(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) **EP 3 342 892 A1**

(12) **EUROPEAN PATENT APPLICATION**
published in accordance with Art. 153(4) EPC

(43) Date of publication:
04.07.2018 Bulletin 2018/27

(21) Application number: **16839120.9**

(22) Date of filing: **12.08.2016**

(51) Int Cl.:
C22C 38/00 *(2006.01)* ***C21D 8/06*** *(2006.01)*
C22C 38/60 *(2006.01)*

(86) International application number:
PCT/JP2016/073769

(87) International publication number:
WO 2017/033773 (02.03.2017 Gazette 2017/09)

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
MA MD

(30) Priority: **25.08.2015 JP 2015166030**
23.06.2016 JP 2016124959

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(54) MECHANICAL STRUCTURE STEEL FOR COLD-WORKING AND MANUFACTURING METHOD THEREFOR

(57) To provide a mechanical structure steel for cold-working that enables the achievement of the spheroidization equal to or better than that in a prior steel and can also be more softened than the prior steel, even when the time for the spheroidizing annealing is shorter than a usual spheroidizing annealing time; and a method for manufacturing the mechanical structure steel.

The present disclosure relates to a mechanical structure steel for cold-working that includes C, Si, Mn, P, S, Al, and N and has a metal microstructure including proeutectoid ferrite and pearlite, in which a total area ratio of the proeutectoid ferrite and the pearlite with respect to the entire microstructure is 90% or more, while an area ratio Af of the proeutectoid ferrite with respect to the entire microstructure satisfies a relationship of Af ≥ A where an A value is represented by formula (1) below, an average circle equivalent diameter of a bcc-Fe crystal grain is in a range of 15 to 30 μm, and a pearlite lamellar spacing is 0.20 μm or less on average:

$$A = (103 - 128 \times [C(\%)]) \times 0.80\ (\%) \qquad (1) \qquad (1)$$

where [C (%)] in the formula (1) indicates the C content in percent by mass.

Printed by Jouve, 75001 PARIS (FR)

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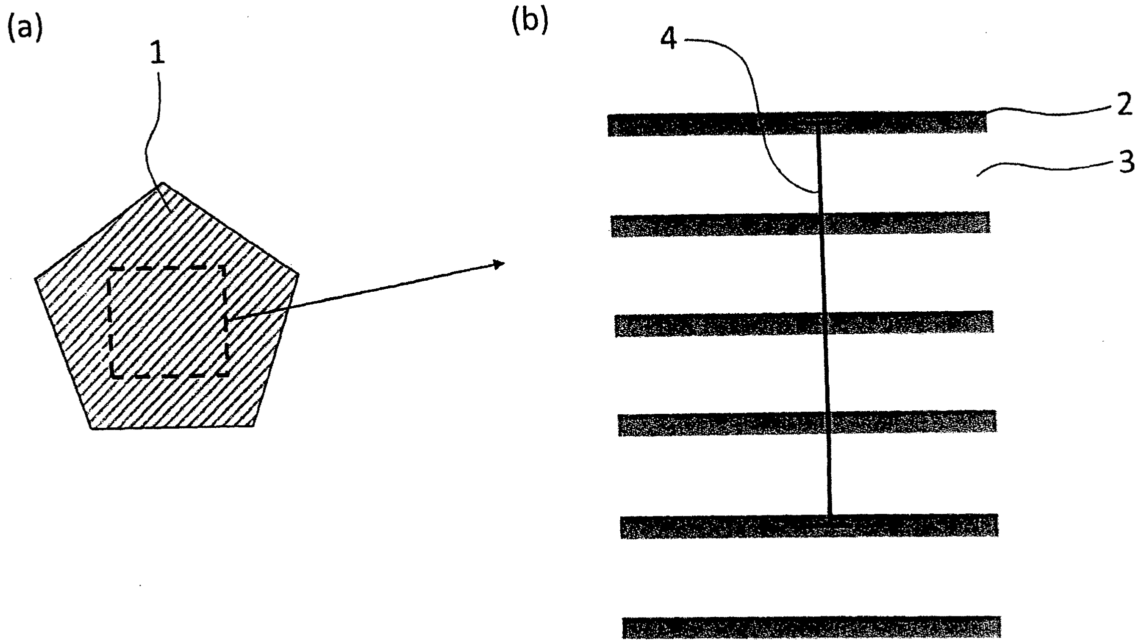
Fig. 1



