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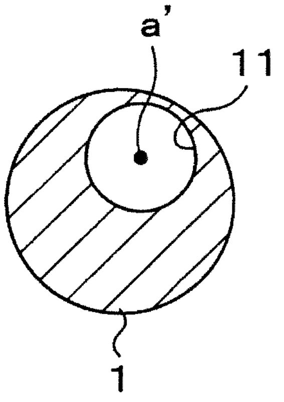
# (54) STEEL MATERIAL HAVING EXCELLENT ROLLING FATIGUE CHARACTERISTICS

(57) A steel material excellent in rolling fatigue property, the steel material including, in mass%: C: 0.10% to 1.50%, Si: 0.01% to 0.80%, Mn: 0.10% to 1.50%, Cr: 0.02% to 2.50%, Al: 0.002% to less than 0.010%, Ce + La + Nd: 0.0001% to 0.0025%, Mg: 0.0005% to 0.0050%, O: 0.0001% to 0.0020%, Ti: 0.000% to less than 0.005%, N: 0.0180% or less, P: 0.030% or less, S: 0.005% or less, Ca: 0.0000% to 0.0010%, V: 0.00 to 0.40%, Mo: 0.00 to 0.60%, Cu: 0.00 to 0.50%, Nb: 0.000 to less than 0.050%, Ni: 0.00 to 2.50%, Pb: 0.00 to 0.10%, Bi: 0.00 to 0.10%, B: 0.0000 to 0.0050%, and the balance being Fe and an impurity, wherein a fatigue-initiating inclusion detected by an ultrasonic fatigue test contains one or more of Ce, La, and Nd, and Mg, Al, and O, and a composition ratio in the fatigue-initiating inclusion satisfies Formula (1).

FIG.5



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## Description

[Technical Field]

**[0001]** The present invention relates to a steel material in which the composition of non-metallic inclusion is controlled, and thus is excellent in rolling fatigue property. In particular, the present invention relates to a steel material that suffers a less fatigue fracture initiated from an inclusion, by making its clustered oxide-based inclusion being turned into a REM-containing inclusion, and thus has a good rolling fatigue property.

[Background Art]

**[0002]** Various kinds of steel materials such as a case-hardened steel material, a steel material for induction hardening, and a steel material for bearing are used in industrial machines, automotive parts, and so on and are also used as materials of rolling bearings such as "ball bearings" and "roller bearings".

**[0003]** A rolling bearing includes "rolling elements" having, for example, a ball shape or a roller shape and "an inner ring" and "an outer ring" which are in contact with the rolling elements to transmit a load. Steel materials used in rolling members such as rolling elements, inner rings, and outer rings are required to have an excellent rolling fatigue property. To improve rolling fatigue life, inclusions contained in the steel materials are desirably as fine as possible and their amount is desirably as small as possible. As inclusions contained in steel materials, oxides such as alumina ($Al_2O_3$), sulfides such as manganese sulfide (MnS), and nitrides such as titanium nitride (TiN) are known.

**[0004]** An alumina-based inclusion is generated when dissolved oxygen left in molten steel refined in a steel converter or a vacuum treatment vessel bonds with Al having a strong affinity with oxygen. Further, ladles and so on are often formed of an alumina-based refractory material. Accordingly, during deoxidation, due to a reaction of the molten steel and the refractory material, alumina liquidates out as Al into the molten steel and Al is reoxidized into alumina-based inclusions. The alumina-based inclusions form a cluster in the solidified steel to reduce rolling fatigue life.

**[0005]** To reduce the alumina cluster, it is known that, in a method of manufacturing Al killed steel containing 0.005 mass% Al or more, an alloy containing Al and two or more of Ca, Mg, and REM is put into molten steel to adjust the amount of $Al_2O_3$ in a generated inclusion to 30 mass% to 85 mass%, and an alumina cluster-free Al killed steel is manufactured.

**[0006]** For example, Patent Document 1 discloses a method that adds two or more of REM, Mg, and Ca to molten steel to form an inclusion whose melting point is low, in order to prevent the generation of an alumina cluster. This method is effective for preventing a sliver defect. This method, however, is not capable of reducing the size of the inclusion down to a level required of steel for bearings. This is because the inclusions with a low melting point easily aggregate and combine to be coarse.

**[0007]** Further, REM turns the inclusion into a spherical shape to improve a fatigue property. However, adding too large an amount of REM, on the contrary, leads to an increase in the number of the inclusions to reduce fatigue life which is one of the fatigue properties. Patent Document 2 discloses that, to prevent a reduction in fatigue life, the content of REM needs to be 0.010 mass% or less. Patent Document 2, however, discloses neither the mechanism of the reduction in fatigue life nor an existing state of inclusions.

**[0008]** There are many examples where the improvement in fatigue property is thus attained by changing the shape of the inclusions from the cluster shape to the spherical shape, but there is no example where a fatigue property is improved through the reforming of the cluster itself.

[Prior Art Document]

[Patent Document]

**[0009]**

Patent Document 1: Japanese Laid-open Patent Publication No. H09-263820
Patent Document 2: Japanese Laid-open Patent Publication No. H11-279695

[Disclosure of the Invention]

[Problems to Be Solved by the Invention]

**[0010]** In consideration of the problems of the conventional arts, it is an object of the present invention to provide a steel material excellent in rolling fatigue property.

[Means for Solving the Problems]

**[0011]** The gist of the present invention is as follows.

[1] A steel material excellent in rolling fatigue property, the steel material including, in mass%:

C: 0.10% to 1.50%,
Si: 0.01% to 0.80%,
Mn: 0.10% to 1.50%,
Cr: 0.02% to 2.50%,
Al: 0.002% to less than 0.010%,
Ce + La + Nd: 0.0001% to 0.0025%,
Mg: 0.0005% to 0.0050%,
O: 0.0001% to 0.0020%,
Ti: 0.000% to less than 0.005%,
N: 0.0180% or less,
P: 0.030% or less,
S: 0.005% or less,
Ca: 0.0000% to 0.0010%,
V: 0.00 to 0.40%,
Mo: 0.00 to 0.60%,
Cu: 0.00 to 0.50%,
Nb: 0.000 to less than 0.050%,
Ni: 0.00 to 2.50%,
Pb: 0.00 to 0.10%,
Bi: 0.00 to 0.10%,
B: 0.0000 to 0.0050%, and
the balance being Fe and an impurity,

wherein a fatigue-initiating inclusion detected by an ultrasonic fatigue test contains Mg, Al, and O and one or more of Ce, La, and Nd, and a composition ratio in the fatigue-initiating inclusion satisfies Formula (1),

$$(\mathrm{Ce}\% + \mathrm{La}\% + \mathrm{Nd}\% + \mathrm{Mg}\%)/\mathrm{Al}\% \geq 0.20 \ldots \text{Formula (1)},$$

where Ce%, La%, Nd%, Mg%, and Al% are atomic (at)% of respective Ce, La, Nd, Mg, and Al contained in the fatigue-initiating inclusion.

[2] The steel material excellent in rolling fatigue property according to [1], wherein, in mass%, C: 0.10% to less than 0.45%, and Cr: 0.02 to 1.50%.

[3] The steel material excellent in rolling fatigue property according to [1], wherein, in mass%, C: 0.45% to less than 0.90%, and Cr: 0.70% to 2.50%.

[4] The steel material excellent in rolling fatigue property according to [1], wherein, in mass%, C: 0.90% to 1.50%, and Cr: 0.70 to 2.50%.

[Effect of the Invention]

**[0012]** According to the present invention, by reforming a clustered Al-O-based inclusion into a REM-Al-Mg-O-based inclusion to reduce an influence of the oxide-based inclusion on a fatigue property, it is possible to provide a steel material excellent in rolling fatigue property.

[Brief Description of the Drawings]

**[0013]**

[FIGs. 1] are explanatory views of a rolling fatigue test piece, (a) being a plan view and (b) being a side view.
[FIG. 2] is an explanatory view of an ultrasonic fatigue test piece.
[FIG. 3] is an explanatory view of inclusions included within a gauge length of the ultrasonic fatigue test piece.

[FIGs. 4] are explanatory views schematically illustrating how a fatigue fracture gradually progresses.
[FIG. 5] is an explanatory view of a fracture surface of the ultrasonic fatigue test piece.
[FIG. 6] is an example of a reflection electron composition image of a fatigue-initiating inclusion. [Embodiments for Carrying out the Invention]
To solve the problems of the conventional arts, the present inventors studiously conducted experiments and studies. As a result, through the adjustment of the content of REM and the contents of Al and S, the following findings were obtained.

(1) Reforming an Al-O-based inclusion which is a clustered oxide into a REM-Al-Mg-O-based inclusion improves adhesion between the oxide-based inclusion and base metal.
(2) To mix Mg and REM-based inclusion in the Al-O-based inclusion which is the clustered oxide, the content of S high in reactivity with Mg and REM should be reduced as much as possible.
(3) Since the Al-O-based inclusion which is the clustered oxide is coarse and adversely affects a fatigue property, an Al amount is preferably reduced as much as possible, but without the addition of Al, a coarse lower oxide is formed, and the effect of Mg and REM reforming the oxide-based inclusion is not obtained. Therefore, the minimum deoxidation with Al is necessary.

**[0014]** A steel material according to an embodiment of the present invention and its manufacturing method which are made based on the above findings will be hereinafter described in detail.
**[0015]** First, a component composition of the steel material according to this embodiment and a reason why it is limited will be described. Note that % regarding the contents of the following elements means mass%.

C: 0.10% to 1.50%

**[0016]** C is an element that imparts hardness to improve fatigue life. To obtain required strength and hardness, the content of C needs to be 0.10% or more. However, a C content exceeding 1.50% leads to excessively high hardness to cause a hardening crack. Therefore, the C content is set to 0.10% to 1.50%. Note that C: 0.10% to less than 0.45% is suitable for a steel material for case hardening. C: 0.45% to less than 0.90% is suitable for a steel material for induction hardening. C: 0.90% to 1.50% is suitable for a steel material for thorough hardening. Further, a lower limit of the C content is preferably 0.15%. An upper limit of the C content is preferably 1.35%.

Si: 0.01% to 0.80%

**[0017]** Si is an element that enhances hardenability to improve fatigue life. To obtain this effect, the content of Si needs to be 0.01% or more. However, if the Si content is more than 0.80%, the effect of enhancing hardenability saturates, and it affects a deoxidation state to affect the formation of an oxide, leading to a poor fatigue property. Therefore, the Si content is set to 0.01% to 0.80%. Further, a lower limit of the Si content is preferably set to 0.07%. An upper limit of the Si content is preferably set to 0.65% or less.

Mn: 0.10% to 1.50%

**[0018]** Mn is an element that enhances hardenability to increase strength, thereby improving fatigue life. To obtain this effect, the content of Mn needs to be 0.10% or more. However, if the Mn content is more than 1.50%, the effect of improving hardenability saturates and a hardening crack is caused on the contrary. Therefore, the Mn content is set to 0.10% to 1.50%. A lower limit of the Mn content is preferably set to 0.20%. An upper limit of the Mn content is preferably set to 1.20%.

