twice in the order of secondary-refining treatment, degassing treatment, and then secondary-refining treatment again to molten steel produced with a converter.

[0050] The first secondary-refining treatment is a treatment to adjust molten steel compositions to prescribed values and the degassing treatment is a treatment to remove gas components such as hydrogen existing in the molten steel. Hence it is necessary to increase an agitation power density at both the treatments while suppressing the inclusion of slag floating on the surface of the molten steel to the minimum.

[0051] Meanwhile, the function of surfacing and separating the slag once included in the molten steel during the degassing treatment is given to the second secondary-refining treatment and it is necessary to agitate the molten steel at a low agitation power density so as not to cause additional slag inclusion while the molten steel is heated and retained.

[0052] More specifically, at the first secondary treatment, the flow rate of injected gas is adjusted so that the agitation power density may be 5 W'/ton or more (preferably 10 W/ton or more) and 60 W/ton or less (preferably 50 W/ton or less) and slag conditioning is carried out so that the slag composition after the degassing treatment may satisfy the expressions $CaO/SiO_2 \geq 3.5$, $CaO/Al_2O_3 = 1.5 - 3.5$, and $T.Fe + MnO \leq 1.0$, in terms of mass%. Here, T.Fe means the total amount of iron atoms.

[0053] At the degassing treatment, the flow rate of injected gas is adjusted so that the agitation power density may be 50 W/ton or more and preferably 60 W/ton or more and 200 W/ton or less and preferably 180 W/ton or less up to the midterm (the halfway) of the degassing treatment and the flow rate of injected gas is adjusted so that the agitation power density may be 140 W/ton or less and preferably 120 W/ton or less (excluding 0 W/ton) at the succeeding degassing

treatment (after the midterm).

[0054] At the second secondary treatment, the flow rate of injected gas is adjusted so that the agitation power density may be 25 W/ton or less and preferably 20 W/ton or less (excluding 0 W/ton).

[0055] More specifically, the following procedures are taken.

[0056] Firstly, molten steel tapped from a converter or an electric furnace to a ladle is conveyed to a secondary-refining apparatus and first secondary-refining treatment (hereunder referred to as LF-I occasionally) is applied. Stillmore specifically, whilemolten steel is heated to T_L = about 1,600°C by generating arc discharge, flux is added by a flux supply means and further the molten steel is agitated by injecting Ar gas by a gas injection means. With regard to strength for agitating the molten steel, the flow rate of Ar gas is adjusted so that the agitation power density ε computed with the expression (2) below may be 5 to 60 W/ton.

[0057] Here, in the computation of the agitation power density ε, the temperature of bottom blow gas before injection To (the temperature of Ar gas before injected) is set at room temperature (298K) and the temperature of bottom blow gas after injection Tg (the temperature of Ar gas after injected) is set at the molten steel temperature T_L.

[0058] The main purposes of LF-I where molten steel tapped from a converter or an electric furnace to a ladle is primarily refined are to heat the molten steel and to adjust the compositions of the molten steel. The molten steel compositions and the molten steel temperature cannot be homogenized unless appropriate agitation is applied on this occasion. Excessive agitation of the molten steel however tends to entangle slag even when the compositions and the temperature are homogeneous and the slag inclusionmay act as the origins of defects afterward. Consequently, the agitation power density ε is set at 5 to 60 W/ton. By so doing, it is possible to homogenize the compositions and temperature of the molten steel while slag inclusion is prevented.

[0059]

[Formula 2]

$$\varepsilon = \frac{371 \cdot Q_g \cdot T_L}{M_L}\left[\ln\left(1+\frac{9.8 \cdot \rho_L \cdot h_0}{P}\right)+\left(1-\frac{T_0}{T_g}\right)\right]$$

[0060] ε: Agitation power density (W/ton)
T_0: Temperature of bottom blow gas before injection (room temperature (298K))
T_L: Molten steel temperature (K)
M_L: Molten steel quantity (ton)
ρ_L: Molten steel density (kg/m^3)
Q_g: Flow rate of bottom blow gas (Nl/min)
T_g: Temperature of bottom blow gas after injection (K)
P: Atmospheric pressure (torr)
H_0: Molten steel depth (m)

[0061] For example, in the first secondary-refining treatment (LF-I), even though some conditions such as the size of the ladle and the actually charged molten steel quantity M_L are different, the agitation power density ε takes a value of 4.7 to 67.2 W/ton by adjusting Q_g/ M_L to 0.30 to 3.75 Nl/min·ton.

[0062] Here, in LF-I, with regard to the type and the quantity of flux, the heating temperature is controlled and the charging amount of an auxiliary material (flux) is adjusted so that the slag composition may simultaneously satisfy the following three conditions after the finish of vacuum degassing treatment that will be stated later (in other words, at the start of the second secondary-refining treatment) ;

(1) the mass of CaO is 3.5 times or more the mass of SiO_2,
(2) the mass of CaO is 1.5 to 3.5 times the mass of Al_2O_3, and
(3) the summation of the mass of T. Fe and the mass of MnO in the slag composition is 1.0% or less of the total slag mass.

[0063] After finishing the first secondary-refining treatment, the molten steel is conveyed together with the ladle to a vacuumdegassing apparatus and vacuum degassing treatment (hereunder referred to as VD occasionally) is applied to the molten steel. More specifically, the atmospheric pressure P in the ladle is reduced close to a vacuum of about 0.5 Torr by activating an exhaust system and thereby evacuating the gas existing above the molten steel in the ladle through an exhaust pipe. In addition, the molten steel is agitated by injecting Ar gas through a gas injecting means. By the above method, the gas component such as hydrogen existing in the molten steel is removed.

[0064] The time for VD is about 20 minutes in total and, during the former half time (before the midterm in the treatment time, the former half 10 minutes), the bottom blow gas flow rate Q_g is adjusted so that the agitation power density ε may be 50 to 200 W/ton and, during the latter half time (after the midterm in the treatment time, the latter half 10 minutes), the bottom blow gas flow rate Q_g is adjusted so that the agitation power density ε may be 140 W/ton or less (excluding 0 W/ton).

[0065] In VD, hydrogen is removed from the molten steel the composition adjustment of which is almost finished and, on this occasion too, it is desirable to adopt an agitation power density ε that can prevent slag from being included in the molten steel and can attain dehydrogenation at the same time. To that end, by controlling the agitation power density ε to 50 to 200 W/ton during the former half of the VD treatment time, dehydrogenation can be attained efficiently while suppressing slag inclusion to the minimum. In addition, by controlling the agitation power density ε to 140 W/ton or less during the latter half time of VD, the surfacing and separation of the entangled slag can be accelerated.

[0066] Further, in the case of the present embodiment, a high cleanliness steel can be produced by applying the second secondary-refining (hereunder referred to as LF-II occasionally) to the molten steel after subjected to VD. That is, after the vacuum degassing treatment is finished, the molten steel is conveyed to the secondary-refining treatment apparatus together with the ladle and the second secondary-refining treatment is applied to the molten steel. More specifically, while the molten steel is heated to T_L = about 1, 600˚C by generating arc discharge, the molten steel is agitated by injecting Ar gas by a gas injection means. With regard to the strength for agitating the molten steel, the Ar gas flow rate Q_g is adjusted so that the agitation power density ε computed with the expression (2) may be 25 W/ton or less (excluding 0 W/ton).