Description

Technical Field

[0001] The present disclosure relates to a mechanical structure steel for cold-working and a manufacturing method therefor. In particular, the present disclosure relates to a mechanical structure steel having a low deformation resistance after spheroidizing annealing and excellent cold workability, and a method useful for manufacturing the mechanical structure steel. The mechanical structure steel for cold-working in the present disclosure is suitable for use in various components, such as automobile components and construction machine components, manufactured by cold-working, such as cold forging, cold heading, and cold rolling. The form of the steel is not limited particularly, and the steel is intended to be used, for example, as a rolled wire rod or the like. Examples of various components above specifically include machine components and electric components, such as bolts, screws, nuts, sockets, ball joints, inner tubes, torsion bars, clutch cases, cages, housings, hubs, covers, cases, cradles, tappets, saddles, bulks, inner cases, clutches, sleeves, outer races, sprockets, cores, stators, anvils, spiders, rocker arms, bodies, flanges, drums, joints, connectors, pulleys, metal fittings, yokes, mouthpieces, valve lifters, spark plugs, pinion gears, steering shafts, and common rails. Note that the term a wire rod as used in the present specification means a rolled wire rod, specifically, indicating a line-shaped steel material produced by cooling a hot-rolled steel to room temperature. Further, the term a steel wire as used herein indicates a line-shaped steel material having its properties adjusted by drawing and/or annealing the rolled wire rod.

Background Art

[0002] When producing various components, such as automobile components and construction machine components, a spheroidizing annealing treatment is usually applied to hot-rolled wire rods made of carbon steel, alloy steel or the like to impart adequate cold workability to the wire rod. Then, the steel wire obtained after the spheroidizing annealing is subjected to cold-working and then machining, such as cutting, to be formed into a predetermined shape, followed by a quenching-tempering treatment to thereby finally adjust its strength.

[0003] In recent years, the conditions for spheroidizing annealing have been revised in terms of energy saving, and especially, shortening of the spheroidizing annealing time has been required. For example, if the spheroidizing annealing time is reduced by 20 to 30 percent, the reduction in energy consumption and CO_2 emission can be expected.

[0004] However, it is known that if the spheroidizing annealing time is shortened, a spheroidization degree as an index of spheroidization of carbides becomes larger (that is, the spheroidized microstructure becomes deteriorated), and thereby the cold workability is deteriorated. Because of this, shortening of the spheroidizing annealing time is not easy to implement.

[0005] Some techniques have been hitherto proposed to achieve the shortening of the spheroidizing annealing time. For example, Patent Document 1 discloses a mechanical structure steel for cold-working that can be softened even after spheroidizing annealing for a relatively short time by controlling the metal microstructure before the spheroidizing annealing, and also discloses a manufacturing method for such a mechanical structure steel. Specifically, in the disclosed mechanical structure steel for cold-working, a total area ratio of pearlite and ferrite to the entire microstructure is set at 95% by area or more, and an area ratio of ferrite is set at a predetermined level or more, and a grain size of a bcc-Fe crystal is controlled within an appropriate range. In the disclosed manufacturing method for the mechanical structure steel for cold-working, finish processing is performed on the steel at a temperature in a range of 750 to 950°C, and then cooled down to a temperature in a range of 600 to 660°C at an average cooling rate of 5°C/sec. or more, followed by cooling at an average cooling rate of 1°C/sec. or less for 20 seconds or more.

