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(54) **FORGING STEEL, AND FORGED PRODUCTS OBTAINABLE THEREFROM**

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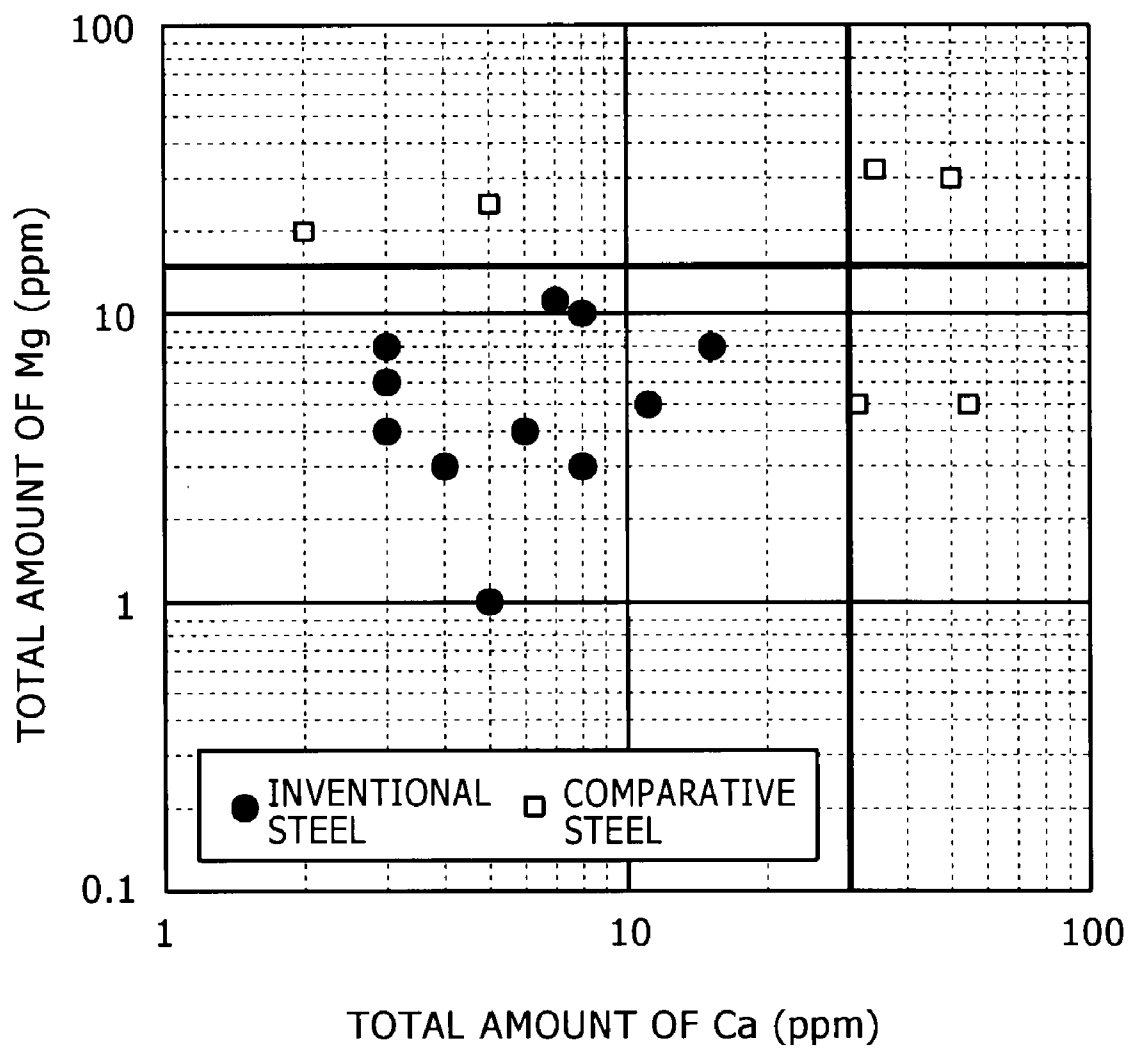
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(57) **ABSTRACT**

Disclosed is a forging steel characterized in that prescribed composition of components must be satisfied. In particular, any one of the below-mentioned (I)-(IV) need be complied with in regard to dissolved Ca and dissolved Mg. (I) Dissolved Ca: 2-500 ppb (meaning "mass ppb" hereafter) and dissolved Mg: 0.04-5 ppm (meaning "mass ppm" hereafter); (II) Dissolved Ca: 2-100 ppb and dissolved Mg: 5-ppm; (III) Dissolved Ca: 2 ppb or less (0% not included) and dissolved Mg: 0.04-5 ppm; (IV) Dissolved Ca: 2-500 ppb and dissolved Mg: 0.04 ppm or less (0% not included).

# FIG. 1



# FIG. 2



## FORGING STEEL, AND FORGED PRODUCTS OBTAINABLE THEREFROM

### BACKGROUND OF THE INVENTION

**[0001]** 1. Field of the Invention

**[0002]** This invention relates to forging steel and forged products obtainable from the use of the above forging steel. While the forged products manufactured from the forging steel of the present invention are being utilized usefully and widely in such industrial fields as machinery, ships and vessels, electrical equipment, etc., explanation hereunder is going to be made centering on an application to the crankshaft used for a power transmission member in a marine driving source as an example of typical application.

**[0003]** 2. Description of the Related Art

**[0004]** The large-size crankshaft used as a power transmission member in a marine driving source requires superior fatigue characteristics that rarely cause fatigue breakdown even under a very severe use environment.

**[0005]** As a method of improving fatigue characteristics of the crankshaft, the Non-patent Document 1 describes that improvement in fatigue characteristics was tried by free command of processing technology. To be more concrete, the Non-patent Document 1 indicates that the RR (Roedere Ruget) method was adopted to achieve a remarkable betterment in fatigue strength as compared to the case of a crankshaft manufactured by the flat die forging method and also that cold roll processing was applied for improvement of fatigue strength.

**[0006]** The Non-patent Document 2 examines possibility of improving fatigue characteristics of the low-alloy steel used for the marine crankshaft. To be more precise, the Non-patent Document 2 indicates that (1) the inclusion in the steel is apt to become a starting point of fatigue breakdown and such inclination is likely to become more apparent as steel develops to have higher strength; (2) the larger the size of the inclusion is, the lower the fatigue strength is likely to be; and (3) any steel material containing elongated inclusion has a tendency of easily showing anisotropy in fatigue strength. The Document concludes that for the betterment of fatigue characteristics of the forging material, it is effective to make the inclusion globular in shape and smaller in size.

**[0007]** However, the above Non-patent Documents do not go as far as to disclose concrete means about how to realize globalizing the shape of the inclusion and making it smaller. It is neither made clear in what range the inclusion should be controlled kind-wise and size-wise. Therefore, further studies seem to be required to realize morphology control of the inclusion useful for enhancement of fatigue characteristics.

**[0008]** Incidentally, various methods have so far been suggested in regard to the method of morphology control for the inclusion. For example, a suggestion is made in the Patent Document 1, about a method in which both sulfides and oxides are reduced in amount and inclusion is controlled in morphology as a means of producing structural low-alloy steel having excellent features in point of lamellar tear resistivity and hydrogen induced cracking resistivity. In more details, the suggestion includes that in order to suppress generation of Mn sulfides which are harmful to the lamellar tear resistivity and hydrogen induced cracking resistivity, it is effective to reduce the amount of sulfur and oxygen content while adding Ca and Mg content at the same time.

**[0009]** In the Patent Document 2, it is described that addition of Mg and Ca works effectively to suppress growth of MnS which is apt to elongate during hot rolling and also growth of inclusions of  $Al_2O_3$  and its relatives which tend to

stretch in clusters, and further to carry out morphology control of the inclusions in such a way as changing the morphology for increased refinement.