[0067] By applying the LF treatment (LF-II) again in this way, it is possible to further promote "the surfacing and separation of entangled slag and deoxidation products" occurring from the midterm of VD. On this occasion, the agitation power density ε in LF-II must be 25 W/ton or less in order to prevent additional slag inclusion. By heating and retaining the molten steel at the agitation power density ε, the surfacing and separation of the slag and the deoxidation products can be attained without fail.

[0068] Here as stated above, the slag composition in LF-II satisfies the following conditions;

(1) basicity, namely $CaO/SiO_2 \geq 3.5$,
(2) CaO/Al_2O_3 = 1.5 - 3.5, and
(3) T.Fe + MnO ≤ 1.0 mass %,

and hence the reoxidation of the molten steel compositions caused by oxides in the slag can be prevented without fail.

[0069] By adopting the production method of a high cleanliness steel as stated above, it is possible to produce a high cleanliness steel having a small amount of inclusions caused by slag inclusion.

[0070] A steel ingot is produced by pouring the obtained high cleanliness molten steel into a mold of 10 to 90 tons class (2 to 4 m in total height) through a bottom pouring ingot-making method. The solidified steel ingot is demolded, thereafter heated to about 1, 300˚C, hot-forged, and produced into a forged material with 150 to 700 mm in cross-sectional diameter. The hot forging is applied by elongating the steel ingot with a pressing machine and thereafter forming into a round cross-section with a special purpose tool.

[0071] In Tables 1 to 3, shown are: the conditions (Conditions 1 to 20) that the agitation power density ε in LF-I, the agitation power density ε during the former half time of VD, the agitation power density ε during the latter half time of VD, and the agitation power density ε in LF-II are variously changed; moreover various conditions of the tests (Test numbers 1 to 59) carried out by changing the basicity (CaO/SiO_2) and the values of CaO/Al_2O_3 and T.Fe + MnO (mass %); and the data of the physical properties of the test pieces cut out from the upper portions and the lower portions of the obtained steel ingots.

[0072] Here, in Tables 1 to 3, in the row "Composition and temperature homogenization", when the variation of the C content is defined as ΔC and the variation of temperature is defined as ΔT from the beginning to the end of the casting of the steel ingot, a case satisfying the expressions $\Delta C \leq 0.01\%$ and $\Delta T \leq 20$˚C is rated as the symbol ○ and the other cases are rated as the symbol ×.

In the row "Hydrogen removal", the hydrogen content [H] is measured immediately before the end of refining, and a case satisfying the expression [H] ≤ 1.2 ppm is rated as the symbol ○ and a case satisfying the expression [H] > 1.2 ppm is rated as the symbol ×.

In the row "Slag inclusion", a case where the number of inclusions 5 μm or more in longest diameter in the microscopic surface observation of a molten steel sample having a Ca content of 5% or more is 30 pieces/cm^2 or less is rated as the symbol ○ and a case where the number exceeds 30 pieces/cm^2 is rated as the symbol ×.

[0073] In Tables 1 to 3, the S content (mass ppm) in steel, the number density of fine inclusions (5 to 10 μm in longest diameter) at a portion corresponding to the upper portion of a steel ingot (D_{TOP}), the number density of fine inclusions (5 to 10 μm in longest diameter) at a portion corresponding to the lower portion of a steel ingot (D_{BOT}). the number density of coarse inclusions (40 μm or more in longest diameter) at a portion corresponding to the upper portion of a

steel ingot, and the number density of coarse inclusions (40 μm or more in longest diameter) at a portion corresponding to the lower portion of a steel ingot are shown for each of the test pieces. The number of inclusions is obtained by examining the number of inclusions per 1 cm^2 on a microscopic surface of a test piece with an EPMA (JXA-8900L made by JEOL Ltd.).

[0074] Here, the chemical compositions in steel of the test pieces are C: 0.3%, Si: 0.25%, Mn: 0.55%, Ni: 1.6%, Cr: 1.6%, Mo: 0.25%, V: 0.01%, Al: 0.03%, S: 0.002%, Ti: 0.003%, O: 0.0013%, and P: 0.01%.

[0075] Further, the value of $(D_{BOT})/(D_{TOP}) \times$ S content in steel (mass ppm) (the expression (1) is satisfied when the value is 18 or less), the size of the largest inclusion (the symbol ○ represents the case of the largest size (ϕ: sphere diameter conversion) < 0.5 mm, the symbol △ represents the case of 0.5 mm < the largest size ≤ 1.0 mm, and the symbol × represents the case of the largest size > 1.0 mm), and cleanliness are measured and the obtained results are also shown in Tables 1 to 3. Here, the results in a case where the upper portion (T) or the lower portion (B) of a steel ingot is not distinctively identified mean the test results of the upper portion of a steel ingot.

[0076] Note that, in the row "Cleanliness", a case of DIN K(3) ≤ 15 is rated as the symbol ○ and a case of DIN K(3) > 15 is rated as the symbol × as the DIN K3 standards, and the cleanliness is rated as the symbol ○ in a case where a steel ingot upper portion is rated as the symbol ○ and also a steel ingot lower portion is rated as the symbol ○, the cleanliness is rated as the symbol Δ in a case where either of a steel ingot upper portion or a steel ingot lower portion is rated as the symbol ○ and the other thereof is rated as the symbol ×, and the cleanliness is rated as the symbol × in a case where both of a steel ingot upper portion and a steel ingot lower portion are rated as the symbol ×.

[0077] Further, in Tables 1 to 3, the endurance limit ratios at the upper portion and the lower portion of a steel ingot and the test results of hydrogen cracking at the upper portion and the lower portion of a steel ingot are described.

(Endurance limit ratio)

[0078] An endurance limit ratio = fatigue strength/tensile strength is obtained from the results of a tensile strength test and a fatigue strength test that are described later. The endurance limit ratios of a steel ingot upper portion (T) and a steel ingot lower portion (B) are separately shown in Tables 1 to 3.

[0079] Then, the results of judging the endurance limit ratio are also shown in Tables 1 to 3 showing with the symbol ○ in a case of Endurance limit ratio ≥ 0.45, the symbol Δ in a case of 0.40 ≤ Endurance limit ratio < 0.45, and the symbol × in a case of Endurance limit ratio < 0.40.

(Tensile strength)

[0080] Tensile test pieces 6 mm in diameter and 30 mm in gauge length (two test pieces for each) are: sampled from the vicinity of the center of a round bar steel after forging; and subjected to tensile tests (JIS Z 2204 and 2241) at room temperature. The test results of a steel ingotupperportion (T) anda steel ingot lowerportion (B) are separately shown with the unit of MPa in Tables 1 to 3.