Cr: 0.02% to 2.50%

**[0019]** Cr is an element that enhances hardenability to improve fatigue life. To stably obtain this effect, the content of Cr is preferably 0.02% or more. However, if the Cr content is more than 2.50%, the effect of improving hardenability saturates and a hardening crack is caused on the contrary. Therefore, an upper limit of the Cr content is set to 2.50%. Further, a lower limit of the Cr content is preferably set to 0.15% or more. An upper limit of the Cr content is preferably set to 2.00% or less. The Cr content may be regulated to 1.90% or less, or 1.80% or less.
**[0020]** Incidentally, in the use as a case-hardened steel material for bearing, Cr: 0.02 to 1.50% is desirable. In the use as an induction-hardened steel material for bearing or a thorough-hardened steel material for bearing, Cr: 0.70 to 2.50% is preferable.

Al: 0.002% to less than 0.010%

**[0021]** Al needs to be contained in an amount of 0.002% or more as a deoxidizing element which reduces T.O (total oxygen amount). However, an Al content of 0.010% or more leads to an increase in an amount of clustered alumina, possibly inhibiting the sufficient reforming into the REM-Al-Mg-O-based inclusion by the addition of Mg and REM. Therefore, the Al content is set to less than 0.010%. A lower limit of the Al content is preferably set to 0.005% or more. An upper limit of the Al content is preferably 0.008% or less.

Ce + La + Nd: 0.0001% to 0.0025%

**[0022]** Ce (cerium), La (lanthanum), and Nd (neodymium) are elements classified as the rare-earth element. The rare-earth element is a generic name for totally seventeen elements, namely, fifteen elements from lanthanum whose atomic number is 57 up to lutetium whose atomic number is 71, with the addition of scandium whose atomic number is 21 and yttrium whose atomic number is 39. The rare-earth elements are strong deoxidizing elements and play a very important role in the steel material for bearing according to this embodiment. The main components of a rare-earth element alloy for steelmaking are three elements of Ce, La, and Nd, and therefore, in the present invention, the limitation is set for Ce, La, and Nd out of the seventeen rare-earth elements. Elements contained in the rare-earth alloy other than the three elements are also strong deoxidizing elements and exhibit the same effect as that of the three elements. One of Ce, La, and Nd may be contained in an amount of 0.0001% to 0.0025%, or two or more of these may be contained totally in an amount of 0.0001% to 0.0025%. In the description of the present invention, Ce, La, and Nd are collectively called REM. REM first reacts with oxygen in molten steel to generate a REM-based oxide. Next, as alumina oxides in the molten steel aggregate into a cluster, the REM-based oxide is also taken in at the same time. Consequently, the Al-O-based oxide is reformed into a REM-Al-Mg-O-based inclusion.

**[0023]** REM in the steel material for bearing according to this embodiment functions as follows. It makes no great difference in the size of the clustered inclusion whether REM is added or not. However, the mixture of the REM-based oxide improves an interface state, specifically adhesion, with the base metal, and accordingly, even if the size does not change, the inclusion does not easily become a fracture initiation point, leading to an improved fatigue property.

**[0024]** To obtain such an effect, a predetermined amount or more of REM needs to be contained according to the T.O amount (total oxygen amount).

**[0025]** Studies made from these points of view have experimentally led to the findings that, if the content of REM is less than 0.0001%, the effect by contained REM is insufficient. Therefore, a lower limit of the REM content is set to 0.0001%, and the REM content is preferably set to 0.0003% or more, and more preferably 0.0008% or more. However, a REM content exceeding 0.0025% leads to not only a cost increase but also easy clogging of a casting nozzle to inhibit the manufacture of steel. Therefore, an upper limit of the REM content is 0.0025%, preferably 0.0020%, and more preferably 0.0018%.

Mg: 0.0005% to 0.0050%

**[0026]** Mg is a strong deoxidizing element similarly to Al and plays a very important role in the steel material according to this embodiment. Mg by itself has a small effect of reducing the fracture initiated from the cluster oxide, but the combination of REM and Mg more increases the effect of improving a fatigue property than REM alone. To obtain this effect, the content of Mg needs to be 0.0005% or more. A large Mg content leads to an increase in an amount of the oxide itself, possibly preventing the reformation into the REM-Al-Mg-O-based inclusion by the addition of REM. Therefore, the Mg content is set to 0.0050% or less. A lower limit of the Mg content is regulated to 0.0010% or more. An upper limit of the Mg content is preferably regulated to 0.0040% or less.

O: 0.0001 % to 0.0020%

**[0027]** O is an impurity and an element to be removed from the steel by deoxidation. If the deoxidation completely eliminates O in the steel, the alumina cluster is not generated and the problem to be solved by the present invention does not naturally occur. However, because of technical and cost reasons, conventional steel inevitably contains 0.0001 % or more of O, and the consequently generated alumina cluster possibly causes a poor fatigue property. In steel whose oxygen content is about equal to a typical oxygen content, the present invention achieves a higher fatigue property than conventionally. Typically, the O content in steel is often 0.0005% or more. On the other hand, if the O content is more than 0.0020%, a large amount of the oxide such as alumina remains, leading to poor fatigue life. Therefore, an upper limit of the O content is set to 0.0020%. The O content is preferably 0.0015% or less.

A composition ratio of Ce, La, Nd, Mg, and Al (Ce% + La% + Nd% + Mg%)/Al% in the fatigue-initiating inclusion: 0.20 or more

**[0028]** Reforming the Al-O-based inclusion which is the clustered oxide into the REM-Al-Mg-O-based inclusion improves adhesion between the oxide-based inclusion and the base metal to improve a fatigue property. This effect is exhibited in the case where a composition ratio of Ce, La, Nd, Mg, and Al (Ce% + La% + Nd% + Mg%)/Al% in the fatigue-initiating inclusion is 0.20 or more. Therefore, (Ce% + La% + Nd% + Mg%)/Al% is set to 0.20 or more. To more increase the above effect, (Ce% + La% + Nd% + Mg%)/Al% is preferably 0.50 or more.

**[0029]** Ce%, La%, Nd%, Mg%, and Al% in the fatigue-initiating inclusion are each a ratio of the atomicity (atomic (at)%) of the relevant element to the total atomicity of Ce, La, Nd, Mg, and Al contained in the fatigue-initiating inclusion. A fatigue-initiating inclusion in which all the three items of Al%, Mg%, and (Ce% + La% + Nd%) are all 0.1 or more is regarded as the "REM-Al-Mg-O-based inclusion". Desirably, Mg% and (Ce% + La% + Nd%) in the fatigue-initiating inclusion are both 1.0 or more. Note that in the calculation of the above atomic (at)%, the atomicity of O and a ratio of O are not taken into consideration, but the aforesaid elements form a composite inclusion through O and the fatigue-initiating inclusion contains O.

**[0030]** The basic component composition of the steel material according to this embodiment is as described above, and the balance is made up of iron and impurities. Note that "impurities" in "the balance is made up of iron and impurities" refers to those that inevitably mix from a raw material such as ore or scrap, a manufacturing environment, or the like during the industrial manufacture of steel. Note that, in the steel material according to this embodiment, the following limitations need to be set for Ti, N, P, S, and Ca which are impurities.

Ti: 0.000% to less than 0.005%

**[0031]** Ti is an impurity and forms TiN if present in the steel, leading to a poor fatigue property. Therefore, the Ti content is limited to less than 0.005%. The Ti content is preferably limited to 0.004% or less.

N: 0.0180% or less

**[0032]** N is an impurity and forms a nitride if present in the steel, leading to a poor fatigue property and also leading to poor ductility and toughness due to strain aging. If the N content is more than 0.0180%, problems such as poor fatigue property, ductility, and toughness noticeably occur. Therefore, an upper limit of the N content is limited to 0.0180%. The N content is preferably limited to 0.0150% or less. The N content may be 0.0000% but there is an industrial limitation in reducing the N content, and excessively reducing the N content is meaningless. As a lower limit practically attained at an ordinary cost, the N content may be limited to 0.0020%.

P: 0.030% or less

**[0033]** P is an impurity and segregates in crystal boundaries if present in the steel, leading to poor fatigue life. A P content exceeding 0.030% leads to poor fatigue life. Therefore, an upper limit of the P content is limited to 0.030%. The P content is preferably limited to 0.020% or less. A lower limit of the P content may be 0.000%, but as an industrial lower limit, it may be 0.001 %.

S: 0.005% or less

**[0034]** S forms a sulfide if present in the steel. If the S content is more than 0.005%, S bonds with REM to form the sulfide to reduce REM effective for the reformation of the alumina cluster, leading to poor fatigue life. Therefore, an upper limit of the S content is limited to 0.005%. The S content is preferably limited to 0.0025% or less. A lower limit of the S content may be 0.000%, but as an industrial lower limit, it may be 0.001%.

Ca: 0.0000% to 0.0010%

**[0035]** Ca forms coarse CaO if present in the steel, leading to poor fatigue life, and therefore, an upper limit of the Ca content is set to 0.0010%. The Ca content is preferably 0.0002% or less, and more preferably 0.0000%.

**[0036]** In addition to the above-described elements, the following elements may be optionally contained. Hereinafter, the optional elements will be described.

**[0037]** The steel material according to this embodiment may further contain one or more of V: 0.00% to 0.40%, Mo: 0.00% to 0.60%, Cu: 0.00% to 0.50%, Nb: 0.000% to 0.050%, Ni: 0.00% to 2.50%, Pb: 0.00 to 0.10%, Bi: 0.00 to 0.10%, and B: 0.0000 to 0.0050%.

V: 0.00% to 0.40%

**[0038]** V is an element that bonds with C and N in the steel to form a carbide, a nitride, or a carbonitride and contributes to the microstructure fining and strengthening of the steel. To stably obtain this effect, the content of V is preferably 0.05% or more. The V content is more preferably 0.10% or more. However, if the V content is more than 0.40%, the effect by contained V saturates and a crack occurs during hot working, and therefore, an upper limit of the V content is set to 0.40%. The V content is preferably set to 0.30% or less.

Mo: 0.00% to 0.60%

**[0039]** Mo is an element that not only enhances hardenability but also bonds with C in the steel to form a carbide to contribute to an improvement in the strength of the steel by precipitation strengthening. To stably obtain this effect, the content of Mo is preferably 0.05% or more. The Mo content is more preferably 0.10% or more. However, a Mo content exceeding 0.60% leads to a hardening crack on the contrary, and therefore, an upper limit of the Mo content is set to 0.60%. The Mo content is preferably 0.50% or less.

Cu: 0.00% to 0.50%

**[0040]** Cu is an element that contributes to an improvement in fatigue property by strengthening the base metal. To stably obtain this effect, the content of Cu is preferably 0.05% or more. However, a Cu content exceeding 0.50% leads to the occurrence of a crack during the hot working, and therefore, an upper limit of the Cu content is set to 0.50%. The Cu content is preferably 0.35% or less.

Nb: 0.000% to less than 0.050%

**[0041]** Nb is an element that contributes to an improvement in fatigue property by strengthening the base metal. To stably obtain this effect, the content of Nb is preferably 0.005% or more. The Nb content is more preferably 0.010% or more. However, if the Nb content is 0.050% or more, the effect by contained Nb saturates and also a crack occurs during the hot working, and therefore, the Nb content is set to less than 0.050%. The Nb content is preferably 0.030% or less.

Ni: 0.00% to 2.50% or less

**[0042]** Ni is an element that contributes to an improvement in fatigue life by increasing corrosion resistance. To stably obtain this effect, the content of Ni is preferably 0.10% or more. The Ni content is more preferably 0.30% or more. However, a Ni content exceeding 2.50% leads to poor machinability of the steel, and therefore, an upper limit of the Ni content is set to 2.50%. The Ni content is preferably 2.00% or less.