[0006] Patent Document 2 discloses a steel wire rod that includes a proeutectoid ferrite microstructure, a pearlite microstructure and a bainite microstructure in a metal microstructure, as well as a manufacturing method for the same. The disclosed steel wire rod can shorten the softening annealing time and can also achieve excellent cold forgeability after the softening annealing. In the disclosed manufacturing method for the steel wire rod, the steel is hot-rolled, wound and immersed into a molten salt bath at a temperature of 500°C or higher and 600°C or lower for 10 seconds or more, and is then maintained isothermally in a molten salt bath of 530°C or higher and 600°C or lower for 20 seconds or more and 150 seconds or less, followed by cooling.

[0007] Patent Document 3 discloses a hot-rolled wire rod for cold forging and a manufacturing method therefor in which a ferrite grain size number is 9 or more, a ferrite fraction is 30% by area or more with the balance being pearlite, bainite, martensite, or a microstructure of a combination thereof, while a bainite-martensite fraction is 50% by area or more of the balance. In the disclosed manufacturing method for the hot-rolled wire rod for cold forging, finish rolling is performed on the steel in a temperature range from Ar_3 point to Ar_3 point + 150°C, and the steel is then cooled down in a temperature range of Ar_1 point to 300°C at a cooling rate of 5 to 40°C/sec.

Prior Art Document

Patent Document

[0008]

Patent Document 1: JP 2013-7091 A
Patent Document 2: JP 5195009 B1
Patent Document 3: JP 4299744 B1

Disclosure of the Invention

Problems to be Solved by the Invention

[0009] However, according to the way disclosed in the Patent Document 2, an area ratio of the proeutectoid ferrite is too low that the hardness of a steel wire obtained after the spheroidizing annealing might become high. According to the way disclosed in the Patent Document 3, an area ratio of the ferrite is too low, and the steel further includes bainite or martensite. Because of this, the hardness of a steel wire obtained after the spheroidizing annealing is expected to become high.

[0010] In this way, the techniques proposed so far are effective in shortening the spheroidizing annealing time. However, the development of the techniques has been required to soften the steel while obtaining a better spheroidized microstructure than that in the related art.

[0011] Accordingly, embodiments of the present invention have been made under such circumstances and have an object to provide a mechanical structure steel for cold-working that enables the achievement of the spheroidization equal to or better than that in a prior steel and can also be more softened than the prior steel, even when the time for the spheroidizing annealing is shorter than a usual spheroidizing annealing time, and to provide a method for manufacturing the steel.

Means for Solving the Problems

[0012] A mechanical structure steel for cold-working according to one embodiment of the present invention that can solve the above-mentioned problems comprises, in percent by mass, C: 0.07% or more and less than 0.3%, Si: 0.05 to 0.5%, Mn: 0.2 to 1.7%, P: more than 0% and 0.03% or less, S: 0.001 to 0.05%, Al: 0.01 to 0.1%, and N: 0 to 0.015%, with the balance being iron and inevitable impurities, wherein the steel has a metal microstructure comprising proeutectoid ferrite and pearlite, a total area ratio of the proeutectoid ferrite and the pearlite with respect to the entire microstructure is 90% or more, while an area ratio Af of the proeutectoid ferrite with respect to the entire microstructure satisfies a relationship of Af ≥ A where an A value is represented by formula (1) below, an average circle equivalent diameter of a bcc-Fe crystal grain is in a range of 15 to 30 μm, and a pearlite lamellar spacing is 0.20 μm or less on average:

$$A = (103 - 128 \times [C(\%)]) \times 0.80\ (\%) \qquad (1)$$

where [C(%)] in the formula (1) indicates the C content in percent by mass.

[0013] In a preferred embodiment of the present invention, the above-mentioned mechanical structure steel for cold-working further comprises, in percent by mass, one or more elements selected from the group consisting of Cr: more than 0% and 0.5% or less, Cu: more than 0% and 0.25% or less, Ni: more than 0% and 0.25% or less, Mo: more than 0% and 0.25% or less, and B: more than 0% and 0.01% or less, the mechanical structure steel satisfying formula (X) below:

$$[Cr\%] + [Cu\%] + [Ni\%] + [Mo\%] \leq 0.75 \qquad (X)$$

where [Cr%], [Cu%], [Ni%], and [Mo%] indicate the contents of Cr, Cu, Ni, and Mo in percent by mass, respectively.