(Fatigue strength)

[0081] Rotating bending fatigue tests are carried out with the test pieces shown below. The test results of a steel ingot upper portion (T) and a steel ingot lower portion (B) are separately shown with the unit of MPa in Tables 1 to 3.
Test piece: smooth test piece 10 mm in diameter,
Test method: rotating bending fatigue test (stress ratio = -1, revolutions: 3,600 rpm),
Fatigue strength evaluation method: step method,
Step stress: 20 MPa,
Number of test pieces: five pieces each, and

$$\text{Fatigue strength of each test piece} = (\text{Fracture stress}) - (\text{Step stress})$$

(Hydrogen cracking resistance)

[0082] Ultrasonic detection test (UT) is carried out at a frequency of 4 MHz (more specifically, "Defects of Forged Steel Products", edited by Forged Steel Study Section, Japan Steel Castings and Forgings Association, P32-33). A case where a defect echo showing hydrogen cracking is detected at the intermediate portion (1/3 to 1/5R) of a steel ingot is

represented with the symbol × regarding the steel ingot as being inferior in hydrogen cracking resistance and a case where a defect echo is not detected is represented with the symbol ○ regarding the steel ingot as being superior in hydrogen cracking resistance. Here, when the side face (surface layer) in the steel ingot width direction is represented by 0R and the center is represented by 1/2R, the center portion is defined as a portion located in the range of 1/2 to 1/3R, the intermediate portion is defined as a portion located in the range of 1/3 to 1/5R, and the surface layer portion is defined as a portion located in the range of 0R to 1/5R.

[0083] In the row "Comprehensive evaluation", a case where all of the endurance limit ratios at a steel ingot upper portion and a steel ingot lower portion and the test results of hydrogen cracking at a steel ingot upper portion and a steel ingot lower portion are rated as the symbol ○ is rated as the symbol •, and the other cases are rated as the symbol ×.

[0084]

[Table 1]

Test number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Condition	1	2	2	2	2	2	3	3	3	3	4	4	4	5	6	7	7	7	7	7
ε in LF-I (W/t)	3	5	5	5	5	5	30	30	30	30	60	60	60	65	30	30	30	30	30	30
Composition and temperature homogenization	×	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Slag inclusion	O	O	O	O	O	O	O	O	O	O	O	O	O	×	O	O	O	O	O	O
ε in the former half of VD (W/t)	150	150	150	150	150	150	150	150	150	150	150	150	150	150	40	50	50	50	50	50
Hydrogen removal	O	O	O	O	O	O	O	O	O	O	O	O	O	O	×	O	O	O	O	O
Slag inclusion	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
ε in the latter half of VD (W/t)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Hydrogen removal	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Slag inclusion	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
ε in LF-II (W/t)	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Composition and temperature homogenization	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Slag inclusion	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
CaO/SiO_2	4.0	3.0	3.5	3.5	3.5	7.0	3.0	3.5	3.5	8.0	3.0	3.5	8.2	3.5	3.5	3.0	3.0	3.5	3.5	8.0
CaO/Al_2O_3	2.0	1.5	1.5	1.5	3.0	2.0	1.5	2.0	2.5	2.0	2.0	1.5	2.0	2.0	2.0	2.0	2.0	1.5	1.8	2.5
T.Fe+MnO(%)	1.0	0.8	1.2	0.8	0.9	0.9	0.7	0.7	1.1	0.8	0.8	0.8	0.8	0.9	0.8	0.8	1.2	1.1	0.7	0.9
S content in steel (ppm)	40	50	30	30	10	45	45	15	40	30	35	15	20	10	15	40	30	20	12	9
5-10μm number density of inclusions(T)	60	120	90	60	90	88	90	50	92	90	90	80	90	50	40	90	80	90	30	40
5-10μm number density of inclusions(B)	90	60	60	20	80	25	80	30	60	55	100	80	80	50	62	10	48	70	10	80
Not less than 40μm number density of inclusions(T)	5	10	6	2	1	0	6	5	5	3	7	1	5	7	6	4	6	3	2	1
Not less than 40μm number density of inclusions(B)	6	5	4	5	0	5	6	4	2	4	6	3	5	6	10	2	8	0	1	2
B/T×[%S]	60	25	20	10	9	13	40	9	26	18	39	15	18	10	23	4	18	16	4	18
Largest inclusion size	O	×	×	O	O	O	×	O	O	O	×	O	O	Δ	O	O	×	O	O	O
Cleanliness	O	Δ	Δ	O	O	O	O	O	Δ	O	Δ	O	O	O	O	O	×	O	O	O
Hydrogen cracking(T)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	×	O	O	O	O	O
Hydrogen cracking(B)	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Tensile strength(T) [MPa]	840	900	960	1021	944	880	870	943	1023	982	900	1083	964	812	996	893	1005	975	925	860
Tensile strength(B) [MPa]	790	870	900	968	873	820	820	881	943	925	878	1016	916	737	956	843	986	919	890	827
Fatigue strength(T) [MPa]	386	297	346	470	453	431	339	462	348	491	351	520	434	309	329	420	352	468	435	404
Fatigue strength(B) [MPa]	300	426	405	455	419	385	320	405	424	426	307	498	440	265	315	422	325	441	427	397
Endurance limit ratio(T)	0.46	0.33	0.36	0.46	0.48	0.49	0.39	0.49	0.34	0.50	0.39	0.48	0.45	0.38	0.33	0.47	0.35	0.48	0.47	0.47
Endurance limit ratio(B)	0.38	0.49	0.45	0.47	0.48	0.47	0.39	0.46	0.45	0.46	0.35	0.49	0.48	0.36	0.33	0.50	0.33	0.48	0.48	0.48
Endurance limit ratio(T) judgment	○	×	×	○	○	○	×	○	×	○	×	○	○	×	×	○	×	○	○	○
Endurance limit ratio(B) judgment	×	○	○	○	○	○	×	○	○	○	×	○	○	×	×	○	×	○	○	○
Comprehensive evaluation	×	×	×	●	●	●	×	●	×	●	×	●	●	×	×	●	×	●	●	●

[0085] [Table 2]

Test number	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Condition	8	8	8	8	8	9	9	9	9	9	10	11	12	12	12	12	13	14	15	16
ε in LF-I (W/t)	68	65	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Composition and temperature homogenization	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Slag inclusion	×	×	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
ε in the former half of VD (W/t)	150	150	150	150	150	200	200	200	200	200	210	200	200	200	200	200	200	200	200	200
Hydrogen removal	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Slag inclusion	○	○	○	○	○	○	○	○	○	○	×	○	○	○	○	○	○	○	○	○
ε in the latter half of VD (W/t)	100	100	100	100	100	100	100	100	100	100	100	15	20	20	20	20	90	140	150	100
Hydrogen removal	○	○	○	○	○	○	○	○	○	○	○	×	○	○	○	○	○	○	○	○
Slag inclusion	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	×	○
ε in LF-II (W/t)	15	20	15	25	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	5
Composition and temperature homogenization	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	×
Slag inclusion	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
CaO/SiO_2	3.0	3.5	3.5	6.0	9.5	3.0	3.5	3.5	6.5	8.0	4.0	3.5	3.0	3.5	3.5	6.5	7.8	5.5	3.5	4.0
CaO/Al_2O_3	2.0	2.5	2.5	2.0	2.5	2.0	2.0	2.0	1.8	2.5	2.0	1.6	2.0	2.0	1.9	2.5	1.9	2.0	1.9	2.5
T.Fe+MnO(%)	0.9	1.2	0.8	0.9	0.9	0.9	1.2	0.8	0.9	0.7	0.9	0.9	1.1	1.1	0.9	0.8	0.9	0.7	0.9	0.9
S content in steel (ppm)	12	20	10	20	50	30	60	30	40	50	20	10	55	11	30	9	18	23	18	20
5-10μm number density of inclusions(T)	30	95	20	40	90	90	90	90	85	90	55	48	92	88	90	41	78	60	90	92
5-10μm number density of inclusions(B)	40	85	11	12	32	50	82	45	38	30	32	35	40	82	54	80	78	45	80	82
Not less than 40μm number density of inclusions (T)	7	6	2	3	5	8	6	2	0	1	8	7	10	8	5	4	3	5	12	6
Not less than 40μm number density of inclusions (B)	12	3	0	3	1	7	8	0	3	5	7	8	12	9	5	5	3	4	10	5
B/T×[%S]	16	18	6	6	18	17	55	15	18	17	12	7	24	10	18	18	18	17	16	18
Largest inclusion size	Δ	Δ	○	○	○	Δ	Δ	○	○	○	○	○	Δ	Δ	○	○	○	○	Δ	Δ
Cleanliness	Δ	×	○	○	○	○	×	○	○	○	○	○	×	Δ	○	○	○	○	○	Δ
Hydrogen cracking(T)	×	○	○	○	○	○	○	○	○	○	×	×	○	×	○	○	○	○	○	○