Pb: 0.00% to 0.10%

**[0043]** Pb is added to enhance the machinability of the steel. However, if its content is more than 0.10%, Pb becomes an initiation point of a fatigue crack to lower fatigue strength. Therefore, an upper limit of the Pb content is set to 0.10%. The Pb content is preferably 0.06% or less.

Bi: 0.00% to 0.10%

**[0044]** Bi is added to enhance the machinability of the steel. However, if its content is more than 0.10%, Bi becomes an initiation point of a fatigue crack to lower fatigue strength. Therefore, an upper limit of the Bi content is set to 0.10%. The Bi content is preferably 0.06% or less.

B: 0.0000% to 0.0050%

**[0045]** B segregates to austenite grain boundaries to have an effect of increasing grain boundary strength to improve toughness. However, a B content exceeding 0.0050% leads to the abnormal growth of austenite grains during a heat treatment, leading to poor fatigue strength. Therefore, an upper limit of the B content is set to 0.0050%. The B content is preferably 0.0030% or less.

**[0046]** In the steel material according to this embodiment, the aforesaid clustered oxide is elongated by being rolled. However, in the steel material according to this embodiment, an alumina simple substance is turned into a composite with the REM oxide, so that the state of the interface with the base metal is improved regardless of the form and size of the steel material, leading to an improvement in fatigue property.

**[0047]** A preferable method of manufacturing the steel material according to this embodiment will be described.

**[0048]** In the method of manufacturing the steel material according to this embodiment, the order of adding deoxidizers when the molten steel is refined is important. In this manufacturing method, Al and Mg are first used for the deoxidation. Then, the deoxidation for sixty seconds or longer using REM is performed, followed by ladle refining including vacuum degassing.

**[0049]** If REM is added at an initial stage of the deoxidation, a REM-O-based oxide is formed to be fixed, and it is not possible to reform alumina or an Al-Mg-O-based oxide which will be formed later. Therefore, Al is added at the beginning of the deoxidation, then Mg is added to fix O contained in the molten steel as an oxide. Thereafter, REM is added to reform the clustered oxide into the REM-Al-Mg-O-based inclusion. For the addition of REM, misch metal (alloy of a plurality of rare-earth metals) or the like is usable, and for example, massive misch metal may be added to the molten steel in a final stage of the refining.

**[0050]** The time of the deoxidation using REM is sixty seconds or longer. This is a time necessary for added REM to take the oxygen thereto from the Al-Mg-O-based oxide, which is once formed, to form the REM-based oxide.

**[0051]** In the case where Ca is added for the deoxidation, a large number of Al-Ca-O-based inclusions which have a low melting point and thus are easily elongated are generated. Therefore, even if REM is added after a large number of the Al-Ca-O-based inclusions are generated, it is difficult to reform the composition of the inclusion. Therefore, the addition or mixture of Ca needs to be reduced as much as possible.

**[0052]** As described above, in this manufacturing method, it is possible to reform the Al-O-based clustered oxide into the REM-Al-Mg-O-based inclusion, leading to an improvement in the rolling property of the steel material.

**[0053]** In the case where the steel material according to this embodiment is used in a bearing, a generation amount of MnS and a generation amount of TiN which is independently present are ideally very small, but they need not be zero. This is because limiting the addition amounts of S and Ti as described above prevents MnS and TiN from becoming coarser than the clustered oxide and becoming initiation points of a fatigue fracture.

**[0054]** This manufacturing method heats a cast slab having undergone casting to a heating temperature, thereafter retains it in a temperature range of 1200°C to 1250°C for not shorter than sixty seconds nor longer than sixty minutes, and thereafter applies hot rolling or hot forging to manufacture the steel material. This steel material as a raw material is cut into a shape close to a final shape and by thereafter applying a heat treatment such as carburizing-quenching, induction hardening, or thorough hardening thereto, it is possible for its surface to have hardness suitable for the bearing. Note that, in the steel material according to this embodiment, C: 0.10% to 1.50%. C: 0.10% to less than 0.45% is suitable for a steel material for case-hardening, and as a result of the carburizing-quenching, the hardness of the surface can be 700 Hv (measurement load 2.94 N) or more in terms of Vickers hardness. Further, in the case of C: 0.45% to 1.50%, as a result of the induction hardening, the hardness of the surface can be 650 Hv (measurement load 2.94 N) or more in terms of Vickers hardness. Further, C: 0.90% to 1.50% is suitable for a thorough-hardened steel material for bearing.

**[0055]** A rolling member made of the steel material of the present invention having undergone the heat treatment such as the carburizing-quenching, the induction hardening, or the thorough hardening is excellent in fatigue property. Incidentally, in the case where the steel material is used as the rolling member, it is usually finished to a final product using a means capable of high-hardness and high-precision working, such as polishing as needed.

## [Examples]

**[0056]** Next, examples of the present invention will be described, but conditions in the examples are only condition examples adopted for confirming the feasibility and effects of the present invention, and the present invention is not limited to the condition examples. The present invention can adopt various conditions without departing from the spirit of the present invention as long as the object of the present invention is attained.

### (Example 1) Example assuming a case-hardened bearing

**[0057]** 150 kg steel types having the components of No. A1 to A16 (present invention examples) and No. B1 to B14 (comparative examples) shown in Table 1 were cast in a vacuum melting furnace. The deoxidation was performed under different deoxidation conditions a to f shown in Table 2, and their influences were examined. In the case where REM was added, misch metal was added with a 40% expected yield.

**[0058]** In all the deoxidation conditions a, b, and d, Al, Mg, and REM were added as deoxidizers in the order mentioned, and in the deoxidation condition a, tapping was performed after ninety seconds passed from the REM addition. In the deoxidation condition b, when it was confirmed that 500 seconds passed from the REM addition, tapping was performed. In the deoxidation condition d, tapping was performed immediately after thirty seconds passed from the REM addition. In the deoxidation condition c, REM, Al, and Mg were added as deoxidizers in the order mentioned, and the time of the deoxidation using REM was set to 120 seconds. In the deoxidation condition e, for the deoxidation, Al and Mg were added as deoxidizers in the order mentioned without the deoxidation by the addition of REM being performed. In the deoxidation condition f, Al and REM were added as deoxidizers in the order mentioned for the deoxidation, and when it was confirmed that ninety seconds passed from the addition of REM, tapping was performed.

**[0059]** The tapping is followed by hot forging into round bars with ϕ80, and they were used as raw materials for test piece collection. The round bars were each cut along a cross section perpendicular to its longitudinal direction, and then rolling fatigue test pieces illustrated in FIG. 1 were collected. Specifically, the rolling fatigue test pieces are each in a disc shape having a thickness of 6.0 mm and a diameter of 60 mm, with its circular surface being perpendicular to the longitudinal direction of the original round bar. These rolling fatigue test pieces each imitate an inner ring and an outer ring in a bearing. In a rolling fatigue test, the circular surface of the rolling fatigue test piece corresponds to a test surface, and this surface comes into contact with a rolling element to be given a fatigue load.

**[0060]** After the rolling fatigue test pieces were collected, they were carburized-quenched and tempered such that the load-applied portions (test surfaces) uniformly came to have a hardness of 700 Hv or more equivalent to that of a material for bearing. Here, Vickers hardness was measured under a measurement load of 2.94 N. A tempering condition was 180°C and 1 hr. After the tempering, the test surfaces were mirror-finished and subjected to the rolling fatigue test. The rolling fatigue test was conducted with a Mori-type thrust test machine (contact surface pressure: 5.33 GPa). Regarding the results of the test conducted ten times on each of the standards (No. 1 to 32 in Table 3), the number of cycles causing 10% out of the evaluation samples to reach fracture was evaluated as a fatigue property L10 using Weibull statistics.

**[0061]** To evaluate a fatigue-initiating inclusion, an ultrasonic fatigue test was conducted using the test pieces shown in FIG. 2. The ultrasonic fatigue test pieces for this test were collected also from the round bars used as the raw materials of the above-described rolling fatigue test pieces. The ultrasonic fatigue test pieces are collected in the manner that, the longitudinal direction of the test pieces was set perpendicular to the longitudinal direction of the round bars serving as the raw materials. In collecting the ultrasonic fatigue test pieces, raw materials whose diameter was about 0.3 mm larger than that of a predetermined shape of the ultrasonic fatigue test pieces were collected, and other steel materials were further welded to form grip portions. Thereafter, test portions were carburized for a time long enough for their surface layers to have a carbon concentration equal to that of the rolling fatigue test pieces and for the test portions to be carburized up to their center portions, and then they were subjected to a hardening treatment and a 1 hr. 180°C tempering treatment. Thereafter, they were finished to the predetermined ultrasonic test piece shape. The ultrasonic fatigue test was executed under a fixed frequency of 20 kHz, a fixed stress ratio of -1, and a fixed stress amplitude of 700 to 850 MPa until a fracture occurred. The composition of the fatigue-initiating inclusion in this ultrasonic fatigue test was analyzed using EDX (Energy Dispersive X-ray Spectroscopy analysis), and the total atomic (at)% of the aforesaid REM and the atomic (at)% of Mg and Al were measured.

**[0062]** The fatigue-initiating inclusion was identified as follows. As illustrated in FIG. 3, within a gauge length L of an ultrasonic fatigue test piece 1, many inclusions a are included. A fatigue fracture is initiated from an inclusion a' that causes a stress concentration most in the ultrasonic fatigue test, among these inclusions a. The inclusion a' that causes the stress concentration most is a fatigue-initiating inclusion whose stress concentration factor is the largest in the ultrasonic fatigue test due to its size, shape, and so on.

**[0063]** FIGs. 4 are explanatory views schematically illustrating how the fatigue fracture gradually progresses. First, as illustrated in FIG. 4(a), around the inclusion a' (fatigue-initiating inclusion), a circular fatigue crack occurs in a cross section, of the ultrasonic fatigue test piece 1, perpendicular to its longitudinal direction. Then, as illustrated in FIG. 4(b), with an increase in the number of the stress amplitudes, a fracture surface 10 circularly spreads. When the fracture surface 10 spreads to a certain degree in accordance with a further increase in the number of the stress amplitudes, the crack progresses to a fracture at a stroke as illustrated in FIG. 4(c).

**[0064]** In the fracture surface of the ultrasonic fatigue test piece 1 which has fractured, a circular pattern 11 called a fisheye remains around the inclusion a' (fatigue-initiating inclusion) as illustrated in FIG. 5. The circular pattern 11 corresponds to the fracture surface 10 immediately before the fracture progresses at a stroke. Here, the atomic (at)% of Ce, La, Nd, Mg, and Al contained in the inclusion a' (fatigue-initiating inclusion) present at the center of this circular pattern 11 is measured and (Ce% + La% + Nd% + Mg%)/Al% is found.