[0014] In another preferred embodiment of the present invention, the above-mentioned mechanical structure steel for cold-working further comprises, in percent by mass, Ti: more than 0% and 0.1% or less.

[0015] A method for manufacturing the above-mentioned mechanical structure steel for cold-working according to the above-mentioned embodiments of the present invention comprises: performing finish rolling at a temperature of 950°C or higher and 1, 150°C or lower; and then performing, in the following order, first cooling to a first-cooling end temperature of 700 to 750°C at an average cooling rate of 3°C/sec. or less and second cooling in a temperature range from the first-cooling end temperature to at least 600°C at an average cooling rate of 5 to 30°C/sec.

Effects of the Invention

[0016] In the mechanical structure steel for cold-working of the present disclosure, each of the total area ratio of the proeutectoid ferrite and the pearlite and the area ratio of the pro-eutectoid ferrite with respect to the entire microstructure is set at a predetermined value or more, while the chemical component composition is appropriately adjusted, and further the average circle equivalent diameter of the body-centered cubic (bcc)-Fe crystal grain (hereinafter simply referred to as a "bcc-Fe average grain size" in some cases) and the pearlite lamellar spacing are respectively set within appropriate ranges. Consequently, the steel can have the spheroidized microstructure equal to or better than that in a prior steel and can be more softened than the prior steel, even when the time for the spheroidizing annealing is shorter than the usual spheroidizing annealing time. Accordingly, when the mechanical structure steel for cold-working in the present disclosure is processed into the above-mentioned various components at room temperature or in the working heat generation region after the spheroidizing annealing, the mechanical structure steel can exhibit a low deformation resistance and suppress cracking in a working die and steel (rawmaterial). As a result, the mechanical structure steel for cold-working in the present disclosure can exert excellent cold workability.

Brief Description of the Drawings

[0017] Fig. 1 is an explanatory diagram showing a measurement method of a lamellar spacing of pearlite.

Mode for Carrying Out the Invention

[0018] The inventors have studied from various point of views to achieve a mechanical structure steel for cold-working that can be more softened than previously possible, while obtaining the spheroidized microstructure equal to or better than that in a prior steel, even when a spheroidizing annealing time is shorter than the usual spheroidizing annealing time (hereinafter referred to as a "short-time spheroidizing annealing"). As a result, it has been found that in the metal microstructure (spheroidized microstructure) of the steel obtained after the spheroidizing annealing, the ferrite grain size is coarsened to enlarge a mean interparticle distance between carbide particles, thereby making it possible to achieve the softening of the steel. It leads to an idea that in order to obtain such a spheroidized microstructure, it is important to control the metal microstructure provided before the spheroidizing annealing (hereinafter referred to as a pre-microstructure). In order to obtain the metal microstructure (spheroidized microstructure) of the above-mentioned steel, on the precondition that the pre-microstructure is a microstructure that includes proeutectoid ferrite and pearlite as a main phase, it has been found to be necessary to control the pre-microstructure so as to set the area ratio of the proeutectoid ferrite as high as possible and so as to make the bcc-Fe crystal grain coarser than that in the prior steel, and to set a pearlite lamellar spacing at a predetermined value or less. Further, it has also been found that the steel with such a pre-microstructure can be more softened than the prior steel, while obtaining a spheroidized microstructure equal to or better than that in the prior steel, as the spheroidized microstructure after the short-time spheroidizing annealing. In these ways, the embodiments of the present invention have been completed.

[0019] Respective requirements defined in the present disclosure will be described below.

[0020] The metal microstructure of a steel according to an embodiment of the present invention includes proeutectoid ferrite and pearlite. These microstructures form a metal microstructure that reduces the deformation resistance of the steel obtained after the spheroidizing annealing and contributes to improving the cold workability. However, only by causing the metal microstructure to simply include proeutectoid ferrite and pearlite, the desired softening cannot be achieved. For this reason, the area ratio of these microstructures and an average grain size of a bcc-Fe crystal grain need to be controlled appropriately as mentioned below.