**[0010]** The Patent Document 3 and the Patent Document 4 show that by super-refining the oxide type inclusions, it is possible to increase plane fatigue strength and tooth-bend fatigue strength in relation to gear material. To be more precise, these documents suggest that MgO and  $MgO \cdot Al_2O_3$ , which are less cohesive and coalesced, should be created as the oxide type inclusions. It is also made clear that replacing a part of sulfide MnS with (Mn.Mg)S can help suppress elongational tendency of the inclusions and reduce anisotropy in mechanical strength.

**[0011]** The Patent Document 5 discloses that as sulfide, MnS, CaS, MgS, (Ca, Mn)S, and (Ca, Mg, Mn)S were made to be present for the purpose of producing machine structural steel with superior machinability. The Patent Document 5 clarifies specifically that if the morphology of sulfide can be controlled by having REM, Ca and Mg contained, it becomes possible to suppress anisotropy of mechanical property and also to enhance the machinability to a level higher than that of a S-contained free cutting steel.

**[0012]** However, the morphology control technology for these inclusions described above is not targeting at forged products used under such severe environmental conditions as the power transmission member in the marine driving source is subjected to. Therefore, it is now required to study and establish an original inclusion control method targeted at forging steel used for manufacturing of forged products with a view to providing the forging steel with much upgraded fatigue characteristics.

**[0013]** The Patent Document 6 may be marked as one that is targeted at forged products used for the above power transmission member, etc., in the marine driving source. This Patent Document 6 prescribes contained amount for each of S, Ca, Mg, Al, and O, and indicates that fatigue characteristic can be improved if the contained amounts of Ca and Mg are so arranged as to satisfy the formula (1). However, to make certain of enhanced fatigue characteristics, further studies seem to be needed on the basis of more concrete knowledge on the morphology of inclusions existing in large-size steel ingots.

[Non-patent Document 1] "Progress and Improvement of Crankshaft," Journal of the Marine Engineering Society of Japan, October 1973, Vol. 8, No. 10, pp. 54-59

[Non-patent Document 2] "Research on Fatigue Strength Characteristics of High-strength Crankshaft Materials," Journal of the Marine Engineering Society of Japan, 2001, Vol. 36, No. 6, pp. 385-390

[Patent Document 1] Japanese Examined Patent Application Publication No. 58-35255 (JP-B-58-35255)

[Patent Document 2] Japanese Examined Patent Application Publication No. 57-59295 (JP-B-57-59295)

[Patent Document 3] Japanese Unexamined Patent Application Publication No. 07-188853 (JP-A-07-188853)

[Patent Document 4] Japanese Unexamined Patent Application Publication No. 07-238342 (JP-A-07-238342)

[Patent Document 5] Japanese Unexamined Patent Application Publication No. 2000-87179 (JP-A-2000-87179)

[Patent Document 6] Japanese Unexamined Patent Application Publication No. 2004-225128 (JP-A-2004-225128)

## SUMMARY OF THE INVENTION

**[0014]** This invention has been made in view of the forging circumstances and has the object of providing forging steel with refined inclusions so as to make available forged products (including parts) having excellent fatigue characteristics and also providing forged products (including parts) (crankshafts in particular) that is obtainable from the use of the above-mentioned forging steel and can exhibit excellent fatigue characteristics.

**[0015]** The forging steel according to a primary aspect of the present invention is to comply with the following conditions concerning contained amounts.

C, 0.2-0.6% (hereafter, % denotes ‘% by mass’);

Si: 0.05-0.5%;

Mn: 0.2-1.5%;

Ni: 0.1-3.5%;

Cr: 0.9-4%

Mo: 0.1-0.7%;

Al: 0.005-0.1%

**[0016]** S: 0.008% or less (0% not included)

**[0017]** O: 0.0025% or less (0% not included)

**[0018]** Total Ca: 0.0030% or less (0% not included)

**[0019]** Total Mg: 0.0015% or less (0% not included)

At the same time, dissolved Ca and dissolved Mg should satisfy any one of the following (I) to (IV). (Hereafter, ppb and ppm denote respectively ‘ppb by mass’ and ‘ppm by mass.’)

**[0020]** (I) Dissolved Ca: 2-500 ppb, and

**[0021]** Dissolved Mg: 0.04-5 ppm

**[0022]** (II) Dissolved Ca: 2-100 ppb, and

**[0023]** Dissolved Mg: 5-10 ppm

**[0024]** (III) Dissolved Ca: 2 ppb (0 ppb not included), and

**[0025]** Dissolved Mg: 0.04-5 ppm

**[0026]** (IV) Dissolved Ca: 2-500 ppb and

**[0027]** Dissolved Mg: 0.04 ppm or less (0 ppm not included)

**[0028]** The forging steel of the aspect of the present invention may as well contain other elements shown below and on the conditions shown together.

(a) One or more elements selected from the group consisting of V, Nb, Ta, and Hf, within the range of 0.005-0.2% for all selected elements added together.

(b) Ti: 0.05% or less (0% not included)

(c) Cu: 1.0% or less (0% not included)

**[0029]** The forging steel of the aspect of the present invention may contain inclusions in it, the largest one of which is less than 100  $\mu\text{m}$  in equivalent of diameter of a circle to which the inclusion is assumed to be approximated.

**[0030]** The aspect of the present invention includes the forged product (a crankshaft in particular) manufactured from the forging steel of the present invention.

**[0031]** The aspect of the present invention is configured as described above, and by adjusting the amount of the dissolved Ca and the dissolved Mg in the steel, it has become possible to control the morphology of the inclusions formed and thereby to provide forging steel with refined inclusions. The forged products available from the use of such forging steel can be expected to show excellent fatigue characteristics and

prove particularly useful for large-size forged products such as crankshafts for ships and vessels.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0032]** Embodiment(s) of the present invention will be described in detail based on the following figures, wherein:

**[0033]** FIG. 1 is a graph showing the range of amount of Total Ca and the range of amount of Total Mg prescribed in the present invention; and

**[0034]** FIG. 2 is a graph showing the correlation between the diameter of an assumed circle equivalent area-wise to the largest inclusion existing in the steel.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

**[0035]** Under the abovementioned circumstances, the inventors of the present invention have been making studies from various angles, while setting our final target at enhancement of fatigue characteristics of the forged products which are subject to use under severe environment. In particular, large-size steel ingots (for example, of a size more than 20 tons) which, because of a longer time needed for solidification, were hard to achieve the targeted level of fatigue strength required us to proceed with the studies from a different angle than before.

**[0036]** As a result, it was found out that if particularly the amounts of dissolved Ca and dissolved Mg contained in the steel could be controlled within any one of the above ranges (I) to (IV) and also the Total Ca amount, the Total Mg amount, and the S amount in the steel could be controlled properly, the size of the largest inclusion in the steel would become remarkably small and there would be an ample room for enhancing fatigue characteristics. Hereafter follows detailed description in regard to the present invention.

**[0037]** The present invention firstly sets forth that the amounts of the dissolved Ca and the dissolved Mg in the steel should be limited within any one of the above ranges (I) to (IV). More explanation follows on each range.

(I) Dissolved Ca: 2-500 ppb and dissolved Mg: 0.04-5 ppm

**[0038]** By limiting the contained amounts of the dissolved Ca and the dissolved Mg within the above ranges, low-melting oxides (Ca, Al, Mg)O {this expression means oxides comprising all the elements in the parenthesis; this applies to other cases hereinafter} are created. As these oxides are easily deformable during forging, it is possible to refine the size of inclusions contained in the forged products. Also, as sulfides, low-melting (Ca, Mg, Mn)S {this means sulfides comprising all the elements in the parenthesis; this applies to other cases hereinafter} or (Ca, Mg)S are created (when the contained amounts of dissolved Ca and dissolved Mg are relatively abounding, the sulfide tends to become (Ca, Mg)S). The sulfides (Ca, Mg)S which get more easily refined and dispersed as compared to MnS, are able to work effectively to make the inclusions contained in the forging products refined in size.