Hydrogen cracking(B)	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Tensile strength(T) [MPa]	870	856	879	900	929	815	880	851	914	977	865	888	862	870	1080	1043	975	804	1012	857
Tensile strength(B) [MPa]	840	812	803	840	887	770	825	791	840	930	822	824	801	825	980	971	896	789	936	804
Fatigue strength(T) [MPa]	296	308	431	450	446	277	317	426	420	459	294	320	284	331	486	511	478	402	324	291
Fatigue strength(B) [MPa]	344	309	385	386	399	254	272	388	412	419	304	305	264	281	480	447	439	387	318	306
Endurance limit ratio(T)	0.34	0.36	0.49	0.50	0.48	0.34	0.36	0.50	0.46	0.47	0.34	0.36	0.33	0.38	0.45	0.49	0.49	0.50	0.32	0.34
Endurance limit ratio(B)	0.41	0.38	0.48	0.46	0.45	0.33	0.33	0.49	0.49	0.45	0.37	0.37	0.33	0.34	0.49	0.46	0.49	0.49	0.34	0.38
Endurance limit ratio(T) judgment	×	×	○	○	○	×	×	○	○	○	×	×	×	×	○	○	○	○	×	×
Endurance limit ratio(B) judgment	△	×	○	○	○	×	×	○	○	○	×	×	×	×	○	○	○	○	×	×
Comprehensive evaluation	×	×	●	●	●	×	×	●	●	●	×	×	×	×	●	●	●	●	×	×

[0086] [Table 3]

Test number	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
Condition	17	17	17	17	17	17	17	18	18	18	18	18	19	19	19	19	19	19	20
ε in LF-I (W/t)	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Composition and temperature homogenization	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Slag inclusion	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
ε in the former half of VD (W/t)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Hydrogen removal	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Slag inclusion	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
ε in the latter half of VD (W/t)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Hydrogen removal	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Slag inclusion	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
ε in LF-II (W/t)	10	10	10	10	10	10	10	15	15	15	15	15	25	25	25	25	25	25	30
Composition and temperature homogenization	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Slag inclusion	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	×
CaO/SiO_2	3.0	3.0	3.5	3.5	6.0	9.0	8.0	3.0	3.0	3.5	3.5	5.0	3.0	3.5	3.8	3.5	5.5	8.0	3.5
CaO/Al_2O_3	1.9	1.9	2.1	1.9	1.5	2.0	2.5	2.1	2.1	1.9	1.9	1.9	2.1	1.9	1.5	1.5	1.9	2.5	1.5
T.Fe+MnO(%)	0.9	0.9	1.1	0.9	0.8	0.8	0.9	0.8	0.8	1.1	0.9	0.9	0.8	1.1	1.1	0.9	0.8	0.9	0.8
S content in steel (ppm)	8	15	22	28	36	16	50	15	8	48	12	33	21	28	6	14	8	48	15
5-10μm number density of inclusions(T)	9	100	91	62	88	77	81	82	10	100	33	76	95	90	9	32	36	88	93
5-10μm number density of inclusions(B)	10	90	75	39	44	80	24	82	9	100	48	38	85	93	9	18	80	33	84
Not less than 40μm number density of inclusions (T)	4	2	8	3	5	2	4	6	6	3	4	4	5	5	6	5	4	5	12
Not less than 40μm number density of inclusions (B)	4	5	5	1	4	0	5	6	2	5	0	2	5	5	4	5	5	2	10
B/T×[%S]	9	14	18	18	18	17	15	15	7	48	17	17	19	29	6	8	18	18	14
Largest inclusion size	○	△	△	○	○	○	○	△	○	×	○	○	△	×	○	○	○	○	×
Cleanliness	○	×	×	○	○	○	○	×	○	△	○	○	×	△	○	○	○	○	×
Hydrogen cracking(T)	×	○	○	○	○	○	○	○	×	○	○	○	○	○	×	○	○	○	○

Hydrogen cracking(B)	×	○	○	○	○	○	○	×	○	○	○	○	×	○	○	○	○
Tensile strength(T) [MPa]	929	937	908	1049	900	877	856	875	937	1032	937	1038	967	865	912	924	961	881	959
Tensile strength(B) [MPa]	898	882	832	981	840	834	798	809	868	968	879	997	903	798	851	865	886	840	902
Fatigue strength(T) [MPa]	362	347	309	514	423	403	419	333	337	361	440	498	377	398	356	434	442	441	297
Fatigue strength(B) [MPa]	296	326	399	461	386	409	383	275	304	358	396	459	334	303	323	415	425	386	289
Endurance limit ratio(T)	0.39	0.37	0.34	0.49	0.47	0.46	0.49	0.38	0.36	0.35	0.47	0.48	0.39	0.46	0.39	0.47	0.46	0.50	0.31
Endurance limit ratio(B)	0.33	0.37	0.48	0.47	0.46	0.49	0.48	0.34	0.35	0.37	0.45	0.46	0.37	0.38	0.38	0.48	0.48	0.46	0.32
Endurance limit ratio(T) judgment	×	×	×	○	○	○	○	×	×	×	○	○	×	○	×	○	○	○	×
Endurance limit ratio(B) judgment	×	×	○	○	○	○	○	×	×	×	○	○	×	×	×	○	○	○	×
Comprehensive evaluation	×	×	×	●	●	●	●	×	×	×	●	●	×	×	×	●	●	●	×

[0085] Here, in Test numbers 41, 49, and 55 in Table 3, the reason why the endurance limit ratios (B) are rated as the symbol × even though the numbers of coarse inclusions at the steel ingot lower portions are smaller than the standard value is that the hydrogen cracking occurs in the test pieces and the fatigue strength deteriorates due to the cracking.