Total area ratio of proeutectoid ferrite and pearlite: 90% or more

[0021] When the pre-microstructure of the steel includes a large amount of fine microstructures, including bainite and martensite, even after general spheroidizing annealing, the microstructure of the steel subjected to the spheroidizing annealing is locally refined due to the influence of bainite and/or martensite. Consequently, the softening of the steel becomes insufficient. From this perspective, to sufficiently soften the steel, the total area ratio of the proeutectoid ferrite and the pearlite to the entire microstructure needs to be 90% or more. The total area ratio of the proeutectoid ferrite and the pearlite is preferably 95% or more, more preferably 97% or more, and most preferably 100%. Examples of the metal microstructure other than the proeutectoid ferrite and the pearlite include martensite, bainite, and austenite. As mentioned above, as the area ratio of these microstructures including martensite is increased, the strength of the steel becomes higher. Thus, these microstructures may not be included at all. The steel may include a carbide, a nitride, an oxide, and/or a sulfide, other than cementite, as other microstructure factors.

Average circle equivalent diameter of bcc-Fe crystal grain: 15 to 30 μm

[0022] When the average circle equivalent diameter of the bcc-Fe crystal grain in the pre-microstructure of the steel, i.e., the bcc-Fe average grain size is set at 30 μm or less, a good spheroidized microstructure is obtained even after the short-time spheroidizing (that is, a spheroidized microstructure with a small spheroidization degree) . If the bcc-Fe average grain size exceeds 30 μm, the spheroidized microstructure is deteriorated during the short-time spheroidizing annealing (that is, the spheroidization degree becomes larger), and consequently the desired spheroidized microstructure cannot be obtained. The bcc-Fe average grain size is preferably 29 μm or less, and more preferably 28 μm or less. However, if the bcc-Fe average grain size of the pre-microstructure is extremely small, the steel is strengthened by refinement of ferrite crystal grains after the spheroidizing annealing, thereby making it difficult to soften the steel. For this reason, the bcc-Fe average grain size is set at 15 μm or more. The bcc-Fe average grain size is preferably 16 μm or more, and more preferably 17 μm or more. Note that the term circle equivalent diameter of a crystal grain means a diameter of a circle that has the same area as each crystal grain.

[0023] The microstructure in which the above-mentioned bcc-Fe average grain size is to be controlled corresponds to bcc-Fe crystal grains surrounded by high angle grain boundaries where a misorientation between two adjacent crystal grains is more than 15°. The microstructure also includes low angle grain boundaries where a misorientation is 15° or less. However, these low angle grain boundaries barely influence the spheroidized microstructure obtained after spheroidizing annealing. To obtain the desired spheroidized microstructure after the spheroidizing annealing, it is necessary to control the high angle grain boundaries of the pre-microstructure before spheroidizing annealing. The bcc-Fe average grain size of the grains surrounded by the high angle grain boundaries is set within a predetermined range, thereby making it possible to achieve good spheroidized microstructure (that is, spheroidized microstructure with a small spheroidization degree) even after the short-time spheroidizing annealing. Note that the above-mentioned "misorientation" is also called a "deviation angle" or an "oblique angle". As the measurement of the misorientation, an electron back scattering pattern (EBSP) method may be adopted. The bcc-Fe implies not only proeutectoid ferrite, but also ferrite included in the pearlite microstructure.

Pearlite lamellar spacing: 0.20 μm or less

[0024] The metal microstructure of the steel according to the embodiment of the present invention includes proeutectoid ferrite and pearlite as mentioned above. By narrowing the pearlite lamellar spacing (i.e., by refining a pearlite lamellar), spheroidizing of carbides (mainly cementite in the pearlite) is promoted by the spheroidizing annealing even for a short time, thereby producing a good spheroidized microstructure. From this perspective, the pearlite lamellar spacing in the pre-microstructure needs to be 0.20 μm or less on average (hereinafter simply referred to as an "average lamellar spacing") . The average lamellar spacing is preferably 0.18 μm or less, and more preferably 0.16 μm or less. The lower limit of the average lamellar spacing is not limited particularly, but usually approximately 0.05 μm.