(II) Dissolved Ca: 2-100 ppb, and dissolved Mg: 5-10 ppm

**[0039]** By limiting the contained amounts of dissolved Ca and dissolved Mg in the steel to the ranges shown above, the oxides available change from high-melting MgO to low-melting (Ca, Al, Mg)O, Sulfides also change from high-melting MgS to low-melting (Ca, Mg)S. The above (Ca, Al, Mg)O which are easily deformable during forging, and (Ca, Mg)S which get more easily refined and dispersed as compared to

MgS, are able to work effectively to make the inclusions contained in the forging products refined in size.

(III) Dissolved Ca: 2 ppb or less (0 ppb not included), and dissolved Mg: 0.04-5 ppm

**[0040]** By limiting the contained amounts of dissolved Ca and dissolved Mg in the steel to the ranges shown above, spinel or (Al, Mg)O, an oxide which is more difficult to coagulate than Al<sub>2</sub>O<sub>3</sub>, and sulfides (Mg, Mn)S, which get more easily refined and dispersed than MnS, are generated, resulting that creation of coarse and large inclusions can be suppressed, contributing to improvement of fatigue characteristics.

**[0041]** (IV) Dissolved Ca: 2-500 ppb, and dissolved Mg: 0.04 ppm or less (0 ppm not included)

**[0042]** By limiting the contained amounts of dissolved Ca and dissolved Mg in the steel to the ranges shown above, such oxides as (Al, Ca)O which are low-melting and more difficult to coagulate than Al<sub>2</sub>O<sub>3</sub>, and such sulfides as (Ca, Mn)S which get more easily refined and dispersed than MnS, are generated resulting that creation of coarse and large inclusions can be suppressed, contributing to improvement of fatigue characteristics.

**[0043]** If the contained amounts of dissolved Ca and dissolved Mg in the steel remain out of the ranges (I) to (IV) shown above, it is no good because coarse and large inclusions become more easily producible. For example, when dissolved Mg is contained in an amount beyond 10 ppm, high-melting MgS and MgO are generated in large amounts during coagulation irrespective of the amount of dissolved Ca. These MgS and MgO are to turn out to be coarse and large inclusions to the undesired effect of downgrading cleanliness of the material. Even though the amount of dissolved Mg remains at 10 ppm or below, if the amount of dissolved Ca is less than 2 ppb, the above-mentioned MgS and MgO are generated and coagulated to grow coarse and large. These MgS and MgO, owing to their high-melting property, are difficult to be deformed in the course of forging but are likely to remain as coarse and large inclusions in the forged product. On the other hand, if the amount of dissolved Mg is below 0.04 ppm and the amount of dissolved Ca is below 2 ppb, this will lead to an undesired result of creating the coarse and large oxide Al<sub>2</sub>O<sub>3</sub> and the coarse and large sulfide MnS.

**[0044]** The contained amounts of the above dissolved Ca and dissolved Mg in the steel were measured by SIMS (Secondary Ion Mass Spectrometer) as shown in the embodiment described afterward.

**[0045]** In the next place, explanation is given below of the reasons why Total Ca amount, Total Mg amount, and the S amount were set out in the present invention.

**[0046]** [Total Ca: 0.0030% or less (0% not included)]

**[0047]** When the Total Ca amount exceeds 0.0030%, this tends to allow generation of coarse and large Ca-contained oxides (CaO, etc.), Ca-contained sulfides (CaS), and composite inclusions comprising the aforesaid compounds. For this reason, the present invention lays it down that the Total Ca amount be suppressed at 0.0030% or less. Preferably it should be 0.0020% or less, and more preferably, it should be 0.0015% or less.

**[0048]** [Total Mg: 0.0015% or less (0% not included)]

**[0049]** When the Total Mg amount exceeds 0.0015%, this tends to allow generation of coarse and large Mg-contained oxides (MgO, etc.), Mg-contained sulfides (MgS), and composite inclusions comprising the aforesaid compounds. For this reason, the present invention lays it down that the Total

Mg amount be suppressed at 0.0015% or less. Preferably it should be 0.0010% or less, and more preferably, it should be 0.0008% or less.

**[0050]** FIG. 1 is a graph showing the ranges of the above Total Ca amount and Total Mg amount prescribed in the present invention, organized by using the data of the embodiment described later.

**[0051]** [S: 0.008% or less (0% not included)]

**[0052]** S tends to form coarse and large sulfides (MnS, CaS, and MgS), and therefore, it may be said to be the element to cause deterioration of fatigue strength of the forging steel ingot. Accordingly, the amount of S contained in the steel should be held at 0.008% or less, preferably at 0.005% or less, more preferably at 0.003% or less, and still more preferably at 0.001% or less.

**[0053]** The present invention is characterized in that adjustment is applied to the above components with a view to refining the inclusions in the steel. However, in order to make it certain that a crankshaft, for example, or any other forged end product will acquire the strength and toughness as required and further the enhanced fatigue strength targeted in the present invention, it is recommended for the steel material to satisfy the composition shown below.

**[0054]** [C, 0.2-0.6%]

**[0055]** C is the element to contribute to improvement of strength, and to secure enough strength it should be contained at 0.2% or more, preferably at 0.25% or more, or more preferably at 0.3% or more. However, if the amount of C is excessive, it will tend to deteriorate toughness, so that C should be held at 0.6% or less, preferably at 0.55% or less, or more preferably at 0.5% or less.

**[0056]** [Si: 0.05-0.5%]

**[0057]** Si also functions as a strength enhancing and deoxidation element, and to have both effect fully exerted, Si should be contained at 0.05% or more, preferably at 0.1% or more, or more preferably at 0.15% or more. However, if the amount of Si is excessive, inverted V segregation will tend to become intensive. It is necessary, therefore, that Si should be held at 0.5% or less, preferably at 0.45% or less, or more preferably at 0.4% or less.

**[0058]** [Mn: 0.2-1.5%]

**[0059]** Mn is another element enhancing strength besides boosting hardenability, and to secure enough strength and hardenability it should be contained at 0.2% or more, preferably at 0.5% or more, or more preferably at 0.8% or more. However, if the amount of Mn is excessive, inverted V segregation tends to become fostered. It is necessary, therefore, that Mn should be held at 1.5% or less, or preferably at 1.2% or less.

**[0060]** [Ni: 0.1-3.5%]

**[0061]** Ni is useful as an element for enhancing toughness, and it should be contained at 0.1% or more, and preferably at 0.2% or more. However, since excessive amount of Ni obliges increase in cost, Ni should be held at 3.5% or less, or preferably at 3.0% or less.

**[0062]** [Cr: 0.9-4%]

**[0063]** Cr is an element useful for increasing toughness as well as enhancing hardenability, and these functions are effectively exhibited when Cr is contained at 0.9% or more, preferably at 1.1% or more, or more preferably at 1.3% or more. However, if the amount of Cr is excessive, it will tend to foster inverted V segregation to become intensive making it

difficult to obtain clean steel ingots, so that Si should be held at 4% or less, or preferably at 2% or less.

**[0064]** [Mo: 0.1-0.7%]

**[0065]** Mo is an element to effectively act on betterment of all of hardenability, strength, and toughness, and for the effective exhibition of these functions, Mo should be contained in the steel at 0.1% or more, preferably at 0.20% or more, or more preferably at 0.25% or more. However, since Mo has a low equilibrium distribution coefficient leading to easy occurrence of micro segregation (normal segregation), the amount of Mo in the steel should be held at 0.7% or less, preferably 0.6% or less, or more preferably 0.5% or less.