**[0065]** The initiating inclusion was observed at a magnification of x500 under an acceleration voltage of 20 kV, and its composition was measured. A field of view of EDS measurement is decided such that the center of the inclusion becomes the center of the field of view. FIG. 6 illustrates an example of a reflected electron composition image of the initiating inclusion used in the composition analysis. As illustrated in FIG. 6, an inclusion portion and a non-inclusion portion are not clearly distinguishable. Therefore, an area corresponding to the inclusion in the field of view (inclusion area) was identified, and this area was extracted and the chemical composition was measured therein. The inclusion has a major axis of about 100 to 300 μm, and even if the entire inclusion does not fit in the field of view, values obtained in one field of view are used as the composition of the inclusion. Regarding the aforesaid field of view, element mapping by EDS is performed with a dwell time of 0.5 μs and a preset of 5, and from an X-ray spectrum obtained from the inclusion area, the atomic (at)% of each of Ce, La, Nd, Mg, and Al was found, and the composition of the inclusion was measured. For data acquisition and analysis of EDS, an EDS analysis system: Analysis Station (manufactured by JEOL Ltd.) is used. Incidentally, in the calculation of the atomic (at)% in Table 3, a ratio of O is not taken into consideration, but any of the fatigue-initiating inclusions is a composite inclusion formed through O and contained O. Further, in some of the comparative examples, the fatigue-initiating inclusion contained other elements (Mn, Ti, and so on), but elements other than Ce, La, Nd, Mg, and Al are not taken into consideration in the calculation of the atomic (at)%.

**[0066]** Table 1 shows the chemical composition of each steel type in Example 1. Table 2 shows the deoxidation conditions a to f. Table 3 shows the steel type, the deoxidation condition, the oxide form and composition of the fatigue-initiating inclusion in the ultrasonic fatigue test, and the fatigue property (L10 life) in the rolling fatigue test, regarding the standards (No. 1 to 34).

**[0067]** The fatigue life L10 of the present invention examples was $10^7$ cycles or more and was superior to those of the steel types of the comparative examples.

[Table 1]

| | No. | C | Si | Mn | P | S | Cr | Al | Mg | REM | Ti | O | N | Ca | V | Mo | Cu | Nb | Ni | Pb | Bi | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRESENT INVENTION EXAMPLE | A1 | 0.21 | 0.43 | 0.72 | 0.014 | 0.002 | 1.54 | 0.009 | 0.0016 | 0.0003 | 0.001 | 0.0010 | 0.0060 | 0.0005 | - | - | - | - | - | - | - | - |
| | A2 | 0.22 | 0.54 | 0.94 | 0.015 | 0.004 | 0.82 | 0.004 | 0.0017 | 0.0004 | 0.002 | 0.0008 | 0.0094 | 0.0008 | - | - | - | - | - | - | - | - |
| | A3 | 0.30 | 0.66 | 0.58 | 0.016 | 0.002 | 1.66 | 0.007 | 0.0043 | 0.0016 | 0.004 | 0.0010 | 0.0094 | 0.0006 | - | - | - | - | - | - | - | - |
| | A4 | 0.24 | 0.62 | 0.54 | 0.012 | 0.003 | 1.18 | 0.008 | 0.0039 | 0.0016 | 0.003 | 0.0009 | 0.0109 | 0.0004 | - | - | - | - | - | - | - | - |
| | A5 | 0.26 | 0.22 | 0.71 | 0.016 | 0.002 | 1.62 | 0.005 | 0.0041 | 0.0012 | 0.003 | 0.0010 | 0.0088 | 0.0009 | 0.08 | - | - | - | - | - | - | - |
| | A6 | 0.23 | 0.25 | 0.32 | 0.015 | 0.004 | 1.57 | 0.007 | 0.0044 | 0.0007 | 0.003 | 0.0011 | 0.0097 | 0.0007 | - | 0.55 | - | - | - | - | - | - |
| | A7 | 0.21 | 0.64 | 0.93 | 0.014 | 0.003 | 0.92 | 0.004 | 0.0031 | 0.0008 | 0.001 | 0.0011 | 0.0104 | 0.0001 | - | - | 0.18 | - | - | - | - | - |
| | A8 | 0.29 | 0.32 | 0.56 | 0.024 | 0.004 | 0.82 | 0.005 | 0.0040 | 0.0009 | 0.004 | 0.0008 | 0.0073 | 0.0005 | - | - | - | 0.035 | - | - | - | - |
| | A9 | 0.29 | 0.52 | 1.28 | 0.017 | 0.004 | 0.99 | 0.005 | 0.0009 | 0.0014 | 0.002 | 0.0009 | 0.0083 | 0.0005 | - | - | - | - | 1.20 | - | - | - |
| | A10 | 0.21 | 0.40 | 1.25 | 0.016 | 0.003 | 1.24 | 0.005 | 0.0038 | 0.0002 | 0.002 | 0.0010 | 0.0107 | 0.0005 | 0.06 | 0.05 | - | - | - | - | - | - |
| | A11 | 0.25 | 0.51 | 1.13 | 0.015 | 0.002 | 1.32 | 0.007 | 0.0011 | 0.0008 | 0.002 | 0.0009 | 0.0085 | 0.0009 | 0.05 | 0.10 | 0.06 | 0.012 | 0.43 | - | - | - |
| | A12 | 0.20 | 0.20 | 0.80 | 0.015 | 0.002 | 1.20 | 0.005 | 0.0015 | 0.0008 | 0.002 | 0.0009 | 0.0085 | 0.0009 | - | - | - | - | - | 0.03 | - | - |
| | A13 | 0.21 | 0.19 | 0.79 | 0.015 | 0.002 | 1.22 | 0.005 | 0.0010 | 0.0008 | 0.002 | 0.0011 | 0.0070 | 0.0003 | - | - | - | - | - | - | 0.10 | - |
| | A14 | 0.20 | 0.05 | 0.78 | 0.015 | 0.003 | 1.19 | 0.007 | 0.0010 | 0.0009 | 0.002 | 0.0009 | 0.0085 | 0.0009 | - | - | - | - | - | - | - | 0.0040 |
| | A15 | 0.12 | 0.20 | 0.79 | 0.015 | 0.002 | 1.20 | 0.007 | 0.0011 | 0.0015 | 0.002 | 0.0009 | 0.0153 | 0.0003 | - | - | - | - | - | - | - | - |
| | A16 | 0.20 | 0.20 | 0.78 | 0.014 | 0.002 | 2.42 | 0.008 | 0.0014 | 0.0010 | 0.001 | 0.0010 | 0.0148 | 0.0003 | - | - | - | - | - | - | - | - |
| COMPARATIVE EXAMPLE | B1 | ***0.07*** | 0.51 | 0.42 | 0.012 | 0.002 | 0.92 | 0.005 | 0.0010 | 0.0003 | 0.001 | 0.0008 | 0.0072 | 0.0002 | - | - | - | - | - | - | - | - |
| | B2 | 0.26 | ***0.85*** | 1.02 | 0.010 | 0.004 | 1.54 | 0.005 | 0.0043 | 0.0012 | 0.002 | 0.0012 | 0.0109 | 0.0008 | - | - | - | - | - | - | - | - |
| | B3 | 0.21 | 0.18 | 1.12 | ***0.038*** | 0.004 | 1.73 | 0.005 | 0.0026 | 0.0012 | 0.003 | 0.0013 | 0.0066 | 0.0006 | - | - | - | - | - | - | - | - |
| | B4 | 0.20 | 0.65 | 0.78 | 0.023 | ***0.008*** | 1.34 | 0.007 | 0.0027 | 0.0005 | 0.003 | 0.0013 | 0.0070 | 0.0008 | - | - | - | - | - | - | - | - |
| | B5 | 0.28 | 0.37 | 0.98 | 0.025 | 0.003 | 1.60 | ***0.013*** | 0.0018 | 0.0007 | 0.002 | 0.0011 | 0.0127 | 0.0007 | - | - | - | - | - | - | - | - |
| | B6 | 0.30 | 0.48 | 0.78 | 0.022 | 0.003 | 1.76 | 0.007 | 0.0014 | - | 0.002 | 0.0009 | 0.0090 | 0.0007 | - | - | - | - | - | - | - | - |
| | B7 | 0.27 | 0.40 | 1.08 | 0.019 | 0.003 | 0.92 | 0.003 | - | 0.0007 | 0.002 | 0.0010 | 0.0080 | 0.0009 | - | - | - | - | - | - | - | - |
| | B8 | 0.25 | 0.59 | 0.70 | 0.011 | 0.003 | 0.81 | 0.005 | ***0.0002*** | 0.0003 | 0.004 | 0.0011 | 0.0080 | 0.0007 | - | - | - | - | - | - | - | - |
| | B9 | 0.27 | 0.23 | 0.34 | 0.013 | 0.004 | 1.51 | 0.006 | ***0.0065*** | 0.0010 | 0.001 | 0.0009 | 0.0090 | 0.0008 | - | - | - | - | - | - | - | - |
| | B10 | 0.33 | 0.59 | 0.69 | 0.016 | 0.004 | 1.51 | 0.004 | 0.0044 | ***0.0027*** | 0.002 | 0.0010 | 0.0061 | 0.0006 | - | - | - | - | - | - | - | - |
| | B11 | 0.19 | 0.24 | 0.58 | 0.024 | 0.003 | 1.31 | 0.007 | 0.0021 | 0.0010 | ***0.007*** | 0.0009 | 0.0096 | 0.0002 | - | - | - | - | - | - | - | - |
| | B12 | 0.19 | 0.61 | 0.70 | 0.022 | 0.004 | 1.73 | 0.008 | 0.0024 | 0.0011 | 0.004 | ***0.0023*** | 0.0069 | 0.0003 | - | - | - | - | - | - | - | - |
| | B13 | 0.29 | 0.66 | 0.55 | 0.019 | 0.003 | 1.51 | 0.007 | 0.0039 | 0.0015 | 0.003 | 0.0012 | ***0.0290*** | 0.0007 | - | - | - | - | - | - | - | - |
| | B14 | 0.29 | 0.31 | 1.16 | 0.019 | 0.004 | 1.71 | 0.003 | 0.0007 | 0.0014 | 0.003 | 0.0010 | 0.0062 | ***0.0013*** | - | - | - | - | - | - | - | - |

[Table 2]

| | DEOXIDATION CONDITION | ORDER OF ADDING DEOXIDIZERS | REM DEOXIDATION TIME (SECOND) |
|---|---|---|---|
| PREFERABLE CONDITION | a | Al-Mg-REM | 90 |
| | b | Al-Mg-REM | 500 |
| | | | |
| UNPREFERABLE CONDITION | c | ***REM-Al-Mg*** | 120 |
| | d | Al-Mg-REM | *30* |
| | e | ***Al-Mg*** | (WITHOUT REM DEOXIDATION) |
| | f | *Al-REM* | 90 |