[0086] Further, in Fig. 8(a), the number density (D_{TOP}) of fine inclusions (5 to 10 μm in longest diameter) at the portion corresponding to a steel ingot upper portion is shown along the vertical axis, and the number density of coarse inclusions (40 μm or more in longest diameter) at the portion corresponding to a steel ingot upper portion is shown along the horizontal axis. Then a case where the comprehensive evaluation is rated as the symbol • is shown with the symbol •, and a case where either of the endurance limit ratio or the test result of hydrogen cracking is rated as the symbol × is shown with the symbol ×. In a case where the value (D_{TOP}) is lower than 20 pieces/cm^2, hydrogen cracking occurs and the case is rated as the symbol ×.

[0087] Yet further, in a case where the value (D_{TOP}) exceeds 90 pieces/cm^2 and a case where the number density of inclusions 40 μm or more in longest diameter exceeds 5 pieces/cm^2, a prescribed endurance limit ratio is not obtained and the cases are rated as the symbol ×.

[0088] Furthermore, in Fig. 8(b), the number density (D_{BOT}) of fine inclusions (5 to 10 μm in longest diameter) at the portion corresponding to a steel ingot lower portion is shown along the vertical axis, and the number density of coarse inclusions (40 μm or more in longest diameter) at the portion corresponding to a steel ingot lower portion is shown along the horizontal axis. Then a case where the comprehensive evaluation is rated as the symbol ● is shown with the symbol ●, and a case where either of the endurance limit ratio or the test result of hydrogen cracking is rated as the symbol × is shown with the symbol ×. In a case where the value (D_{BOT}) is lower than 10 pieces/cm^2, hydrogen cracking occurs and the case is rated as the symbol ×.

[0089] In addition, in a case where the value (D_{BOT}) exceeds 80 pieces/cm^2 and a case where the number density of inclusions 40 μm or more in longest diameter exceeds 5 pieces/cm^2, a prescribed endurance limit ratio is not obtained and the cases are rated as the symbol ×.

Claims

1. A forging steel ingot cast with a mold wherein:

the number density D_{BOT} of inclusions 5 to 10 μm in longest diameter observed on a steel cross-section is 10 to 80 pieces/cm^2 at the steel ingot lower portion ranging from the bottom end of the steel ingot to the bottom 20% of the total height of the steel ingot in the direction of the gravity;
the number density D_{TOP} of inclusions 5 to 10 μm in longest diameter observed on a steel cross-section is 20 to 90 pieces/cm^2 at the steel ingot upper portion ranging from the top end of the steel ingot to the top 20% of the total height of the steel ingot;
the number density of inclusions 40 μm or more in longest diameter observed on a steel cross-section is 5 pieces/cm^2 or less at both of the steel ingot lower portion and said steel ingot upper portion; and
the following expression (1) is satisfied,

$$(D_{TOP})/(D_{BOT}) \geq [S]/18 \qquad (1),$$

here, [S] represents the content (in mass ppm) of S in steel.

2. A forging steel ingot according to Claim 1, comprising
C: 0.2 to 0.6% (in mass %, the same is applied hereunder),
Si: 0.05 to 0.5%,
Mn: 0.2 to 1.2%,
Ni: 0.1 to 3.5%,
Cr: 0.9 to 2.5%,
Mo: 0.1 to 0.7%,
V: 0.005 to 0.2%,
Al: 0.01 to 0.1%,
S: 0.005% or less,
Ti: 0.005% or less, and
O: 0.0015% or less,
with the remainder composed of iron and unavoidable impurities.