**[0066]** [Al: 0.005-0.1%]

**[0067]** Al is effective as a deoxidation element and as well effective for resistance to cracking of steel. Thus, Al amount (hereafter, Al amount means "total Al amount") should be set at 0.005% or more, or preferably at 0.010% or more. On the other hand, Al has the tendency of fixing N in the form of AlN, etc., thus disturbing such functions as reinforcing the steel with composition of N, V, or other added elements. Combining with other various elements, Al also lends a hand in creating non-metallic inclusions or intermetallic compounds which may result in deteriorating toughness of the steel. Therefore, the Al amount should be limited to 0.1% or less, or preferably to 0.08% or less.

**[0068]** [O: 0.0025% or less (0% not included)]

**[0069]** O (oxygen) is an element to adversely affect fatigue strength of the steel ingots, since it forms such oxides as SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MgO, and CaO, which then turn out to be inclusions. Therefore, the amount of O (total O amount) is desirable to be kept as low as possible and should be held at 0.0025% or less, or preferably at 0.0015% or less.

**[0070]** The composition used in the forging steel of the present invention is as explained above, and the remaining portion not shown above is composed of iron and inevitable impurities. The latter may include P, N, etc., for example. P is desired to be 0.03% or less, or preferably 0.02% or less. N should be 0.01%, or preferably 0.008% or less.

**[0071]** It is also possible that the forging steel in which any other elements are positively added may be used insofar as such addition of other elements does not adversely affect the above-mentioned functions and effects of the present invention.

**[0072]** [One or More Elements Chosen Out of the Group Consisting Of V, Nb, Ta, and Hf: 0.005-0.2% in Total for all Chosen]

**[0073]** V, Nb, Ta, and Hf have a good effect on precipitation strengthening and structural refinement and are useful for supporting the tendency toward intensified high-strength steel. In order to have these elements to effectively show their functionalities, one or more elements selected out of the group consisting of V, Nb, Ta, and Hf, it is desirable for the steel to contain a total of 0.005% or more, and preferably 0.01%. However, if the contained amount is excessive, the above effects will become saturated ending up economically wasted. Therefore, the total of contained amount should be held at 0.2% or less, and preferably at 0.15% or less

**[0074]** [Ti: 0.05% or less (0% not included)]

**[0075]** Ti is an element inevitably included in the impurities or otherwise contained purposely in expectation for the effect of improvement on resistance to hydrogen induced cracking. Ti-related inclusions take the form of refined inclusions such as TiN, TiC, and Ti<sub>4</sub>C<sub>2</sub>S<sub>2</sub>, which, dispersed in the steel, occludes and captures excess hydrogen in the steel, achieving

substantial effect in improving resistance to hydrogen cracking of the steel. To bring about the above effect, the amount of Ti to be contained in the steel should be 0.0002% or more, preferably 0.0004% or more, and still more preferably 0.0006% or more. Whichever the case may be concerning whether Ti is to be included as inevitable impurities or for the effects described above, the amount of Ti included over 0.05% is likely to cause formation of coarse and large nitrides in the steel leading to decrease in fatigue strength. Therefore, the amount of Ti in the steel should be held at 0.05% or less, preferably at 0.03% or less, and more preferably 0.01% or less.

**[0076]** [Cu: 1.0% or less (0% not included)]

**[0077]** Cu may be either included in the steel as inevitable impurities or purposely added as a toughness enhancing element (when Cu is contained as a toughness enhancing element, the amount of Cu should be set at 0.05% or more, preferably 0.1% or more). However, if the contained amount of Cu becomes over 1.0%, this will probably necessitate increase in cost and might cause hot tearing. Therefore, the amount of Cu should be set at 1.0% or less, and preferably at 0.5% or less.

**[0078]** The examples of other elements which are permissible to be positively added to the composition cover such elements as B having the effect of hardenability improvement, W, Ce, La, Zr, and Te which are good for either solid solubility enhancement or precipitation strengthening. These elements may be added either individually or two or more elements in combination, but it is desirable to suppress the contained amount at about 0.1% or less in total for all added items combined of the above examples.

**[0079]** In trying to set the S amount, the Total Ca amount, the Total Mg amount, the dissolved Ca amount, and the dissolved Mg amount within the ranges prescribed above, the following method is recommendable as one suitable. However, the present invention does not go as far as to specify the manufacturing method of forging steel and is not limited to the process described afterward.

**[0080]** The contained amount of S can be adjusted by controlling the composition of the top slag at the time of secondary refining. More precisely, the ratio of the CaO concentration in the top slag against the SiO<sub>2</sub> concentration (CaO/SiO<sub>2</sub>; this may be expressed as C/S herein) should be set preferably at as high as 3.0 or over, thereby making it possible for the contained amount of S in the steel to be reduced. As a supplementary means, if the ratio of the Ca concentration against the Al<sub>2</sub>O<sub>3</sub> concentration (CaO/Al<sub>2</sub>O<sub>3</sub>) is set as well high, it becomes possible to reduce the contained amount of S in the steel.

**[0081]** It is recommended that the MgO concentration in the top slag be set at 5% or over and the CaO concentration be set at 30% or over. On the other hand, if the concentrations of MgO and CaO in the top slag are excessively high, slag may become solidified making it difficult to proceed with the refinery work itself. Therefore, it is suggested that the MgO concentration in the top slag should be maintained at 25% or below and the CaO concentration in the top slag should be maintained at 65% or below.

**[0082]** It is recommended that the concentration of the dissolved Al in the molten steel at the time of refinery is maintained within the range of 50-900 ppm. If the concentration of the dissolved Al in the molten steel is less than 50 ppm, the amount of dissolved oxygen increases and the number of oxides crystallized into the solidified steel also increases with

the unfavorable result that the cleanliness of the steel changes for the worse. On the other hand, if the dissolved Al concentration goes up higher than 900 ppm, it leads to an unfavorable result that the concentration of dissolved oxygen decreases and the amounts of the dissolved Ca and Mg in the steel become excessive.

**[0083]** By adopting these methods, the amounts of dissolved Ca and the dissolved Mg in the steel can be maintained within the prescribed ranges.

**[0084]** Further, in the present invention, it is effective to conduct the first course of heating and composition adjustment to the molten steel tapped out of a converter or electrical furnace, apply degassing treatment to the molten steel after the above first course of heating and composition adjustment, and again conduct second course of heating and composition adjustment to the molten steel after degassing treatment; that is to say, it is effective to carry out the operation of a series of refining processes including [heating and composition adjustment—degassing treatment—heating and composition adjustment].

**[0085]** The above first course of heating and composition adjustment is a treatment to control the composition of the molten steel within the prescribed range, and the degassing treatment is a treatment to remove hydrogen and other gas content from the inside of the molten steel. Therefore, both the treatments need to intensify the stirring power density, while avoiding entrapment of the top slag floating on the surface of the molten steel as much as possible.

**[0086]** The second course of heating and composition adjustment is mainly assigned the function to promote the flotation of the top slag particles entrapped into the molten steel during the above degassing treatment process and to do fine adjustment of composition and temperature. In this connection, it is suggested that while the temperature of the molten steel being adjusted according to the casting conditions, stirring be carried on with a low stirring power density so that entrapment of any new top slag may not occur.

**[0087]** Concretely speaking, it is suggested that at the time of degassing treatment after the composition adjustment (including adjustment of Al amount) and until the midterm of the degassing treatment (in mid-course), the stirring power density ( $\epsilon$ ; this value is obtainable from the formula (1) shown afterward; the same remark is applicable to other similar cases hereinafter): stirring at 50-200 W/ton is recommendable. The flow rate of blowing gas should be adjusted so that the stirring power density may be controlled preferably at 50 W/ton or over; more preferably at 60 W/ton or over and 200 W/ton or below; still more preferably at 180 W/ton or below. It is also suggested that after the midterm of the degassing treatment, the flow rate of blowing gas should be adjusted so that the stirring power density may be controlled at 140 W/ton or below, or preferably at 120 W/ton or below (0 W/ton not included).