[0025] Note that the term "pearlite lamellar spacing" as used in the present specification means a distance between the adjacent lamellar cementite layers. More specifically, the pearlite lamellar spacing is the shortest distance from a center position of a thickness of a certain lamellar cementite layer to a center position of a thickness of another lamellar cementite layer adjacent to the certain lamellar cementite layer.

Area ratio of proeutectoid ferrite Af ≥ A

[0026] As the area ratio of the proeutectoid ferrite increases in the pre-microstructure, the amount of carbide precipitation sites during the spheroidizing annealing is decreased, so that the number density of carbide particles is decreased, thus promoting the coarsening of the carbide. Consequently, the interparticle distance between carbide particles is widened, thereby making it possible to further soften the metal microstructure. Meanwhile, the area ratio of the proeutectoid ferrite changes by the influence of a carbon content. As the carbon content increases, the area ratio of the proeutectoid ferrite decreases. Likewise, the area ratio of the proeutectoid ferrite suitable for obtaining the good spheroidized material also changes depending on the carbon content. As the carbon content increases, the area ratio of the suitable proeutectoid ferrite decreases. As a result of analysis of a number of experimental results from this perspective, it is found that the area ratio Af of the proeutectoid ferrite in the pre-microstructure to the entire microstructure satisfies the relationship of Af ≥ A where an A value is represented by formula (1) below, thereby making it possible to further soften the metal microstructure:

$$A = (103 - 128 \times [C(\%)]) \times 0.80\ (\%) \qquad (1)$$

where [C(%)] in the formula (1) indicates a content of carbon (C) in percent by mass.

[0027] Af is preferably (103 - 128 × [C(%)]) × 0.85 or more, and more preferably (103 - 128 × [C(%)]) × 0.90 or more. From the above point of view, the upper limit of Af is not limited particularly. However, as the Af is increased, the manufacturing cost will increase. When considering the productivity, Af is preferably (103 - 128 × [C(%)]) × 0.97 or less.

[0028] The embodiment of the present invention relates to the mechanical structure steel for cold-working, and its steel type can be any type as long as it includes a general chemical component composition as the mechanical structure steel for cold-working. However, the contents of C, Si, Mn, P, S, Al and N are adjusted within respective appropriate ranges mentioned below. The term % as used for the chemical component composition in the present specification means "% by mass".

C: 0.07% or more and less than 0.3%

[0029] C is an element effective in ensuring the strength of steel, that is, the strength of a final product. To efficiently exert this effect, the C content needs to be 0.07% or more. The C content is preferably 0.09% or more, and more preferably 0.11% or more. However, any excessive C content enhances the strength of steel, thereby degrading the cold workability. Because of this, the C content needs to be less than 0.3%. The C content is preferably 0.28% or less, and more preferably 0.26% or less.

Si: 0.05 to 0.5%

[0030] Si is effective as a deoxidizing element and as a strength improving element of the final product by solid-solution hardening. To effectively exert these effects, the Si content is set at 0.05% or more. The Si content is preferably 0.07% or more, and more preferably 0.10% or more. Meanwhile, an excessive Si content extremely raises the hardness of the steel, thereby deteriorating the cold workability. Thus, the Si content is set at 0.5% or less. The Si content is preferably 0.45% or less, and more preferably 0.40% or less.

Mn: 0.2 to 1.7%

[0031] Mn is an effective element in increasing the strength of the final product through the improvement of hardenability of the steel. To effectively exert these effects, the Mn content is set at 0.2% or more. The Mn content is preferably 0.3% or more, and more preferably 0.4% or more. Meanwhile, an excessive Mn content raises the hardness of the steel, thereby deteriorating the cold workability. Thus, the Mn content is set at 1.7% or less. The Mn content is preferably 1.5% or less, and more preferably 1.3% or less.