[Table 3]

| | No. | STEEL TYPE | DEOXIDATION CONDITION | OXIDE FORM | COMPOSITION IN INITIATING INCLUSION (at%) | | | | FATIGUE PROPERTY (L10 LIFE) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | REM(a) | Mg(b) | Al(c) | (a+b)/c | NUMBER OF CYCLES (× 10^5) |
| PRESENT INVENTION EXAMPLE | 1 | A1 | a | Al-REM-Mg-O-BASED (CLUSTER) | 30.1 | 5.0 | 64.9 | 0.54 | 110.4 |
| | 2 | A2 | a | Al-REM-Mg-O-BASED (CLUSTER) | 17.1 | 4.0 | 78.9 | 0.27 | 107.8 |
| | 3 | A3 | a | Al-REM-Mg-O-BASED (CLUSTER) | 34.0 | 4.6 | 61.4 | 0.63 | 118.0 |
| | 4 | A4 | a | Al-REM-Mg-O-BASED (CLUSTER) | 24.3 | 9.2 | 66.5 | 0.50 | 119.1 |
| | 5 | A5 | a | Al-REM-Mg-O-BASED (CLUSTER) | 39.7 | 9.0 | 51.3 | 0.95 | 106.5 |
| | 6 | A6 | a | Al-REM-Mg-O-BASED (CLUSTER) | 27.0 | 7.2 | 65.8 | 0.52 | 108.2 |
| | 7 | A7 | a | Al-REM-Mg-O-BASED (CLUSTER) | 33.9 | 10.3 | 55.8 | 0.79 | 102.3 |
| | 8 | A8 | b | Al-REM-Mg-O-BASED (CLUSTER) | 31.1 | 5.7 | 63.2 | 0.58 | 119.6 |
| | 9 | A9 | b | Al-REM-Mg-O-BASED (CLUSTER) | 18.5 | 11.9 | 69.6 | 0.44 | 119.4 |
| | 10 | A10 | b | Al-REM-Mg-O-BASED (CLUSTER) | 23.1 | 11.3 | 65.6 | 0.53 | 107.2 |
| | 11 | A11 | b | Al-REM-Mg-O-BASED (CLUSTER) | 23.1 | 10.3 | 66.6 | 0.50 | 101.2 |
| | 12 | A12 | b | Al-REM-Mg-O-BASED (CLUSTER) | 22.8 | 7.6 | 69.6 | 0.44 | 105.7 |
| | 13 | A13 | b | Al-REM-Mg-O-BASED (CLUSTER) | 23.2 | 8.3 | 68.5 | 0.46 | 110.2 |
| | 14 | A14 | b | Al-REM-Mg-O-BASED (CLUSTER) | 25.4 | 8.5 | 66.1 | 0.51 | 111.4 |
| | 15 | A15 | a | Al-REM-Mg-O-BASED (CLUSTER) | 23.3 | 10.8 | 65.9 | 0.52 | 118.4 |
| | 16 | A16 | a | Al-REM-Mg-O-BASED (CLUSTER) | 21.4 | 11.9 | 66.7 | 0.50 | 115.6 |
| COMPARATIVE EXAMPLE | 17 | B1 | a | Al-REM-Mg-O-BASED (CLUSTER) | 32.2 | 5.1 | 62.7 | 0.59 | 20.4 |
| | 18 | B2 | a | Al-REM-Mg-O-BASED (CLUSTER) | 20.0 | 6.8 | 73.2 | 0.37 | 32.0 |
| | 19 | B3 | a | Al-REM-Mg-O-BASED (CLUSTER) | 22.9 | 9.4 | 67.8 | 0.48 | 32.3 |
| | 20 | B4 | a | ***Al-REM-Mg-O-BASED (CLUSTER)+ SULFIDE*** | ***9.5*** | 4.7 | 85.8 | ***0.17*** | 21.0 |
| | 21 | B5 | a | Al-REM-Mg-O-BASED (CLUSTER) | 10.3 | 3.9 | 85.8 | ***0.17*** | 33.9 |
| | 22 | B6 | e | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 17.8 | 82.2 | 0.22 | 28.7 |
| | 23 | B7 | f | ***Al-REM-O-BASED (CLUSTER)*** | 39.4 | ***0.0*** | 60.6 | 0.65 | 24.7 |
| | 24 | B8 | a | Al-REM-Mg-O-BASED (CLUSTER) | 40.6 | 0.8 | 58.6 | 0.71 | 20.1 |
| | 25 | B9 | a | Al-REM-Mg-O-BASED (CLUSTER) | 3.6 | 12.1 | 84.3 | ***0.19*** | 20.8 |
| | 26 | B10 | a | Al-REM-Mg-O-BASED (CLUSTER) | 40.2 | 8.7 | 51.1 | 0.96 | 28.2 |
| | 27 | B11 | a | ***Al-REM-Mg-O-BASED (CLUSTER)+ COARSE TiN*** | 36.6 | 11.0 | 52.4 | 0.91 | 24.2 |
| | 28 | B12 | a | Al-REM-Mg-O-BASED (CLUSTER) | 39.9 | 4.0 | 56.1 | 0.78 | 28.8 |
| | 29 | B13 | a | ***Al-REM-Mg-O-BASED (CLUSTER)+ COARSE TiN*** | 31.5 | 5.0 | 63.4 | 0.58 | 30.4 |
| | 30 | B14 | a | ***Al-Ca-O-BASED (COARSE SPHERICAL)*** | ***7.2*** | ***0.0*** | ***92.8*** | ***0.08*** | 32.3 |
| | 31 | A1 | c | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 8.5 | 91.5 | ***0.09*** | 27.3 |
| | 32 | A2 | c | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 10.4 | 89.6 | ***0.12*** | 27.2 |
| | 33 | A1 | d | Al-REM-Mg-O-BASED (CLUSTER) | 1.3 | 8.2 | 90.5 | ***0.10*** | 35.8 |
| | 34 | A2 | d | Al-REM-Mg-O-BASED (CLUSTER) | 1.1 | 7.5 | 91.4 | ***0.09*** | 35.9 |

**[0068]** (Example 2) Example assuming an induction-hardened bearing 150 kg steel types containing the components of No. C1 to C14 (present invention examples) and No. D1 to D10 (comparative examples) shown in Table 4 were cast in a vacuum melting furnace and were hot-forged into round bars (raw materials for the collection of test pieces) with ϕ80 mm as in Example 1. The deoxidation was performed under different deoxidation conditions a to f shown in Table 2 as in Example 1. After rolling fatigue test pieces were collected, their test portions were subjected to an induction hardening treatment and a 1 hr. 150°C tempering treatment. In the induction hardening treatment, a condition was set such that surface hardness after the tempering became 650 $H_V$ (measurement load 2.94 N) or more. Further, test surfaces were mirror-finished and subjected to a rolling fatigue test. The rolling fatigue test was conducted with a Mori-type thrust test machine (contact surface pressure: 5.33 GPa). Regarding the results of the test conducted ten times on each of the standards (No. 1 to 28 in Table 5), the number of cycles causing 10% out of the evaluation samples to reach fracture was evaluated as a fatigue property L10 using Weibull statistics.

**[0069]** To evaluate a fatigue-initiating inclusion, the same ultrasonic fatigue test as that in Example 1 was conducted. As a heat treatment of ultrasonic fatigue test pieces, test portions were subjected to an induction hardening treatment and then a 1 hr. 150°C tempering treatment. In the induction hardening treatment, a condition was set such that the hardness became 650 Hv (measurement load 2.94 N) or more from the surfaces to the centers of the test portions after the tempering. The fatigue test was executed under a fixed frequency of 20 kHz, a fixed stress ratio of -1, and a fixed stress amplitude of 700 to 850 MPa until a fracture occurred. The composition of the initiating inclusion in this ultrasonic fatigue test was analyzed using EDX (Energy Dispersive X-ray Spectroscopy analysis), and the total atomic (at)% of the aforesaid REM and the atomic (at)% of Mg and Al were measured. In Table 5 as well, a ratio of O is not taken into consideration in the calculation of the atomic (at)% as in Table 3, but in any of the examples, the initiating inclusion contained O.

**[0070]** Table 4 shows the chemical composition of each steel type in Example 2. Table 5 shows the steel type, the deoxidation condition, the oxide form and composition of the fatigue-initiating inclusion in the ultrasonic fatigue test, and the fatigue property (L10 life) in the rolling fatigue test, regarding the standards (No. 101 to 128).

**[0071]** The fatigue property L10 of the present invention examples each containing an appropriate amount of REM was $10^6$ cycles or more and was superior to those of the steel types of the comparative examples.

[Table 4]

| | STEEL TYPE | C | Si | Mn | P | S | Cr | Al | Mg | REM | Ti | O | N | Ca | V | Mo | Cu | Nb | Ni | Pb | Bi | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRESENT INVENTION EXAMPLE | C1 | 0.64 | 0.23 | 1.23 | 0.022 | 0.004 | 0.23 | 0.006 | 0.0019 | 0.0007 | 0.003 | 0.0009 | 0.0091 | 0.0003 | - | - | - | - | - | - | - | - |
| | C2 | 0.56 | 0.31 | 1.28 | 0.021 | 0.002 | 0.53 | 0.005 | 0.0034 | 0.0004 | 0.004 | 0.0009 | 0.0068 | 0.0001 | - | - | - | - | - | - | - | - |
| | C3 | 0.67 | 0.21 | 1.26 | 0.025 | 0.002 | 0.35 | 0.008 | 0.0031 | 0.0006 | 0.003 | 0.0011 | 0.0129 | 0.0006 | - | - | - | - | - | - | - | - |
| | C4 | 0.57 | 0.64 | 0.49 | 0.018 | 0.003 | 0.42 | 0.008 | 0.0009 | 0.0009 | 0.002 | 0.0012 | 0.0065 | 0.0003 | - | - | - | - | - | - | - | - |
| | C5 | 0.57 | 0.45 | 0.52 | 0.020 | 0.002 | 0.32 | 0.007 | 0.0030 | 0.0009 | 0.002 | 0.0008 | 0.0097 | 0.0004 | - | - | - | - | - | - | - | - |
| | C6 | 0.62 | 0.31 | 0.53 | 0.010 | 0.003 | 0.76 | 0.008 | 0.0032 | 0.0008 | 0.003 | 0.0010 | 0.0071 | 0.0004 | 0.10 | - | - | - | - | - | - | - |
| | C7 | 0.51 | 0.33 | 0.82 | 0.014 | 0.003 | 0.42 | 0.006 | 0.0020 | 0.0012 | 0.002 | 0.0011 | 0.0077 | 0.0008 | - | 0.20 | - | - | - | - | - | - |
| | C8 | 0.57 | 0.47 | 0.70 | 0.014 | 0.004 | 0.55 | 0.005 | 0.0037 | 0.0012 | 0.004 | 0.0012 | 0.0110 | 0.0004 | - | - | 0.20 | - | - | - | - | - |
| | C9 | 0.62 | 0.40 | 1.29 | 0.020 | 0.002 | 0.47 | 0.004 | 0.0028 | 0.0006 | 0.001 | 0.0010 | 0.0067 | 0.0004 | - | - | - | 0.044 | - | - | - | - |
| | C10 | 0.52 | 0.40 | 0.44 | 0.010 | 0.002 | 0.27 | 0.006 | 0.0043 | 0.0007 | 0.002 | 0.0009 | 0.0107 | 0.0003 | 0.06 | 0.05 | - | - | - | - | - | - |
| | C11 | 0.52 | 0.31 | 0.98 | 0.024 | 0.004 | 0.46 | 0.004 | 0.0020 | 0.0002 | 0.003 | 0.0011 | 0.0098 | 0.0007 | 0.08 | 0.05 | 0.08 | 0.015 | - | - | - | - |
| | C12 | 0.54 | 0.30 | 1.00 | 0.020 | 0.004 | 0.46 | 0.003 | 0.0021 | 0.0005 | 0.002 | 0.0011 | 0.0140 | 0.0006 | - | - | - | - | 0.46 | - | - | - |
| | C13 | 0.55 | 0.30 | 0.98 | 0.021 | 0.003 | 0.50 | 0.004 | 0.0022 | 0.0010 | 0.001 | 0.0009 | 0.0150 | 0.0002 | - | - | - | - | - | 0.08 | - | - |
| | C14 | 0.55 | 0.31 | 0.98 | 0.020 | 0.004 | 0.45 | 0.004 | 0.0025 | 0.0007 | 0.001 | 0.0011 | 0.0120 | 0.0003 | - | - | - | - | - | - | 0.06 | - |
| COMPARATIVE EXAMPLE | D1 | 0.53 | ***0.86*** | 0.39 | 0.023 | 0.003 | 0.61 | 0.007 | 0.0039 | 0.0007 | 0.003 | 0.0010 | 0.0087 | 0.0002 | - | - | - | - | - | - | - | - |
| | D2 | 0.74 | 0.46 | 0.56 | ***0.035*** | 0.002 | 0.72 | 0.009 | 0.0022 | 0.0014 | 0.002 | 0.0011 | 0.0067 | 0.0002 | - | - | - | - | - | - | - | - |
| | D3 | 0.58 | 0.34 | 0.55 | 0.019 | 0.004 | 0.46 | 0.004 | 0.0017 | - | 0.002 | 0.0011 | 0.0120 | 0.0008 | - | - | - | - | - | - | - | - |
| | D4 | 0.66 | 0.36 | 0.69 | 0.020 | 0.002 | 0.42 | 0.006 | - | 0.0005 | 0.000 | 0.0012 | 0.0080 | 0.0005 | - | - | - | - | - | - | - | - |
| | D5 | 0.56 | 0.23 | 0.81 | 0.010 | 0.004 | 0.59 | 0.007 | ***0.0003*** | 0.0004 | 0.003 | 0.0011 | 0.0080 | 0.0005 | - | - | - | - | - | - | - | - |
| | D6 | 0.63 | 0.36 | 0.68 | 0.016 | 0.003 | 0.42 | 0.007 | ***0.0061*** | 0.0012 | 0.004 | 0.0010 | 0.0100 | 0.0008 | - | - | - | - | - | - | - | - |
| | D7 | 0.59 | 0.64 | 0.46 | 0.013 | 0.004 | 0.41 | 0.008 | 0.0044 | ***0.0028*** | 0.003 | 0.0008 | 0.0100 | 0.0003 | - | - | - | - | - | - | - | - |
| | D8 | 0.60 | 0.35 | 1.02 | 0.024 | 0.003 | 0.50 | 0.007 | 0.0021 | 0.0013 | ***0.008*** | 0.0011 | 0.0077 | 0.0004 | - | - | - | - | - | - | - | - |
| | D9 | 0.59 | 0.22 | 1.04 | 0.013 | 0.003 | 0.26 | 0.008 | 0.0035 | 0.0002 | 0.003 | ***0.0023*** | 0.0108 | 0.0005 | - | - | - | - | - | - | - | - |
| | D10 | 0.49 | 0.41 | 0.55 | 0.023 | 0.004 | 0.65 | 0.008 | 0.0013 | 0.0005 | 0.002 | 0.0012 | 0.0120 | ***0.0014*** | - | - | - | - | - | - | - | - |