**[0088]** In the second course of heating and composition adjustment, the flow rate of blowing gas should be adjusted so that the stirring power density may be controlled at 25 W/ton or below, or preferably at 20 W/ton or below, and at 2.0 W/ton or over.

**[0089]** In more detail, the below-mentioned procedures should be followed. The molten steel is first tapped out of the converter or electrical furnace into the ladle and is brought to the secondary refining, where the molten steel goes through the first course of heating and composition adjustment (hereafter, this process may be called as “LF-I”). Concretely

speaking, while the molten steel is being heated up to  $T_L=1600^\circ\text{C}$ . or thereabout by generation of arc discharge, flux is added to the molten steel by a flux feeding means. Furthermore, the molten steel is stirred by Ar gas blowing with a gas blowing means.

**[0090]** At the step of LF-1, it is suggested that the kinds and amounts of flux should be determined so that the composition of the top slag after finishing the vacuum degassing treatment (in other words, at the time the second course of heating and composition adjustment has started) may satisfy the following three conditions at the same time.

**[0091]** (i) The mass of CaO is more than three times as much as the mass of  $\text{SiO}_2$ .

**[0092]** (ii) The mass of CaO is 1.5-3.5 times as much as the mass of  $\text{Al}_2\text{O}_3$ .

**[0093]** (iii) The summation of the mass of T.Fe and the mass of MnO in the composition of the top slag is less than 1.0% of the total mass of the top slag.

It is also suggested that the heating temperature and the feed amount of the auxiliary material (flux) should be controlled or adjusted accordingly.

**[0094]** The molten steel that has gone through the first course of heating and composition adjustment is transported to the vacuum degassing equipment ladle by ladle, by which the molten steel is processed for vacuum degassing treatment (hereafter the treatment may be called as “VD”).

**[0095]** Precisely, by operation of the exhaust system the gas above the molten steel in the ladle is exhausted through an exhaust pipe to the extent that the ambient pressure “P” inside the ladle comes close to a vacuum state of about 0.5 Torr. Additionally, stirring is applied to the molten steel by blowing Ar gas by a gas blowing means. In the above manner, the treatment of removing hydrogen is carried out from the molten steel for which adjustment of composition is almost completed.

**[0096]** In the current treatment, it is preferable to adopt a stirring power density  $\epsilon$  at which both the prevention of entrapment of top slag into the molten steel and the dehydrogenation are compatible. In this regard, if in the first half of VD, the flow rate  $Q_g$  of bottom blowing gas is controlled so as to maintain the stirring power density  $\epsilon$  within the range of 50-200 W/ton, it becomes possible to effectively conduct dehydrogenation while holding entrapment of top slag to a minimum. In the latter half of VD, if the flow rate  $Q_g$  of bottom blowing gas is controlled so as to maintain the stirring power density  $\epsilon$  at 140 W/ton or below (0 W/ton not included), result will be favorable since surfacing and segregation of entrapped top slag can be promoted.

**[0097]** In the calculation of the stirring power density  $\epsilon$ , the temperature of the bottom blowing gas before blowing  $T_0$  (temperature of Ar gas before blowing) is to be ordinary temperature (298K), and the temperature of the bottom blowing gas after blowing  $T_g$  (temperature of Ar gas after blowing) is to be equal to the temperature of the molten steel  $T_L$ .

[Mathematical Formula 1]

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

**[0098]**  $\epsilon$ : Stirring power density (W/ton)

**[0099]**  $T_0$ : Temperature before blowing of bottom blowing gas (ordinary temperature of 298K)

**[0100]**  $T_L$ : Molten temperature (K)

**[0101]**  $M_L$ : Quantity of molten steel (ton)

**[0102]**  $P_L$ : Molten steel density ( $\text{kg}/\text{m}^3$ )

$Q_g$ : Flow rate of bottom blowing gas ( $\text{Nl}/\text{min}$ )

$T_g$ : Temperature after blowing of bottom blowing gas (K)

**[0103]** P: Ambient pressure (torr)

**[0104]**  $h_0$ : Depth of molten steel (m)

**[0105]** For example, in the first course of heating and composition adjustment (LF-I), there are difference in conditions in respect of the size of ladle, the loaded quantity of molten steel  $M_L$ , etc., but if  $Q_g/M_L$  can fall in the range of 0.30-3.75  $\text{Nl}/\text{min}\cdot\text{ton}$ , the stirring power density E is obtainable in the range of 4.7-67.2 W/ton

**[0106]** Further, by conducting the second course of heating and composition adjustment (this second course may hereafter be called as "LF-II") to the molten steel after VD, it becomes possible to manufacture super clean steel.

**[0107]** That is, the molten steel after completion of the vacuum degassing treatment, just as is in the ladle, is transported to the secondary refining equipment and is made to go through the second course of heating and composition adjustment. In more detail, for example, the molten steel, while it is being heated up to  $T_L=1600^\circ\text{C}$ . or thereabout by generation of arc discharge, is stirred by Ar gas blowing by a gas blowing means. In regard to stirring strength in the molten steel, it is recommended that the flow of Ar gas  $Q_g$  should be controlled so that the stirring power density  $\epsilon$  calculated according to the above formula (1) may be kept within the range of 25 W/ton or below to 2.0 W/ton or over. Keeping the above stirring power density  $\epsilon$  at 25 W/ton or below makes it possible to prevent any new top slag from being entrapped into the molten steel. At this stage of LF-II, it may as well be exercised to do analysis of composition and also fine adjustment thereof, according to need.

**[0108]** By carrying out the LF treatment (LF-II) once again as above, this can further promote the "surfacing and segregation of entrapped-in top slag and deoxidation products," the work which has been put in action from the midway of VD.

**[0109]** As explained above, LF-II starts with the top slag having the following composition.

**[0110]** (i) The degree of basicity, namely  $\text{CaO}/\text{SiO}_2 \geq 3.0$

**[0111]** (ii)  $\text{CaO}/\text{Al}_2\text{O}_3 = 1.5-3.5$

**[0112]** (iii)  $T. \text{Fe} + \text{MnO} \leq 1.0\%$  by mass

Conditions being such, it is favorable that composition of the molten steel is surely prevented from reoxidation by the oxides in the top slag.

**[0113]** As described above, the refinery process is enough if it includes the processes of [heating and composition adjustment  $\rightarrow$  degassing treatment  $\rightarrow$  heating and composition adjustment], and it is not limited to anteroposterior processes. Hence, for example, after the above processes of [heating and composition adjustment  $\rightarrow$  degassing treatment  $\rightarrow$  heating and composition adjustment], the processes of [degassing treatment  $\rightarrow$  heating and composition adjustment] or [degassing treatment  $\rightarrow$  heating] may be added by one cycle on the same conditions as above or on any other conditions than the above, or otherwise, either or both of these two sets of processes to be repeated plural times may be added; or further otherwise, after the above processes of [heating and composition adjustment  $\rightarrow$  degassing treatment  $\rightarrow$  heating and composition adjustment], it is all right if only the process of [degassing] may be repeated again on the same conditions as above or on any other conditions than the above.

**[0114]** The present invention includes the forged products obtainable from the use of the above forging steel, but there is no particular limitation on the manufacturing method for the forged products. For example, manufacturing can be conducted if it covers such processes as heating of the above forging steel to forging in material stage, in-process inspection followed by heating and forging into product shape, heated homogenization treatment followed by quench hardening and normalizing, and finishing by machining.

**[0115]** As the forged products available from the above processes, first comes crankshafts (solid type crankshaft and assembly type crankshaft). Because of the excellent fatigue strength, other high-strength products than crankshafts can also be listed, such as intermediate shafts and transmission shafts for marine ships and vessels, throws of assembly type crankshafts, parts for general machinery, pressure vessels, hollow forgings, and so forth.