3. A solid type crankshaft produced by hot-forging a forging steel ingot according to Claim 1 or 2.

FIG. 1

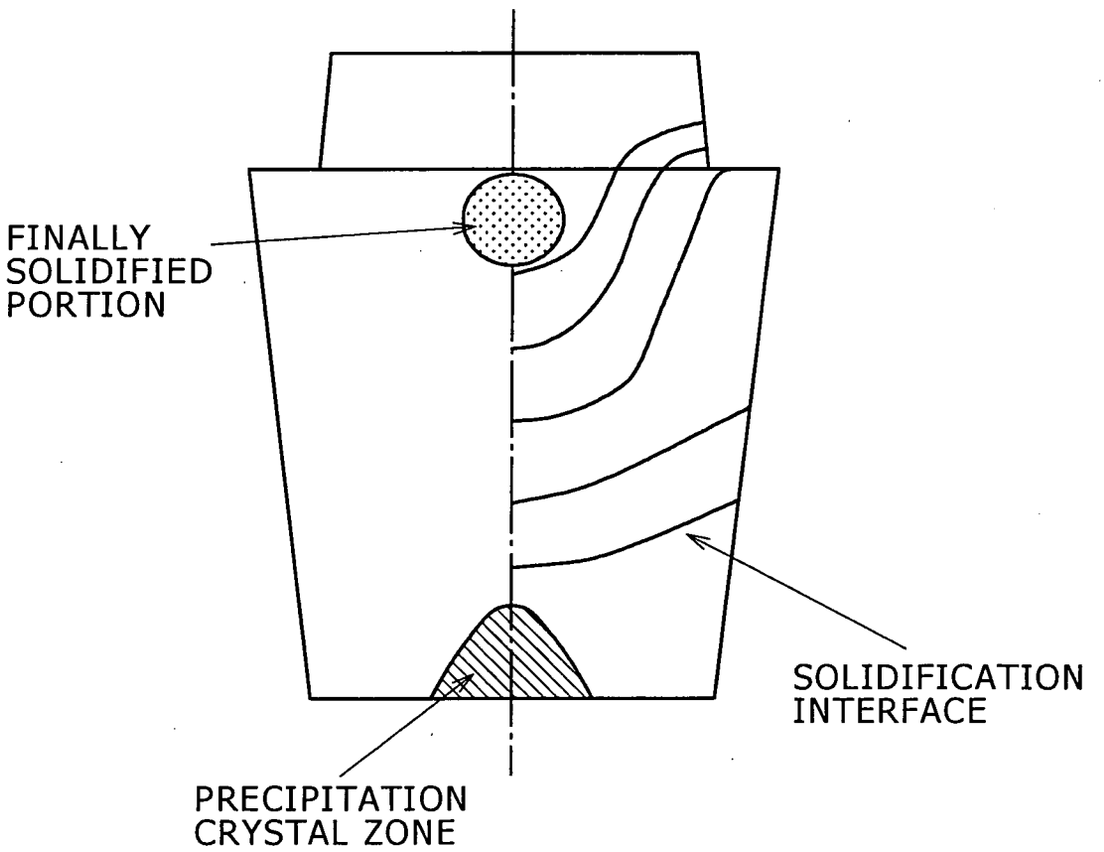

FINALLY
SOLIDIFIED
PORTION
SOLIDIFICATION
INTERFACE
PRECIPITATION
CRYSTAL ZONE

FIG. 2

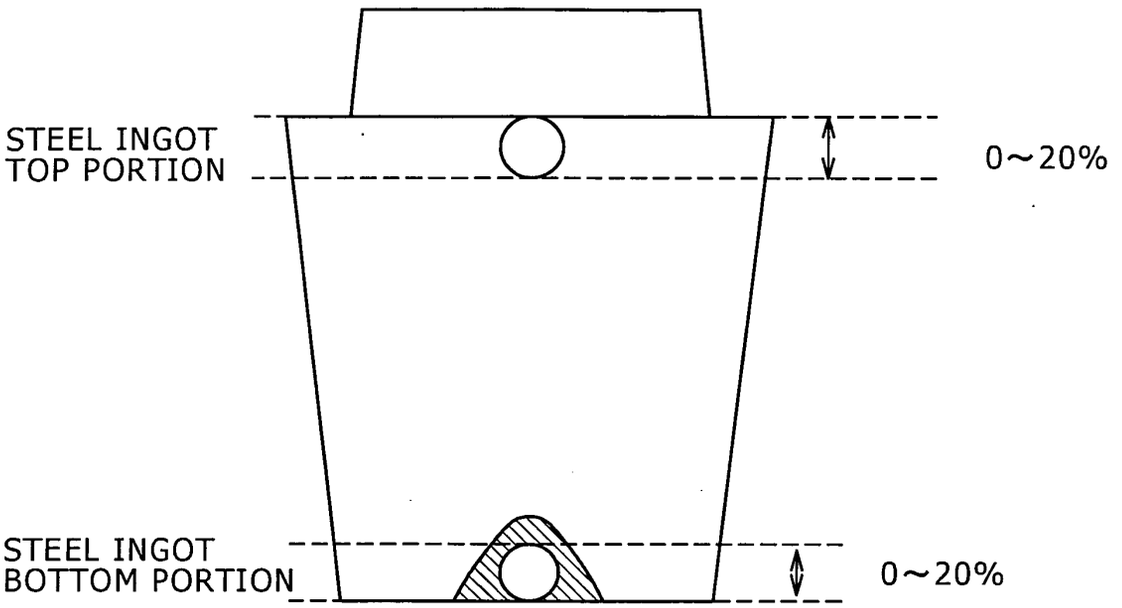


FIG. 3

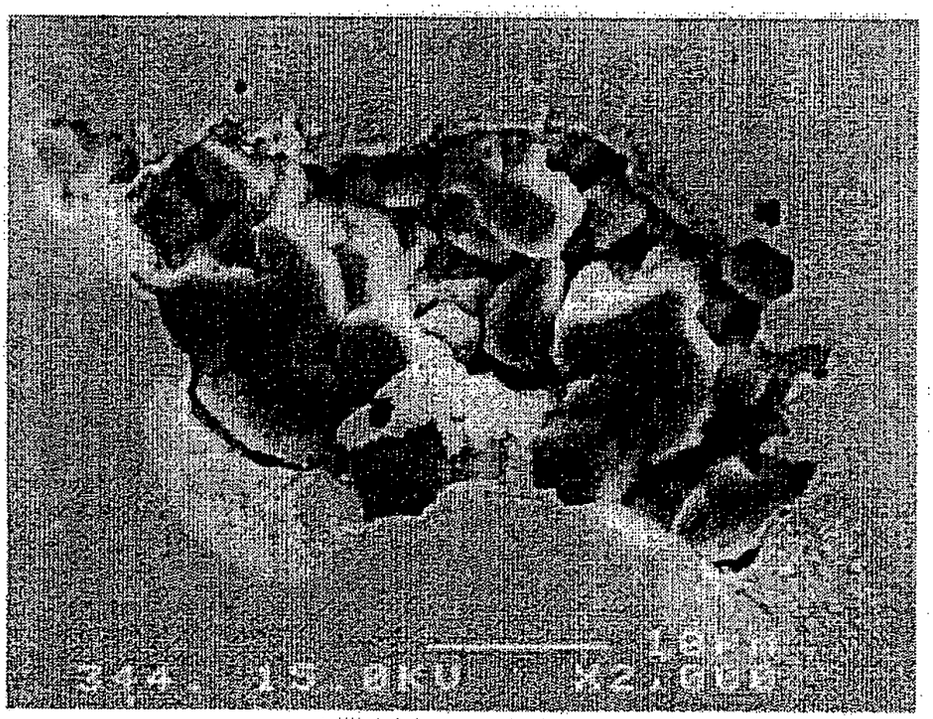


FIG. 4

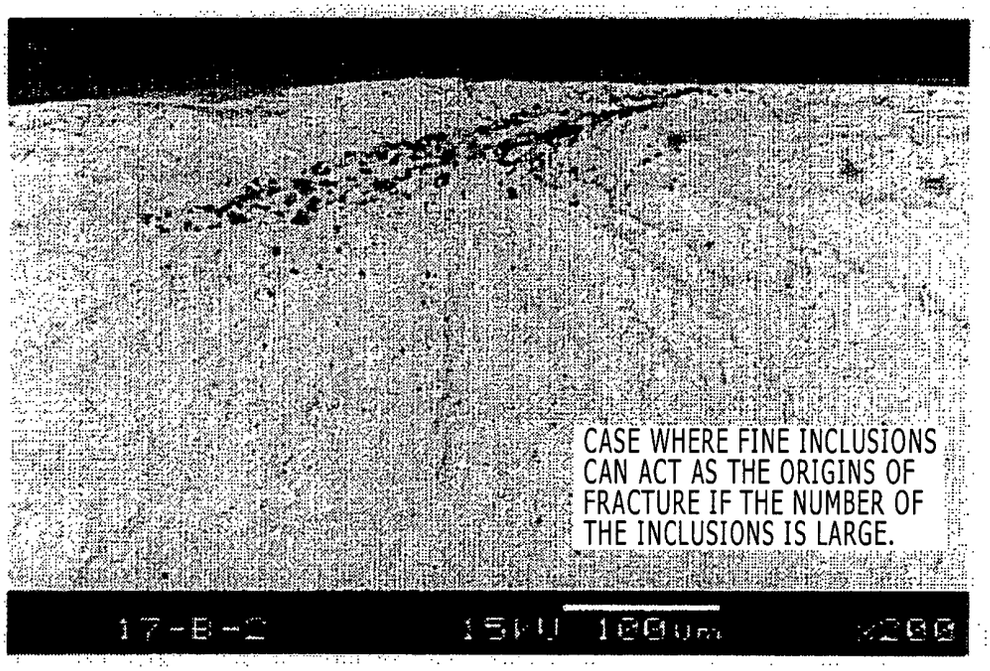

CASE WHERE FINE INCLUSIONS CAN ACT AS THE ORIGINS OF FRACTURE IF THE NUMBER OF THE INCLUSIONS IS LARGE.
17-B-2
15kV
100μm
×200