[Table 5]

| | No. | STEEL TYPE | DEOXIDATION CONDITION | OXIDE FORM | COMPOSITION IN INITIATING INCLUSION (at%) | | | | FATIGUE PROPERTY (L10 LIFE) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | REM(a) | Mg(b) | Al(c) | (a+b)/c | NUMBER OF CYCLES (× 10^5) |
| PRESENT INVENTION EXAMPLE | 101 | C1 | a | Al-REM-Mg-O-BASED (CLUSTER) | 21.7 | 10.3 | 68.0 | 0.47 | 35.3 |
| | 102 | C2 | a | Al-REM-Mg-O-BASED (CLUSTER) | 38.1 | 9.9 | 52.0 | 0.92 | 36.2 |
| | 103 | C3 | a | Al-REM-Mg-O-BASED (CLUSTER) | 42.3 | 10.4 | 47.3 | 1.11 | 40.3 |
| | 104 | C4 | a | Al-REM-Mg-O-BASED (CLUSTER) | 40.9 | 3.4 | 55.7 | 0.80 | 29.8 |
| | 105 | C5 | a | Al-REM-Mg-O-BASED (CLUSTER) | 26.8 | 6.1 | 67.2 | 0.49 | 32.2 |
| | 106 | C6 | a | Al-REM-Mg-O-BASED (CLUSTER) | 44.6 | 10.0 | 45.4 | 1.20 | 33.6 |
| | 107 | C7 | b | Al-REM-Mg-O-BASED (CLUSTER) | 44.3 | 5.4 | 50.3 | 0.99 | 32.7 |
| | 108 | C8 | b | Al-REM-Mg-O-BASED (CLUSTER) | 23.2 | 9.8 | 67.0 | 0.49 | 41.6 |
| | 109 | C9 | b | Al-REM-Mg-O-BASED (CLUSTER) | 44.0 | 8.5 | 47.5 | 1.11 | 37.2 |
| | 110 | C10 | b | Al-REM-Mg-O-BASED (CLUSTER) | 31.0 | 6.1 | 62.9 | 0.59 | 33.7 |
| | 111 | C11 | b | Al-REM-Mg-O-BASED (CLUSTER) | 23.0 | 8.4 | 68.6 | 0.46 | 31.9 |
| | 112 | C12 | a | Al-REM-Mg-O-BASED (CLUSTER) | 31.2 | 6.5 | 62.3 | 0.61 | 42.3 |
| | 113 | C13 | a | Al-REM-Mg-O-BASED (CLUSTER) | 33.1 | 7.1 | 59.8 | 0.67 | 32.1 |
| | 114 | C14 | a | Al-REM-Mg-O-BASED (CLUSTER) | 30.2 | 5.8 | 64.0 | 0.56 | 33.5 |
| COMPARATIVE EXAMPLE | 115 | D1 | a | Al-REM-Mg-O-BASED (CLUSTER) | 20.1 | 11.1 | 68.8 | 0.45 | 6.7 |
| | 116 | D2 | a | Al-REM-Mg-O-BASED (CLUSTER) | 26.2 | 5.3 | 68.5 | 0.46 | 7.2 |
| | 117 | D3 | e | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 17.8 | 82.2 | 0.22 | 5.9 |
| | 118 | D4 | f | ***Al-REM-O-BASED (CLUSTER)*** | 22.5 | ***0.0*** | 77.5 | 0.29 | 8.9 |
| | 119 | D5 | a | Al-REM-Mg-O-BASED (CLUSTER) | 40.9 | 0.8 | 58.3 | 0.71 | 5.2 |
| | 120 | D6 | a | Al-REM-Mg-O-BASED (CLUSTER) | 3.8 | 12.2 | 84.0 | ***0.19*** | 8.5 |
| | 121 | D7 | a | Al-REM-Mg-O-BASED (CLUSTER) | 35.1 | 5.8 | 59.2 | 0.69 | 7.8 |
| | 122 | D8 | a | ***Al-REM-Mg-O-BASED (CLUSTER) + COARSE TiN*** | 31.3 | 6.9 | 61.8 | 0.62 | 6.8 |
| | 123 | D9 | a | Al-REM-Mg-O-BASED (CLUSTER) | 35.4 | 10.1 | 54.5 | 0.84 | 6.2 |
| | 124 | D10 | a | ***Al-Ca-O-BASED (COARSE SPHERICAL)*** | 5.8 | ***0.0*** | 94.2 | ***0.06*** | 8.3 |
| | 125 | C1 | c | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 11.2 | 88.8 | ***0.13*** | 7.2 |
| | 126 | C2 | c | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 12.3 | 87.7 | ***0.14*** | 7.3 |
| | 127 | C1 | d | Al-REM-Mg-O-BASED (CLUSTER) | 1.3 | 8.2 | 90.5 | ***0.10*** | 8.8 |
| | 128 | C2 | d | Al-REM-Mg-O-BASED (CLUSTER) | 1.1 | 7.5 | 91.4 | ***0.09*** | 8.9 |

**[0072]** (Example 3) Example assuming a thorough-hardened bearing 150 kg steel types containing the components of No. E1 to E12 (present invention examples) and No. F1 to F12 (comparative examples) shown in Table 6 were cast in a vacuum melting furnace and were hot-forged into round bars (raw materials for the collection of test pieces) with ϕ80 mm as in Example 1. The deoxidation was performed under different deoxidation conditions a to f shown in Table 2 as in Example 1. After rolling fatigue test pieces were collected, the test pieces were heated to 850°C and then subjected to a hardening treatment and thereafter to a 1 hr. 180°C tempering treatment. Further, test surfaces were mirror-finished and were subjected to a rolling fatigue test. The rolling fatigue test was conducted with a Mori-type thrust test machine (contact surface pressure: 5.33 GPa). Regarding the results of the test conducted ten times on each of the standards (No. 201 to 228 in Table 7), the number of cycles causing 10% out of the evaluation samples to reach fracture was evaluated as a fatigue property L10 using Weibull statistics.

**[0073]** To evaluate a fatigue-initiating inclusion, the same ultrasonic fatigue test as that in Example 1 was conducted. A heat treatment of ultrasonic fatigue test pieces was conducted under the same condition as that for the rolling fatigue test pieces. The fatigue test was executed under a fixed frequency of 20 kHz, a fixed stress ratio of -1, and a fixed stress amplitude of 700 to 850 MPa until a fracture occurred. The composition of the initiating inclusion in this ultrasonic fatigue test was analyzed using EDX (Energy dispersive X-ray Spectroscopy analysis), and the total atomic (at)% of the aforesaid REM and the atomic (at)% of Mg and Al were measured. In Table 7 as well, a ratio of O is not taken into consideration in the calculation of the atomic (at)% as in Table 3, but in any of the examples, the initiating inclusion contained O.

**[0074]** Table 6 shows the chemical composition of each steel type in Example 3. Table 7 shows the steel type, the deoxidation condition, the oxide form and composition of the fatigue-initiating inclusion in the ultrasonic fatigue test, and the fatigue property (L10 life) in the rolling fatigue test, regarding the standards (No. 201 to 228).

**[0075]** The fatigue property L10 of the present invention examples each containing an appropriate amount of REM was $5.0 \times 10^6$ cycles or more and was superior to those of the steel types of the comparative examples.