**[0116]** In manufacturing a crankshaft as a forged product, the solid type crankshaft is preferable, because the portion of the steel where cleanliness is higher can be arranged to occupy the surface layer of the shaft thereby enabling the shaft to obtain excellent strength and fatigue characteristics. The manufacturing method of the solid type crankshaft in such a case is not particularly specified, but recommendable is to manufacture the crankshaft according to the R.R. and T.R. forging method (wherein, forging processing is performed so that the axis center of the ingot may become concentric with the shaft center of the crankshaft, and further, forging processing is made in such a state that the portion of the ingot where deterioration in characteristics is likely to occur due to center segregation may compose the entire shaft center of the crankshaft, in a unified manner).

**[0117]** As another method of forging processing, the free-forging method may as well be employed. (In this method, the crank arm and crankpins are forged in one block and formed into the shape of crankshaft by gas-cutting and machining.)

**[0118]** Hereafter, some embodiments are going to be presented for more concrete explanation of the present invention. In the nature of the case, the present invention is by no means limited to the embodiments, but the embodiments can be implemented with proper modifications insofar as such modifications are within the scope conforming to the purport of what is mentioned above and below herein. All of such modifications shall be regarded an integral part of the technical scope of the present invention.

## EMBODIMENTS

**[0119]** In an electric furnace, 20-100 tons of scrap material was melted and tapped to fill the ladle. Then, by using the ladle-heating type refining equipment with a bottom-blowing agitator, molten steel processing was carried out. In this molten steel processing, the first course of heating and composition adjustment (LF-I) was conducted to the molten steel tapped out of the converter or electric furnace; the degassing treatment (VD) was applied to the molten steel after completion of the first heating and composition adjustment; and the second heating and composition adjustment (LF-II) was carried out to the molten steel after completion of the degassing treatment.

**[0120]** At the time of the above first course of heating and composition adjustment, such slag formation agents as CaO,  $\text{Al}_2\text{O}_3$ , and MgO were added to the surface of the molten steel for formation of top slag including CaO and MgO in the amounts shown in Table 1. In the next place, Al was added to

deoxidize the molten steel, and also dehydronegation was conducted by vacuum treatment with lid degassing equipment. While processing of the molten steel, sampling of the molten steel was made properly to measure the concentration of the dissolved Al. In order to maintain the concentration of the dissolved Al within a preferred range, Al was additionally supplied according to need. The concentrations of the dissolved Al in the molten steel are shown in Table 1. Addition of S-contained alloy, Mg-contained alloy, and Ca-contained alloy shown in Table 1 was made at the stage of LF-II. The stirring power density till the midterm (first half of VD) of the above degassing treatment (VD), the stirring power density in the degassing treatment thereafter (after the midterm or the latter half of VD), and the stirring power density in the LF-II were set respectively as shown in Table 1.

**[0121]** When the above molten steel treatment was completed, samples of top slag were taken, and the molten steel was cast by the bottom pouring casting method into steel ingots (20-100 tons). The steel ingots, after solidification was completed, were taken out from the moulds, and were made to go through hot forging under heating at 1150° C. or over to produce various sizes of forged products in the shape of round bars in various sizes. On that occasion, the 20-ton steel ingot was treated by hot forging into the product in a shape of 250-450 mm diameter round bars, 50-ton steel ingot was treated by hot forging into the product in a shape of 350-700 mm diameter round bars, and 100-ton steel ingot was treated by hot forging into the product in a shape of 600-1200 mm diameter round bars. At the same time, availing of the above top slag samples, the concentrations of CaO and MgO in the top slag were investigated by the ICP emission spectro chemical analysis. The results therefrom are as shown in Table 1.

**[0122]** The chemical compositions of respective forged materials were investigated by chemical analysis, obtained results being shown in Table 2. Further, the amounts of dissolved Ca and dissolved Mg in steel ingots were measured along with composition analysis of inclusions in forged products and fatigue test carried out in the following manner at the same time. Meanwhile, the amounts of Total Ca and Total Mg in the steel shown in Table 2 were obtained by ICP mass spectrometer method (ICP-MS method).

**[0123]** [Measurement of Amount of Dissolved Ca (Sol. Ca) and Amount of Dissolved Mg (Sol. Mg) in Steel]

**[0124]** The samples taken from the steel ingot are ground and loaded in the secondary ion mass spectrometer ("ims5F" registered trademark of AMETEK, Inc.). For each sample, secondary ion image of Ca or Mg was observed within a region of 500×500 (μm<sup>2</sup>) to select therein three places where Ca or Mg is not thickened locally, and analysis was made in the direction of depth in those three places. The first ion source in that case was O<sup>2+</sup>. And, if the depth-wise distribution of concentration was uniform, the concentration value at that time was deemed to be the concentration of the dissolved element. In case there were found inclusions in the course of depth-wise analysis, the distribution of concentration showed large fluctuations, but analysis was proceeded with until it reaches where inclusions were no longer existing and when the distribution of concentration became uniform, the value available therefrom was adopted as the value of the dissolved element. Incidentally, with regard to the determination method for concentration, pure iron with ion implantation of <sup>24</sup>Mg (150 keV, 1×10<sup>14</sup> atoms/cm<sup>2</sup>) and <sup>27</sup>Al (200 keV, 1×10<sup>14</sup> atoms/cm<sup>2</sup>) were measured as the standard specimen, and the relative sensitivity factors (RSF) obtained therefrom

were used to determine atomic concentrations. These results of measurements are also included in Table 2.

**[0125]** [Chemical Composition Analysis of Inclusions]

**[0126]** In relation to round bars after forging, sample was cut out from the central part of the portion corresponding to the bottom part of the steel ingot and was made available for chemical composition analysis of inclusions by EPMA (electron probe X-ray microanalysis). For this analysis, more than 50 pieces of inclusions were randomly chosen for each sample. The result of this analysis is as shown in Table 3. The same table also shows the largest inclusion among the above-mentioned more than 50 pieces of inclusions along with the diameter of an assumed circle equivalent area-wise to the largest inclusion.

**[0127]** Additionally on Table 3, the expression "Refined" in the columns of "Oxide Type" and "Sulfide Type" means that the diameter of an assumed circle equivalent area-wise to the largest inclusion is less than 100 μm. The composition of inclusion indicated together in the table denotes the composition of the oxide, in case of oxide type inclusion, that covered more than 50% in number of pieces among all the oxide type inclusions having undergone the above analysis; in case of sulfide type inclusion, it denotes the composition of the sulfides that covered more than 50% in number of pieces among all the sulfide type inclusions having undergone the above analysis. The expression "coarse and large" applies to the case in which one or more number of pieces of coarse and large inclusions were detected to have 100 μm or over in diameter of assumed circles equivalent area-wise to the inclusions; also, the compositions of the inclusion shown together indicate the compositions of the above coarse and large inclusions. The expression "Inclusions in forged product," covers oxides and sulfides when these exist individually, but it also includes the case where oxides and sulfides are in adjacent or composite state (for example, the case of composite inclusions such as an oxide taking the role of core while a sulfide surrounding the oxide core). It is to be understood that even in case of a composite inclusion, the sizes of the oxide and the sulfide in that composite inclusion are individually and separately determined and evaluated.

**[0128]** [Fatigue Test and Measurement of Inclusion Size]

**[0129]** From a round bar after forging, smooth specimens were cut out from the center part of the portion corresponding to the bottom position of the steel ingot, in a size of 10 mm in diameter in the radius direction of the bar by 30 mm in length, and the specimens were subjected to the fatigue test on the following conditions. Another set of test specimens was taken from the same position as the fatigue test specimens, and it was used for conducting tensile test at normal temperature. As an index of fatigue limit, the endurance limit ratio (fatigue strength σ<sub>w</sub>/tensile strength σ<sub>B</sub>) was measured. This test was conducted with 5 pieces of specimens to obtain average endurance limit ratio. If the ratio obtained was over 0.42, the specimen was evaluated excellent. The result is shown in Table 3.