FIG. 5

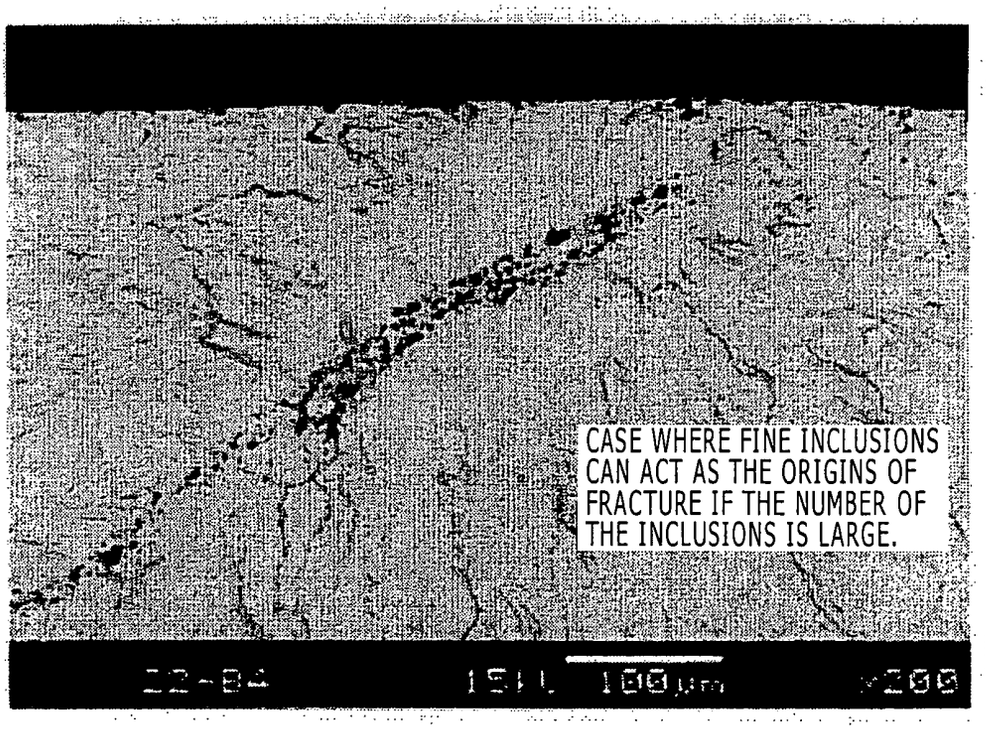

CASE WHERE FINE INCLUSIONS CAN ACT AS THE ORIGINS OF FRACTURE IF THE NUMBER OF THE INCLUSIONS IS LARGE.
22-B4
15kV
100μm
×200

FIG. 6

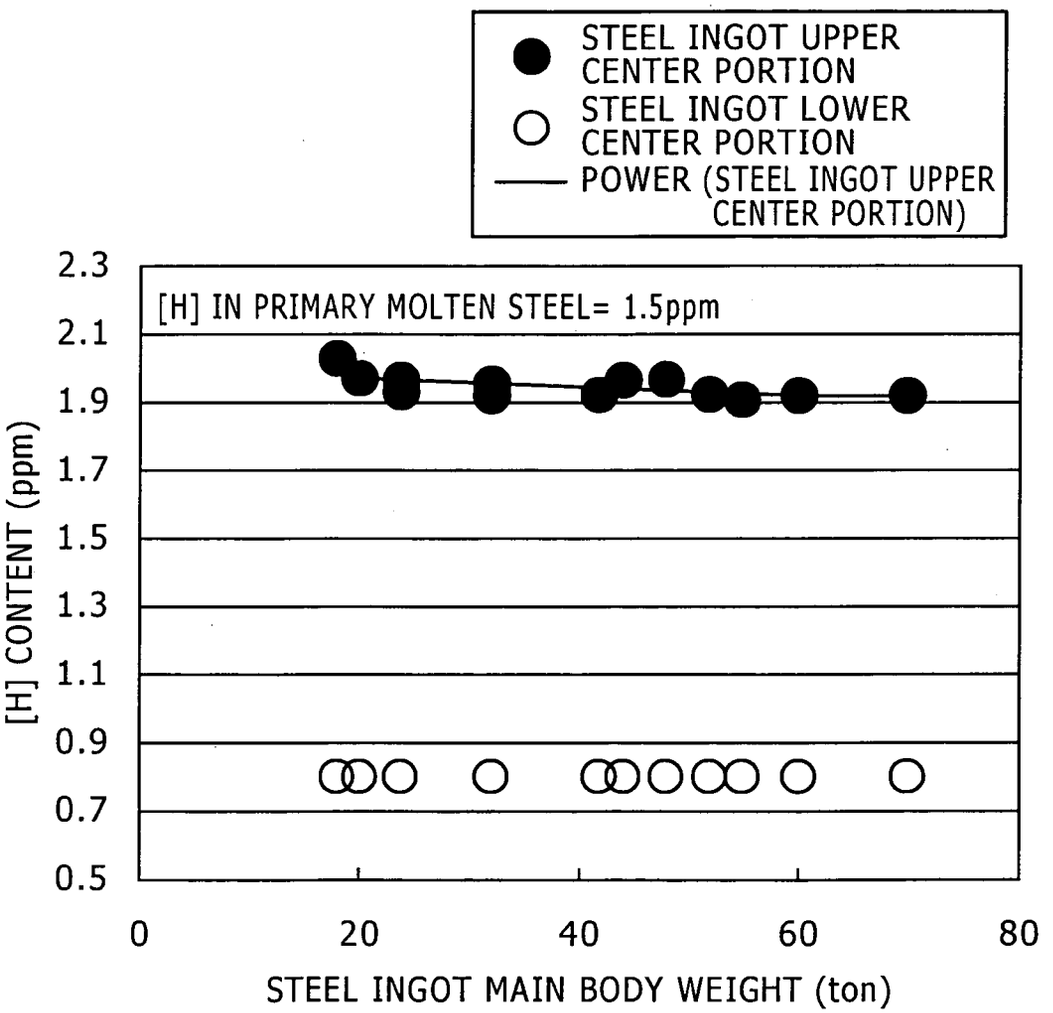

STEEL INGOT UPPER CENTER PORTION
STEEL INGOT LOWER CENTER PORTION
POWER (STEEL INGOT UPPER CENTER PORTION)
[H] IN PRIMARY MOLTEN STEEL= 1.5ppm
[H] CONTENT (ppm)
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0
20
40
60
80
STEEL INGOT MAIN BODY WEIGHT (ton)