[Table 6]

| | No. | C | Si | Mn | P | S | Cr | Al | Mg | REM | Ti | O | N | Ca | V | Mo | Cu | Nb | Ni | Pb | Bi | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRESENT INVENTION EXAMPLE | E1 | 0.99 | 0.50 | 0.56 | 0.014 | 0.003 | 0.94 | 0.004 | 0.0020 | 0.0008 | 0.003 | 0.0010 | 0.0081 | 0.0006 | - | - | - | - | - | - | - | - |
| | E2 | 0.93 | 0.29 | 0.50 | 0.016 | 0.002 | 1.49 | 0.003 | 0.0031 | 0.0001 | 0.003 | 0.0011 | 0.0129 | 0.0005 | - | - | - | - | - | - | - | - |
| | E3 | 1.18 | 0.49 | 1.17 | 0.018 | 0.003 | 1.72 | 0.006 | 0.0014 | 0.0004 | 0.003 | 0.0009 | 0.0102 | 0.0008 | - | - | - | - | - | - | - | - |
| | E4 | 0.98 | 0.45 | 0.76 | 0.023 | 0.002 | 0.93 | 0.004 | 0.0045 | 0.0004 | 0.001 | 0.0013 | 0.0120 | 0.0005 | - | - | - | - | - | - | - | - |
| | E5 | 1.22 | 0.45 | 0.33 | 0.011 | 0.003 | 1.44 | 0.004 | 0.0017 | 0.0012 | 0.003 | 0.0012 | 0.0125 | 0.0004 | - | - | - | - | - | - | - | - |
| | E6 | 0.98 | 0.31 | 1.02 | 0.013 | 0.003 | 1.02 | 0.008 | 0.0046 | 0.0015 | 0.003 | 0.0012 | 0.0073 | 0.0008 | 0.10 | - | - | - | - | - | - | - |
| | E7 | 1.23 | 0.24 | 0.57 | 0.019 | 0.003 | 1.60 | 0.004 | 0.0039 | 0.0008 | 0.004 | 0.0011 | 0.0107 | 0.0001 | - | 0.52 | - | - | - | - | - | - |
| | E8 | 1.03 | 0.26 | 1.29 | 0.024 | 0.003 | 1.65 | 0.009 | 0.0028 | 0.0006 | 0.004 | 0.0009 | 0.0081 | 0.0002 | - | - | 0.16 | | - | - | - | - |
| | E9 | 0.94 | 0.51 | 1.17 | 0.017 | 0.003 | 0.89 | 0.006 | 0.0031 | 0.0008 | 0.001 | 0.0011 | 0.0129 | 0.0002 | - | - | - | 0.032 | - | - | - | - |
| | E10 | 0.97 | 0.27 | 0.38 | 0.010 | 0.003 | 1.08 | 0.006 | 0.0022 | 0.0013 | 0.003 | 0.0010 | 0.0090 | 0.0007 | 0.07 | 0.06 | - | - | - | - | - | - |
| | E11 | 1.19 | 0.19 | 0.48 | 0.018 | 0.002 | 1.26 | 0.006 | 0.0017 | 0.0008 | 0.002 | 0.0013 | 0.0111 | 0.0005 | 0.05 | 0.11 | 0.04 | 0.010 | - | - | - | - |
| | E12 | 1.20 | 0.11 | 0.41 | 0.005 | 0.002 | 1.46 | 0.005 | 0.0015 | 0.0009 | 0.002 | 0.0012 | 0.0111 | 0.0003 | - | - | - | - | 2.00 | - | - | - |
| COMPARATIVE EXAMPLE | F1 | 0.99 | 0.57 | 0.50 | ***0.038*** | 0.003 | 1.42 | 0.004 | 0.0019 | 0.0010 | 0.004 | 0.0011 | 0.0103 | 0.0008 | - | - | - | - | - | - | - | - |
| | F2 | 1.22 | 0.37 | 0.38 | 0.011 | ***0.008*** | 1.19 | 0.008 | 0.0039 | 0.0009 | 0.002 | 0.0010 | 0.0106 | 0.0007 | - | - | - | - | - | - | - | - |
| | F3 | 0.95 | 0.32 | 1.19 | 0.020 | 0.003 | 1.71 | ***0.013*** | 0.0017 | 0.0012 | 0.003 | 0.0009 | 0.0121 | 0.0005 | - | - | - | - | - | - | - | - |
| | F4 | 1.10 | 0.41 | 0.79 | 0.010 | 0.002 | 1.09 | 0.008 | 0.0042 | **-** | 0.002 | 0.0009 | 0.0066 | 0.0007 | - | - | - | - | - | - | - | - |
| | F5 | 1.22 | 0.33 | 0.65 | 0.017 | 0.003 | 1.05 | 0.008 | **-** | 0.0015 | 0.003 | 0.0010 | 0.0063 | 0.0003 | - | - | - | - | - | - | - | - |
| | F6 | 1.21 | 0.25 | 0.60 | 0.010 | 0.003 | 1.21 | 0.007 | ***0.0002*** | 0.0002 | 0.003 | 0.0009 | 0.0078 | 0.0008 | - | - | - | - | - | - | - | - |
| | F7 | 1.25 | 0.20 | 0.93 | 0.013 | 0.003 | 1.74 | 0.006 | ***0.0064*** | 0.0002 | 0.002 | 0.0011 | 0.0121 | 0.0001 | - | - | - | - | - | - | - | - |
| | F8 | 1.22 | 0.29 | 1.17 | 0.012 | 0.003 | 1.32 | 0.007 | 0.0025 | ***0.0027*** | 0.003 | 0.0010 | 0.0060 | 0.0005 | - | - | - | - | - | - | - | - |
| | F9 | 0.95 | 0.58 | 0.79 | 0.010 | 0.003 | 1.36 | 0.003 | 0.0045 | 0.0012 | ***0.007*** | 0.0010 | 0.0124 | 0.0006 | - | - | - | - | - | - | - | - |
| | F10 | 0.94 | 0.65 | 1.11 | 0.016 | 0.002 | 1.35 | 0.009 | 0.0035 | 0.0006 | 0.003 | ***0.0023*** | 0.0064 | 0.0002 | - | - | - | - | - | - | - | - |
| | F11 | 0.97 | 0.39 | 0.62 | 0.022 | 0.003 | 0.92 | 0.006 | 0.0011 | 0.0008 | 0.002 | 0.0008 | ***0.0190*** | 0.0003 | - | - | - | - | - | - | - | - |
| | F12 | 1.26 | 0.28 | 0.74 | 0.016 | 0.002 | 1.27 | 0.005 | 0.0041 | 0.0012 | 0.003 | 0.0010 | 0.0111 | ***0.0013*** | - | - | - | - | - | - | - | - |

[Table 7]

| | No. | STEEL TYPE | DEOXIDATION CONDITION | OXIDE FORM | COMPOSITION IN INITIATING INCLUSION (at%) | | | | FATIGUE PROPERTY (L10 LIFE) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | REM(a) | Mg(b) | Al(c) | (a+b)/c | NUMBER OF CYCLES (× 10^5) |
| PRESENT INVENTION EXAMPLE | 201 | E1 | b | Al-REM-Mg-O-BASED (CLUSTER) | 19.0 | 3.6 | 77.4 | 0.29 | 72.3 |
| | 202 | E2 | b | Al-REM-Mg-O-BASED (CLUSTER) | 38.3 | 7.1 | 54.6 | 0.83 | 67.2 |
| | 203 | E3 | b | Al-REM-Mg-O-BASED (CLUSTER) | 32.9 | 5.2 | 61.8 | 0.62 | 69.4 |
| | 204 | E4 | b | Al-REM-Mg-O-BASED (CLUSTER) | 17.9 | 8.8 | 73.4 | 0.36 | 74.6 |
| | 205 | E5 | b | Al-REM-Mg-O-BASED (CLUSTER) | 36.0 | 3.8 | 60.2 | 0.66 | 64.2 |
| | 206 | E6 | b | Al-REM-Mg-O-BASED (CLUSTER) | 36.8 | 10.6 | 52.6 | 0.90 | 64.5 |
| | 207 | E7 | a | Al-REM-Mg-O-BASED (CLUSTER) | 28.2 | 6.8 | 65.1 | 0.54 | 74.8 |
| | 208 | E8 | a | Al-REM-Mg-O-BASED (CLUSTER) | 35.8 | 12.3 | 52.0 | 0.92 | 72.5 |
| | 209 | E9 | a | Al-REM-Mg-O-BASED (CLUSTER) | 42.8 | 11.7 | 45.4 | 1.20 | 64.6 |
| | 210 | E10 | a | Al-REM-Mg-O-BASED (CLUSTER) | 17.4 | 6.2 | 76.4 | 0.31 | 63.5 |
| | 211 | E11 | a | Al-REM-Mg-O-BASED (CLUSTER) | 46.8 | 11.4 | 41.8 | 1.39 | 69.6 |
| | 212 | E12 | a | Al-REM-Mg-O-BASED (CLUSTER) | 46.8 | 11.4 | 41.8 | 1.39 | 75.5 |
| COMPARATIVE EXAMPLE | 213 | F1 | b | Al-REM-Mg-O-BASED (CLUSTER) | 33.7 | 7.2 | 59.2 | 0.69 | 15.3 |
| | 214 | F2 | b | ***Al-REM-Mg-O-BASED (CLUSTER) + COARSE MnS*** | 9.0 | 4.5 | 86.5 | ***0.16*** | 11.1 |
| | 215 | F3 | b | Al-REM-Mg-O-BASED (CLUSTER) | 9.8 | 3.3 | 86.9 | ***0.15*** | 33.2 |
| | 216 | F4 | e | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 17.8 | 82.2 | 0.22 | 25.3 |
| | 217 | F5 | f | ***Al-REM-O-BASED (CLUSTER)*** | 23.2 | ***0.0*** | 76.8 | 0.30 | 33.1 |
| | 218 | F6 | b | Al-REM-Mg-O-BASED (CLUSTER) | 33.5 | 0.8 | 65.7 | 0.52 | 21.3 |
| | 219 | F7 | b | Al-REM-Mg-O-BASED (CLUSTER) | 3.2 | 12.1 | 84.7 | ***0.18*** | 31.3 |
| | 220 | F8 | b | Al-REM-Mg-O-BASED (CLUSTER) | 44.4 | 8.5 | 47.1 | 1.00 | 13.7 |
| | 221 | F9 | b | ***Al-REM-Mg-O-BASED (CLUSTER) + COARSE TiN*** | 22.6 | 11.8 | 65.7 | 1.12 | 15.5 |
| | 222 | F10 | b | Al-REM-Mg-O-BASED (CLUSTER) | 46.7 | 10.4 | 42.9 | 1.33 | 16.8 |
| | 223 | F11 | b | ***Al-REM-Mg-O-BASED (CLUSTER) + COARSE TiN*** | 21.8 | 3.9 | 74.3 | 0.35 | 13.1 |
| | 224 | F12 | b | ***Al-Ca-O-BASED (COARSE SPHERICAL)*** | 6.9 | ***0.0*** | 93.1 | ***0.07*** | 11.9 |
| | 225 | E1 | c | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 11.2 | 88.8 | ***0.13*** | 12.2 |
| | 226 | E2 | c | ***Al-Mg-O-BASED (CLUSTER)*** | ***0.0*** | 12.3 | 87.7 | ***0.14*** | 12.3 |
| | 227 | E1 | d | Al-REM-Mg-O-BASED (CLUSTER) | 1.1 | 9.5 | 89.4 | ***0.12*** | 38.3 |
| | 228 | E2 | d | Al-REM-Mg-O-BASED (CLUSTER) | 0.9 | 10.0 | 89.1 | ***0.12*** | 39.8 |

[Industrial Applicability]

**[0076]** According to the present invention, it is possible to provide a steel material excellent in fatigue property, by turning a clustered Al-O-based inclusion into a composite REM-Al-Mg-O-based inclusion.

[Explanation of Codes]

**[0077]**

| | |
|---|---|
| 1 | ultrasonic fatigue test piece |
| 10 | fracture surface |
| 11 | concentric circular pattern (fisheye) |
| L | gauge length |
| a | inclusion |
| a' | inclusion (fatigue-initiating inclusion) |

## Claims

1. A steel material excellent in rolling fatigue property, the steel material comprising, in mass%:

    C: 0.10% to 1.50%,
    Si: 0.01% to 0.80%,
    Mn: 0.10% to 1.50%,
    Cr: 0.02% to 2.50%,
    Al: 0.002% to less than 0.010%,
    Ce + La + Nd: 0.0001% to 0.0025%,
    Mg: 0.0005% to 0.0050%,
    O: 0.0001% to 0.0020%,
    Ti: 0.000% to less than 0.005%,
    N: 0.0180% or less,
    P: 0.030% or less,
    S: 0.005% or less,
    Ca: 0.0000% to 0.0010%,
    V: 0.00 to 0.40%,
    Mo: 0.00 to 0.60%,
    Cu: 0.00 to 0.50%,
    Nb: 0.000 to less than 0.050%,
    Ni: 0.00 to 2.50%,
    Pb: 0.00 to 0.10%,
    Bi: 0.00 to 0.10%,
    B: 0.0000 to 0.0050%, and
    the balance being Fe and an impurity,
    wherein a fatigue-initiating inclusion detected by an ultrasonic fatigue test contains Mg, Al, and O, and one or more of Ce, La, and Nd, and a composition ratio in the fatigue-initiating inclusion satisfies Formula (1),

    $$(\mathrm{Ce}\% + \mathrm{La}\% + \mathrm{Nd}\% + \mathrm{Mg}\%)/\mathrm{Al}\% \geq 0.20 \ldots \text{Formula (1)},$$

    where Ce%, La%, Nd%, Mg%, and Al% are atomic (at)% of respective Ce, La, Nd, Mg, and Al contained in the fatigue-initiating inclusion.