Testing method: Rotary bending fatigue test (stress ratio=-1; 3600 rpm)

Fatigue strength evaluation method: Difference method.

Difference stress: 20 MP a

Initial stress: 300 MP a

Number of test specimens: 5 pieces each

Fatigue strength of each specimen:

$$\text{Fatigue strength} = (\text{Rupture stress}) - (\text{Difference stress})$$

TABLE 1

Experiment No.	Concentration of Al in Molten Steel ppm	Slag Basicity —	CaO in Slag %	MgO in Slag %	Stirring Power Density for First Half VD W/t	Stirring Power Density for Latter Half VD W/t	Stirring Power Density for L-F-II W/t	Additive after Composition Adjustment	
1		180		4.8	58.2	15	50	40	5.5 —
2		370		5.5	55.4	13	120	60	15 —
3		420		5.0	47.9	13	180	100	18 —
4		60		3.5	43.3	6	60	80	20 —
5		648		10.0	42.0	15	200	130	25 —
6		306		6.0	58.6	11	150	40	10 —
7		89		5.0	52.5	10	70	80	15 —
8		270		5.8	48.4	21	140	120	15 —
9		146		4.5	41.9	17	180	100	18 —
10		220		5.2	57.2	20	160	100	20 —
11		290		3.2	31.0	7	160	100	15 —
12		240		3.0	32.0	23	190	130	25 —
13		110		4.2	45.1	20	180	120	22 —
14		190		8.0	55.0	25	180	130	25 —
15		450		11.0	64.8	8	180	60	13 —
16		50		4.0	43.9	5	100	50	5.5 —
17		140		4.6	51.0	5	100	50	2 —
18		510		6.5	60.0	12	200	200	30 S-contained Alloy, Mg-contained Alloy and Ca-contained Alloy Added
19		505		5.5	58.1	12	220	150	45 —
20		290		4.2	55.5	20	160	120	23 Mg-contained Alloy Added
21		150		5.0	40.1	15	160	120	23 Ca-contained Alloy Added
22		500		5.5	64.0	10	60	30	1.5 Mg-contained Alloy Added
23		150		6.0	43.2	6	80	30	1.5 Ca-contained Alloy Added
24		310		4.0	51.6	18	80	60	18 S-contained Alloy Added
25		70		5.0	45.5	7	45	28	1.5 —
26		940		6.0	50.6	15	180	100	15 —
27		35		5.5	48.4	13	140	70	15 —
28		340		1.8	25.5	25	180	120	20 —

TABLE 2

Experiment No.	Chemical Composition (% denotes mass %, ppm denotes mass ppm, and ppb denotes mass ppb)*												
	C %	Si %	Mn %	Ni %	Cu %	Ti %	Cr %	Mo %	V %	Nb %	Ta %	Hf %	O ppm
1	0.40	0.35	1.02	0.35	—	<0.001	1.60	0.25	0.09	—	—	—	5
2	0.45	0.25	1.01	0.21	—	0.001	1.98	0.25	0.10	—	—	—	4
3	0.50	0.20	0.99	0.12	—	0.006	2.30	0.20	0.02	—	—	—	5
4	0.22	0.18	0.22	1.78	—	0.050	1.03	0.40	0.06	—	—	—	14
5	0.30	0.30	0.60	1.32	—	0.018	1.40	0.19	0.10	—	—	—	4
6	0.20	0.05	0.90	2.50	1.00	<0.001	1.10	0.11	0.05	—	—	—	7
7	0.30	0.30	0.30	3.50	—	0.010	2.00	0.70	0.20	—	—	—	7
8	0.45	0.10	0.70	0.60	—	0.028	3.54	0.20	0.05	—	—	—	8
9	0.51	0.49	0.60	0.80	—	0.005	0.90	0.23	0.10	—	—	—	8
10	0.45	0.25	1.00	0.20	—	0.010	2.00	0.30	0.10	—	—	—	6
11	0.55	0.40	1.20	0.10	—	0.001	4.00	0.27	0.005	0.005	—	—	6
12	0.20	0.08	0.20	3.40	—	0.015	1.31	0.30	—	—	0.006	0.006	7
13	0.40	0.10	0.92	0.80	—	0.007	1.00	0.25	—	0.20	—	—	25
14	0.30	0.08	1.00	0.60	—	0.015	1.50	0.20	—	—	0.18	—	6
15	0.55	0.05	1.03	0.40	—	0.014	1.20	0.10	—	—	—	0.16	10
16	0.35	0.28	0.99	2.00	—	0.015	1.01	0.25	0.04	—	—	—	8
17	0.42	0.35	1.50	0.20	0.05	0.018	1.98	0.20	0.05	—	—	—	9
18	0.40	0.26	1.02	0.22	—	0.015	1.94	0.25	0.10	—	—	—	25
19	0.40	0.26	1.02	0.22	—	0.012	1.94	0.25	0.10	—	—	—	20
20	0.45	0.26	0.80	0.16	—	0.030	1.72	0.10	0.005	—	—	—	5
21	0.36	0.30	1.20	0.30	—	0.010	1.90	0.25	0.11	—	—	—	6
22	0.45	0.26	0.80	0.16	—	0.001	1.71	0.61	0.005	—	—	—	4
23	0.36	0.30	1.20	0.30	—	0.005	1.90	0.25	0.11	—	—	—	10

TABLE 2-continued

24	0.31	0.22	1.00	0.21	—	0.012	1.95	0.26	0.11	—	—	—	8
25	0.45	0.27	0.80	0.21	—	<0.001	2.40	0.57	0.01	—	—	—	11
26	0.40	0.28	1.01	0.25	—	0.025	2.20	0.50	0.12	—	—	—	5
27	0.44	0.20	1.10	0.25	—	0.020	2.00	0.40	0.10	—	—	—	15
28	0.20	0.40	1.50	1.80	—	0.008	1.50	0.20	—	—	—	—	10

Chemical Composition (% denotes mass %, ppm denotes mass ppm, and ppb denotes mass ppb)*							
Experiment No.	Total Al ppm	S %	Total Ca ppm	Total Mg ppm	Sol. Ca ppb	Sol. Mg ppm	
1	190	0.004	4	3	3	0.59	
2	430	0.002	8	10	6	1.2	
3	460	0.0004	11	5	15	1.9	
4	80	0.007	5	1	2	0.05	
5	670	0.0003	15	8	60	4.6	
6	360	0.0004	8	3	8	0.50	
7	110	0.002	3	4	2	0.38	
8	320	0.003	5	1	7	0.89	
9	200	0.003	4	3	4	0.45	
10	290	0.007	5	1	4	0.15	
11	300	0.0006	4	3	1	0.04	
12	250	0.0004	3	6	1	4	
13	120	0.0003	3	8	2	7	
14	200	0.002	7	11	90	9.5	
15	460	0.002	6	4	30	0.2	
16	50	0.003	8	1	2	0.02	
17	150	0.0007	4	2	80	0.03	
18	530	0.012	35	32	110	7	
19	520	0.001	50	31	110	6	
20	330	0.002	2	20	20	12	
21	180	0.002	55	5	120	0.2	
22	510	0.002	5	25	30	5	
23	160	0.001	32	5	30	0.2	
24	320	0.009	8	15	10	0.67	
25	80	0.008	3	1	1	0.01	
26	960	0.002	25	10	110	7	
27	40	0.002	15	2	1	0.02	
28	350	0.004	5	9	1	7	

\*Balance composed of Fe and inevitable impurities.