P: more than 0% and 0.03% or less

[0032] P is an element inevitably contained in steel and causes grain boundary segregation in the steel, thereby deteriorating ductility of the steel. Thus, the P content is set at 0.03% or less. The P content is preferably 0.02% or less, more preferably 0.017% or less, and still more preferably 0.01% or less. The smaller the P content is, the better the quality of the steel becomes. The P content is most preferably 0%. However, in practice, approximately 0.001% of P occasionally remains due to manufacturing process constraints.

S: 0.001 to 0.05%

[0033] S is an element inevitably contained in steel, specifically, a harmful element for the cold workability because S is present in the form of MnS in the steel to degrade the ductility of the steel. Thus, the S content is set at 0.05% or less. The S content is preferably 0.04% or less, and more preferably 0.03% or less. Note that the S content of 0.001% or more is effective because S has the function of improving machinability of the steel. Thus, the S content is preferably 0.002% or more, and more preferably 0.003% or more.

Al: 0.01 to 0.1%

[0034] Al is effective as a deoxidizing element and also effective in fixing solid-solution N existing in the steel, in the form of AlN. To efficiently exert these effects, the Al content is set at 0.01% or more. Thus, the Al content is preferably 0.013% or more, and more preferably 0.015% or more. However, any excessive Al content forms Al_2O_3 excessively, thereby deteriorating the cold workability. Thus, the Al content is set at 0.1% or less. The Al content is preferably 0.090% or less, and more preferably 0.080% or less.

N: 0 to 0.015%

[0035] N is an element inevitably contained in steel. If the solid-solution N is contained in the steel, the hardness of the steel is raised and the ductility thereof is degraded due to strain aging, thus deteriorating the cold workability. Thus, the N content is set at 0.015% or less. The N content is preferably 0.013% or less, and more preferably 0.010% or less. The smaller N content is preferred. The N content is most preferably 0%. However, in practice, approximately 0.001% of N occasionally remains due to manufacturing process constraints.

[0036] The basic components of the mechanical structure steel according to the embodiment of the present invention have been mentioned above, with the balance substantially being iron as one embodiment. The expression "substantially iron "as used herein means that for example, a small content of components other than iron, such as Sb and Zn, can exist in the steel as long as the properties of the present disclosure are not inhibited, and inevitable impurities other than P, S, and N, such as O and H, can be contained in the steel. Furthermore, the embodiment of the present invention may selectively contain the following arbitrary elements as appropriate. The properties of copper can be further improved depending on the kind of selected arbitrary element (selective component).

[0037] As mentioned above, P, S, and N are elements inevitably contained (inevitable impurities), and their composition ranges are specified separately as mentioned above. Because of this, the term "inevitable impurities" contained as the balance, as used in the present specification, means elements inevitably contained, except for elements with their composition ranges separately specified.

[0038] One or more elements selected from the group consisting of Cr: more than 0% and 0.5% or less, Cu: more than 0% and 0.25% or less, Ni: more than 0% and 0.25% or less, Mo: more than 0% and 0.25% or less, and B: more than 0% and 0.01% or less

[0039] All Cr, Cu, Ni, Mo and B are elements effective in increasing the strength of the final product by improving the hardenability of the steel material. These elements may be contained alone or in combination as needed. Such effects are enhanced as the contents of these elements are increased. To efficiently exert the above-mentioned effect, the Cr content is preferably 0.015% or more, and more preferably 0.020% or more. Each of the Cu content, the Ni content and the Mo content is preferably 0.02% or more, and more preferably 0.05% or more. The B content is preferably 0.0003% or more, and more preferably 0.0005% or more.

[0040] However, if the contents of Cr, Cu, Ni and Mo are excessive, the strength of the steel becomes extremely high, whereby the cold workability might be deteriorated. Thus, the Cr content is preferably set at 0.5% or less, and each of the Cu content, the Ni content and the Mo content is preferably 0.25% or less. The Cr content is more preferably 0.45% or less, and still more preferably 0.40% or less. Each of the Cu content, the Ni content and the Mo content is more preferably 0.22% or less, and still more preferably 0.20% or less.