FIG. 7

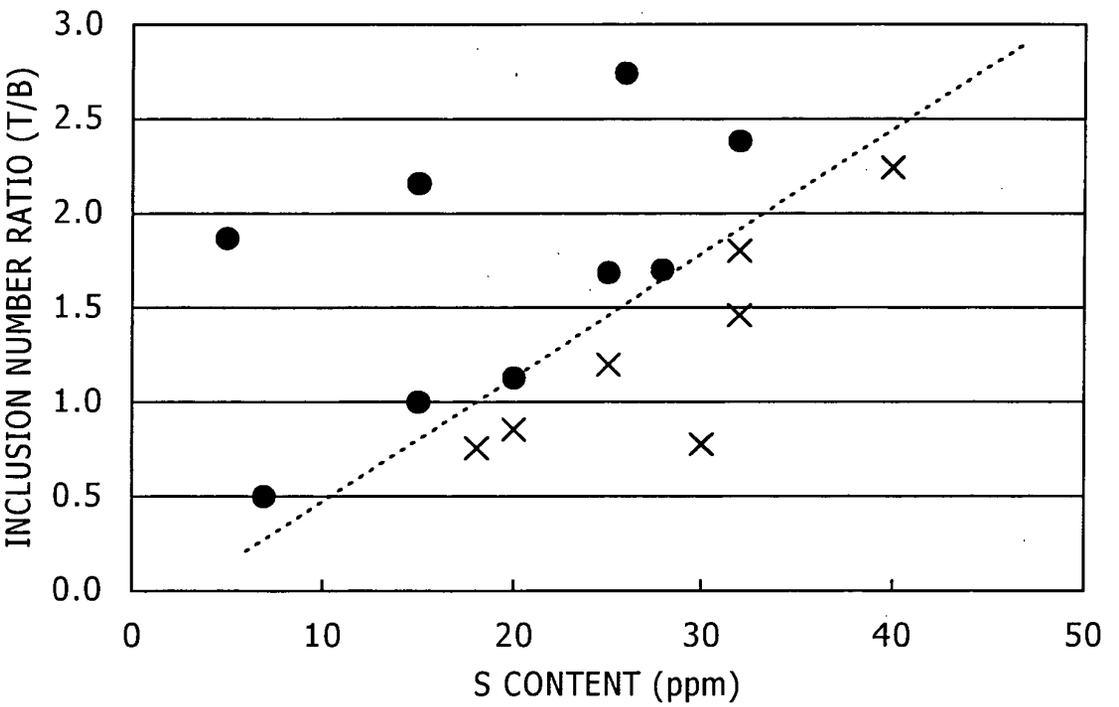
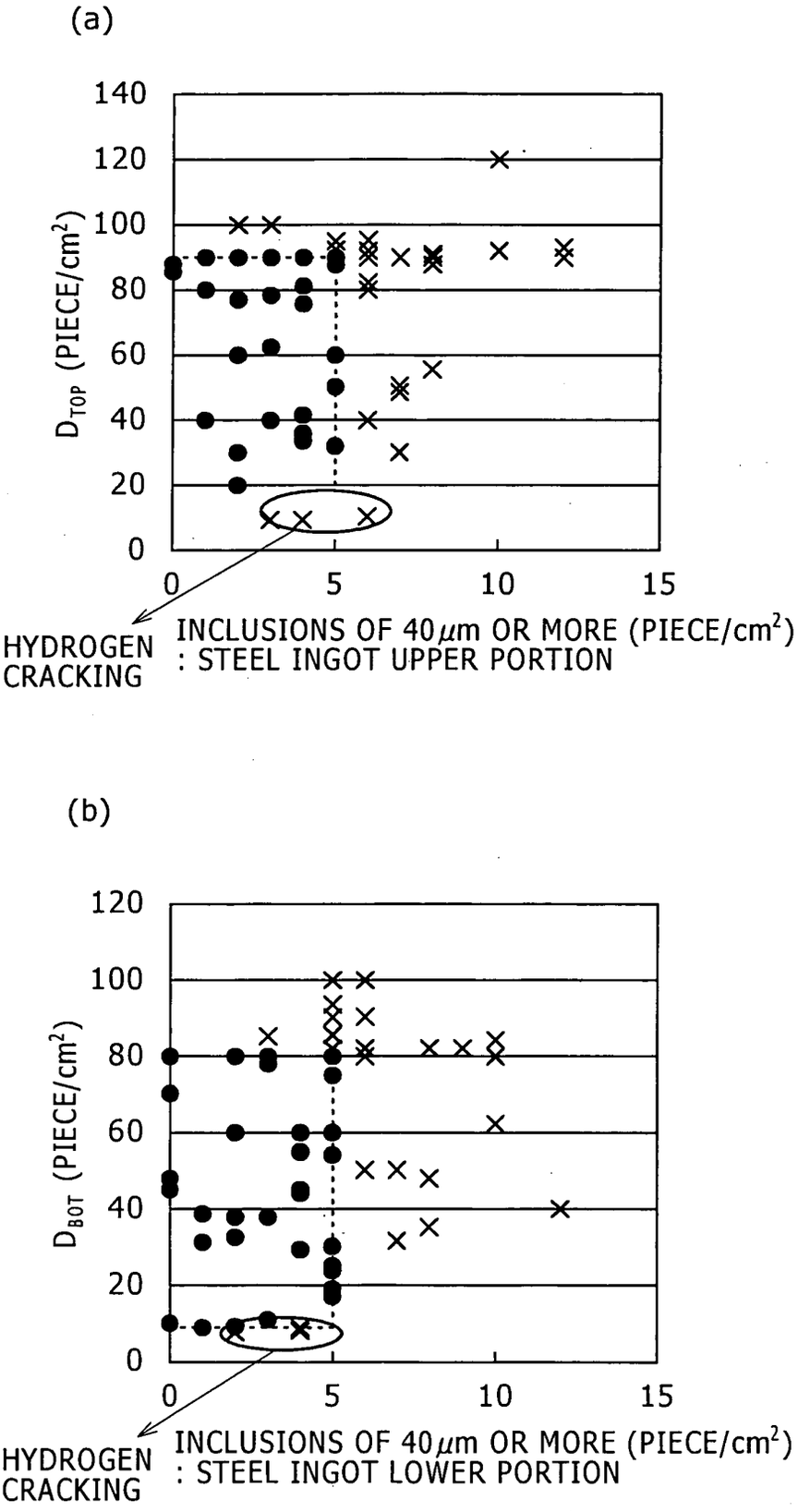

INCLUSION NUMBER RATIO (T/B)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
S CONTENT (ppm)

FIG. 8


(a)
140
120
100
80
60
40
20
0
D_{TOP} (PIECE/cm^2)
0
5
10
15
HYDROGEN CRACKING
INCLUSIONS OF 40μm OR MORE (PIECE/cm^2)
: STEEL INGOT UPPER PORTION
(b)
120
100
80
60
40
20
0
D_{BOT} (PIECE/cm^2)
0
5
10
15
HYDROGEN CRACKING
INCLUSIONS OF 40μm OR MORE (PIECE/cm^2)
: STEEL INGOT LOWER PORTION

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2008/054966

A. CLASSIFICATION OF SUBJECT MATTER
C22C38/00(2006.01)i, *B22D7/00*(2006.01)i, *C22C38/50*(2006.01)i, *C21C7/00*(2006.01)n, *C21C7/072*(2006.01)n, *C21C7/10*(2006.01)n, *C22C38/60*(2006.01)n

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C22C1/00-49/14, B22D7/00, C21C7/00-7/10

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2008
Kokai Jitsuyo Shinan Koho 1971-2008 Toroku Jitsuyo Shinan Koho 1994-2008

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 10-8132 A (Sumitomo Metal Industries, Ltd.), 13 January, 1998 (13.01.98), Full text (Family: none)	1-3
A	JP 10-25536 A (Sumitomo Metal Industries, Ltd.), 27 January, 1998 (27.01.98), Full text (Family: none)	1-3
A	JP 2007-113071 A (Kobe Steel, Ltd.), 10 May, 2007 (10.05.07), Full text (Family: none)	1-3

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 May, 2008 (13.05.08)	27 May, 2008 (27.05.08)
Name and mailing address of the ISA/ Japanese Patent Office Facsimile No.	Authorized officer Telephone No.

Form PCT/ISA/210 (second sheet) (April 2007)

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Patent documents cited in the description

- JP 2006336092 A **[0002]**
- JP 2002194502 A **[0003]**

Non-patent literature cited in the description

- Defects of Forged Steel Products. Japan Steel Castings and Forgings Association, 32-33 **[0082]**