2. The steel material excellent in rolling fatigue property according to claim 1, wherein, in mass%, C: 0.10% to less than 0.45%, and Cr: 0.02 to 1.50%.

3. The steel material excellent in rolling fatigue property according to claim 1, wherein, in mass%, C: 0.45% to less than 0.90%, and Cr: 0.70 to 2.50%.

**4.** The steel material excellent in rolling fatigue property according to claim 1, wherein, in mass%, C: 0.90% to 1.50%, and Cr: 0.70 to 2.50%.

**FIG.1**

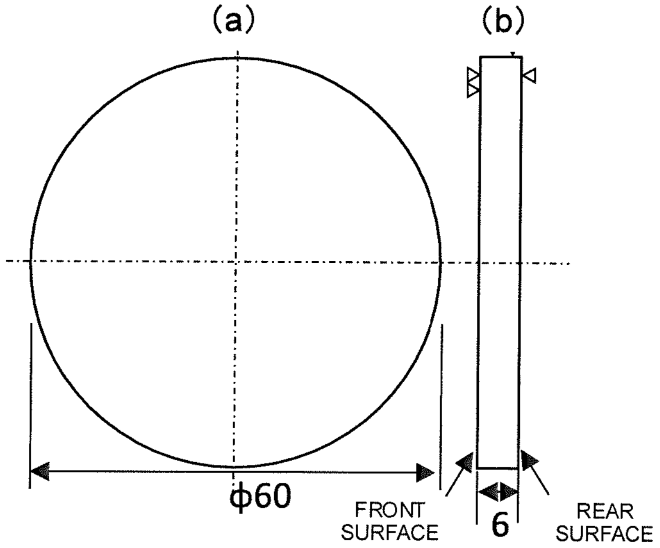

(a)
(b)
ϕ60
FRONT SURFACE
6
REAR SURFACE

**FIG.2**

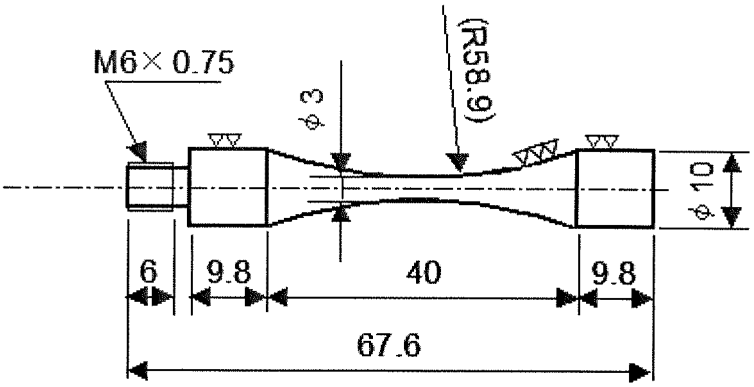

M6× 0.75
ϕ 3
(R58.9)
ϕ 10
6
9.8
40
9.8
67.6

**FIG.3**

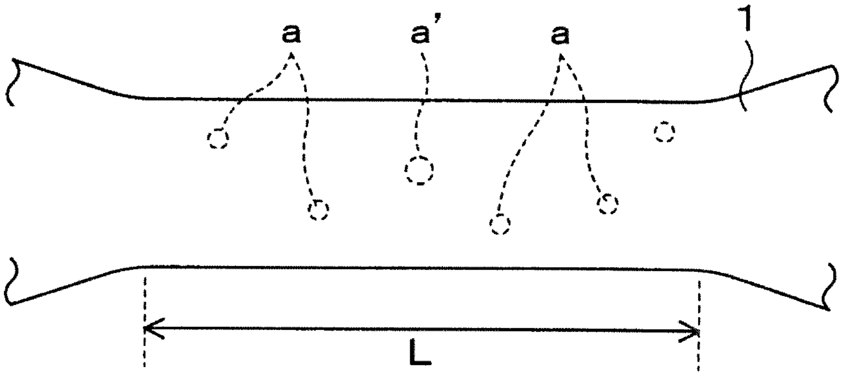


**FIG.4**

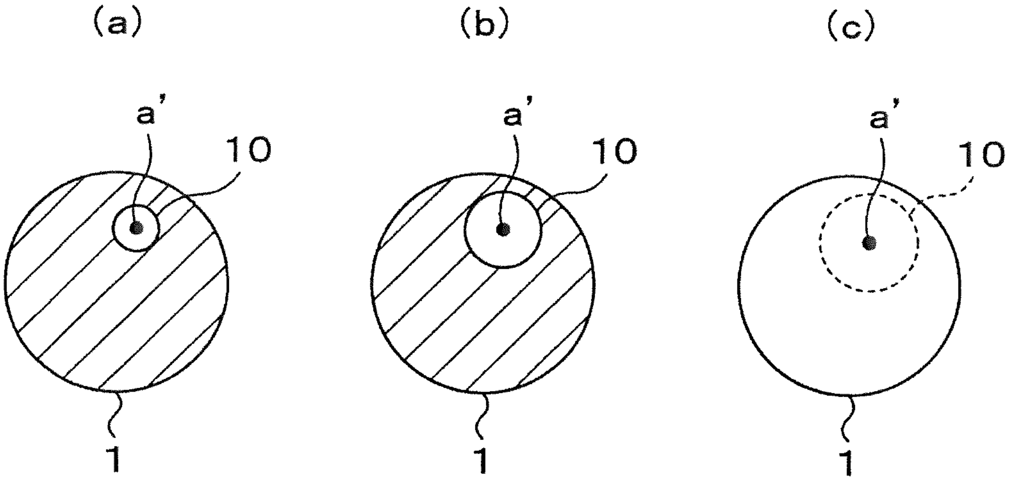


**FIG.5**

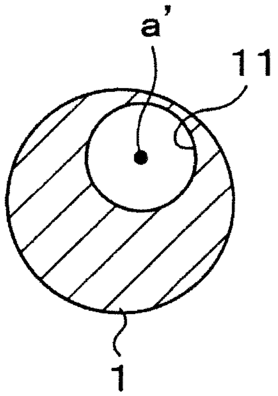
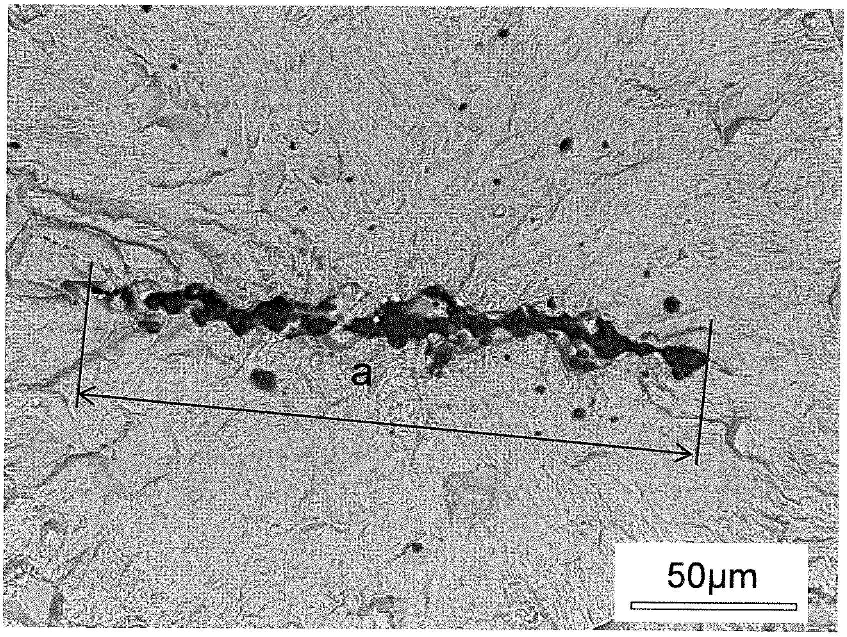


**FIG.6**



## INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2018/034008

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl. C22C38/00(2006.01)i, C22C38/28(2006.01)i, C22C38/60(2006.01)i, C21C7/06(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)
Int.Cl. C22C38/00, C22C38/28, C22C38/60, C21C7/06

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

| | |
|---|---|
| Published examined utility model applications of Japan | 1922-1996 |
| Published unexamined utility model applications of Japan | 1971-2018 |
| Registered utility model specifications of Japan | 1996-2018 |
| Published registered utility model applications of Japan | 1994-2018 |

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 2005-2420 A (NIPPON STEEL CORP.) 06 January 2005, claims 1-3, paragraphs [0001], [0016], [0032]-[0034], tables 1-4 (Family: none) | 1-4 |
| A | JP 9-263820 A (KAWASAKI STEEL CORP.) 07 October 1997, claims 1, 2, paragraphs [0001], [0014]-[0020], [0025]-[0029], fig. 1, 2 & EP 829546 A1, claims 1, 2, page 1, lines 5-6, page 3, lines 7-34, page 4, lines 15-32, fig. 1, 2 & US 6120578 A & CA 2220272 A1 & CN 1185813 A & BR 9702137 A | 1-4 |

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

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Date of the actual completion of the international search
06 December 2018 (06.12.2018)

Date of mailing of the international search report
18 December 2018 (18.12.2018)

Name and mailing address of the ISA/
Japan Patent Office
3-4-3, Kasumigaseki, Chiyoda-ku,
Tokyo 100-8915, Japan

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**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/JP2018/034008

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | WO 2015/076384 A1 (NIPPON STEEL & SUMITOMO METAL CORPORATION) 28 May 2015, claim 1, paragraphs [0021], [0023]-[0027], [0030]-[0032], [0072]-[0074], tables 1, 2 & EP 3072987 A1, claim 1, paragraphs [0017], [0019]-[0023], [0026]-[0028], [0068]-[0071], tables 1, 2 & US 2016/0289787 A1 & CN 105745348 A & TW 201525157 A & KR 10-2016-0072233 A & MX 2016006596 A | 1-4 |
| A | JP 2009-287111 A (KOBE STEEL, LTD.) 10 December 2009, claims 1, 2, paragraphs [0001], [0009], [0017], [0023], [0025], [0028]-[0031], table 1 (Family: none) | 1-4 |
| A | JP 11-279695 A (KAWASAKI STEEL CORP.) 12 October 1999, claim 1, paragraphs [0001], [0012], [0014], table 1 (Family: none) | 1-4 |

## REFERENCES CITED IN THE DESCRIPTION

### Patent documents cited in the description

- JP H09263820 B **[0009]**
- JP H11279695 B **[0009]**