TABLE 3

Experiment No.	Oxide Type	Sulfide Type	Dia. ( $\mu\text{m}$ ) of assumed circle equivalent to the largest inclusion	Endurance Limit Ratio $\sigma_w/\sigma_B$ (—)
1	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,Mn)S	11	0.500
2	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,)S	20	0.479
3	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,)S	28	0.474
4	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,Mn)S	87	0.431
5	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,)S	40	0.427
6	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,Mn)S	16	0.485
7	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,Mn)S	26	0.480
8	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,Mn)S	43	0.453
9	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,Mn)S	26	0.452
10	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg,Mn)S	48	0.450
11	Refined: (Al,Mg)O	Refined: (Mg,Mn)S	15	0.438
12	Refined: (Al,Mg)O	Refined: (Mg,Mn)S	15	0.454

TABLE 3-continued

Experiment No.	Oxide Type	Sulfide Type	Dia. ( $\mu\text{m}$ ) of assumed circle equivalent to the largest inclusion	Endurance Limit Ratio $\sigma_w/\sigma_B$ (—)
13	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg)S	35	0.444
14	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg)S	94	0.440
15	Refined: (Ca,Al,Mg)O	Refined: (Ca,Mg)S	34	0.439
16	Refined: (Al,Ca)O	Refined: (Ca,Mn)S	31	0.431
17	Refined: (Al,Ca)O	Refined: (Ca,Mn)S	70	0.449
18	Coarse and large: (Ca,Mg,Al)O	Coarse and large: CaS	388	0.311
19	Coarse and large: (Ca,Mg,Al)O	Coarse and large: CaS	339	0.318
20	Coarse and large: MgO	Coarse and large: MgS	231	0.327
21	Coarse and large: (Ca,Mg,Al)O	Coarse and large: CaS	188	0.362
22	Coarse and large: MgO	Coarse and large: MgS	167	0.356
23	Coarse and large: (Ca,Al)O	Coarse and large: CaS	175	0.332
24	Refined: (Ca,Al,Mg)O	Coarse and large: (Ca,Mn)S	146	0.387
25	Coarse and large: $\text{Al}_2\text{O}_3$	Coarse and large: MnS	130	0.400
26	Coarse and large: (Ca,Mg,Al)O	Coarse and large: CaS	284	0.330
27	Coarse and large: $\text{Al}_2\text{O}_3$	Coarse and large: MnS	415	0.306
28	Coarse and large: MgO	Coarse and large: MgS	115	0.419

**[0130]** From Tables 1 to 3, the following views are derivable. (The Nos. appearing below are the Experiment Nos. used in Tables 1-3.) Since Nos. 1-17 satisfy the component composition prescribed in the present invention, it can be conceived that the largest inclusion existing in the steel was small, leading to the result of high endurance limit ratio made available.

**[0131]** In contrast to the above, the chemical compositions in the steel for Nos. 18-28 were not in accordance with the specific requirements of the present invention, as a result of which the largest inclusion existing in the steel became coarse and large as described below, causing decrease in endurance limit ratio.

**[0132]** More concretely, No. 18 is an example in which S-contained alloy, Mg-contained alloy, and Ca-contained alloy were added with stirring in refining being too strong. For this reason, amounts of all of S, Total Ca, Total Mg, and dissolved Ca exceeded the upper limits, failing to prevent oxides and sulfides from growing coarse and large beyond limit.

**[0133]** As for No. 19, the stirring in refining was so strong that MgO and CaO in the top slag were entrapped into the molten steel. As a result, amounts of Total Ca, Total Mg, and dissolved Ca increased beyond upper limits, with oxides and sulfides turning out to be coarse and large.

**[0134]** With regard to No. 20, addition of Mg-contained alloy obliged both amounts of Total Mg and dissolved Mg to increase beyond upper limit, resulting in formation of coarse and large inclusion of dissolved Mg.

**[0135]** The case of No. 21 involved addition of Ca-contained alloy, which made the amounts of Total Ca and dissolved Ca to increase beyond the upper limit, resulting in formation of coarse and large Ca-contained inclusion.

**[0136]** No. 22 was a case of Mg-contained alloy added with weak stirring at the stage of LF-II. Though the amount of dissolved Mg remained within the prescribed range, the amount of Total Mg went over the upper limit, failing to prevent growth of coarse and large Mg-contained inclusion.

**[0137]** No. 23 was a case of Ca-contained alloy added with weak stirring at the stage of LF-II. Though the amount of dissolved Mg remained within the prescribed range, the amount of Total Ca went over the upper limit, failing to prevent growth of coarse and large Ca-contained inclusion.

**[0138]** In the case of No. 24, addition of S-contained alloy brought about over-limit increase of S amount and resultant coarse and large sulfide.

**[0139]** No. 25 was an example in which the stirring strength in the first half of VD was small and the stirring strength in the stage of LF-II was also weak. In this case, the amounts of dissolved Ca and dissolved Mg was not able to fill the prescribed lower limits, ending up generation of coarse and large  $\text{Al}_2\text{O}_3$  and MnS

**[0140]** In the case of No. 26, the concentration of dissolved Al in the molten steel was over the recommended range and the amount of dissolved Ca was beyond the upper limit, resulting that coarse and large Ca-contained inclusion was generated.

[0141] No. 27 was a case in which the concentration of dissolved Al in the molten steel was below the recommended range and the amounts of dissolved Ca and Mg were short of the prescribed lower limits, ending up generation of coarse and large  $Al_2O_3$  and MnS.

[0142] In the case of No. 28, the composition of the top slag is not in conformity with the range as recommended, and the amount of dissolved Ca is short of the prescribed lower limit. As a result, coarse and large  $Al_2O_3$  and MnS were generated.

[0143] FIG. 2 is a graph in which the relation between the diameter of an assumed circle equivalent area-wise to the above largest inclusion existing in the steel as detected by EPMA and the endurance limit ratio is shown in an organized manner. It will be seen from this FIG. 2 that there is a good correlation between the endurance limit ratio and the diameter of an assumed circle equivalent to the above largest inclusion. When the diameter of an assumed circle equivalent to the above largest inclusion is less than 100  $\mu m$ , it turns out that the steel can prove as excellent a fatigue characteristic as over 0.42 in endurance limit ratio.

What is claimed is:

1. Forging steel satisfying the following requirements concerning component composition:

C: 0.2-0.6% (hereafter, % denotes '% by mass'),

Si: 0.05-0.5%,

Mn: 0.2-1.5%,

Ni: 0.1-3.5%,

Cr: 0.9-4%,

Mo: 0.1-0.7%,

Al: 0.005-0.1%,

S: 0.008% or less (0% not included),

O: 0.0025% or less (0% not included),

Total Ca: 0.0030% or less (0% not included), and

Total Mg: 0.0015% or less (0% not included);

and simultaneously, said forging steel also satisfying any one of the following (I) to (IV) in regard to dissolved Ca and dissolved Mg (hereafter, ppb and ppm denote respectively "ppb by mass" and "ppm by mass"):

(I) Dissolved Ca: 2-500 ppb, and

Dissolved Mg: 0.04-5 ppm;

(II) Dissolved Ca: 2-100 ppb, and

Dissolved Mg: 5-10 ppm;

(III) Dissolved Ca: 2 ppb (0 ppb not included), and

Dissolved Mg: 0.04-5 ppm; or

(IV) Dissolved Ca: 2-500 ppb, and

Dissolved Mg: 0.04 ppm or less (0 ppm not included).

2. The forging steel according to claim 1, also comprising at least one out of the following groups (A), (B), and (C)

(A) One or more elements selected from the group consisting of V, Nb, Ta, and Hf, in an amount within the range of 0.005-0.2% for all selected elements added together;

(B) Ti: 0.05% or less (0% not included); and/or

(C) Cu: 1.0% or less (0% not included).

3. The forging steel according to claim 2, wherein the diameter of an assumed circle equivalent area-wise to the largest piece of inclusion existing in said forging steel is less than 100  $\mu m$ .

4. Forged products (including parts) manufactured from the forging steel according to claim 3.

5. The forged products according to claim 4, wherein crankshafts are particularly referred to as said forged products.

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