[0041] If the B content is excessive, the toughness of the steel might be deteriorated. Thus, the B content is preferably set at 0.01% or less. The B content is more preferably 0.007% or less, and still more preferably 0.005% or less.

$$[\mathrm{Cr}\%] + [\mathrm{Cu}\%] + [\mathrm{Ni}\%] + [\mathrm{Mo}\%] \leq 0.75$$

[0042] When the steel according to the embodiment of the present invention contains one or more elements of Cr, Cu, Ni and Mo within the above-mentioned respective ranges, the steel preferably satisfy the following formula (X).

$$[\mathrm{Cr}\%] + [\mathrm{Cu}\%] + [\mathrm{Ni}\%] + [\mathrm{Mo}\%] \leq 0.75 \qquad (X)$$

where [Cr%], [Cu%], [Ni%], and [Mo%] indicate the contents of Cr, Cu, Ni and Mo in percent by mass, respectively.

[0043] The contents of Cr, Cu, Ni and Mo satisfy the formula (X) mentioned above, thereby preventing the strength of the steel from becoming extremely high, which can improve the cold workability.

Ti: more than 0% and 0.1% or less

[0044] Ti forms a compound with N to reduce the amount of solid-solution N, and thereby exerts the softening effect of steel. For this reason, Ti may be contained as needed. To effectively exert these effects, the Ti content is preferably set at 0.01 or more, and more preferably 0.02 or more. However, any excessive Ti content causes an increase in the hardness of the formed compound. Thus, the Ti content is preferably 0.08% or less, and more preferably 0.05 or less.

[0045] Preferably, in order to manufacture the mechanical structure steel for cold-working according to the embodiment of the present invention, for the steel satisfying the above-mentioned component composition, a finish rolling temperature is adjusted during hot-rolling, and thereafter the cooling rate and the cooling temperature range are adjusted appropriately by setting the cooling rate in two stages. Specifically, following steps are performed in this order: finish rolling at a temperature of 950°C or higher and 1,150°C or lower; first cooling from a temperature of 950°C or higher and 1,150°C or lower to a first-cooling end temperature of 700 to 750°C at an average cooling rate of 3°C/sec. or less; and second cooling in a temperature range from the first-cooling end temperature to at least 600°C at an average cooling rate of 5 to 30°C/sec.

[0046] The finish rolling temperature, the first cooling, and the second cooling will be respectively described in detail below.

(a) Finish rolling temperature: 950°C or higher and 1,150°C or lower

[0047] To set a bcc-Fe average grain size at 15 to 30 μm, the finish rolling temperature needs to be controlled appropriately. If the finish rolling temperature exceeds 1,150°C, it becomes difficult to set the bcc-Fe average grain size at 30 μm or less. Thus, the finish rolling temperature is preferably 1,150°C or lower. If the finish rolling temperature is lower than 950°C, it becomes difficult to set the bcc-Fe average grain size at 15 μm or more. Thus, the finish rolling temperature is preferably 950°C or higher. The finish rolling temperature is preferably 970°C or higher, and more preferably 990°C or higher. The finish rolling temperature is preferably 1,130°C or lower, and more preferably 1,110°C or lower.

(b) First cooling

Average cooling rate of the first cooling: 3°C/sec. or less

[0048] The first cooling is started at the finish rolling temperature of 950°C or higher and 1,150°C or lower and ended at the first-cooling end temperature of 700 to 750°C. As the cooling rate is increased in the first cooling, the proeutectoid ferrite area ratio Af becomes smaller, whereby the steel could not satisfy the relationship of $Af \geq A$. Here, the average cooling rate of the first cooling is 3°C/sec. or less. The average cooling rate of the first cooling is preferably 2.5°C/sec. or less, and more preferably 2°C/sec. or less. The lower limit of the average cooling rate in the first cooling is not limited particularly. However, the lower limit is preferably set at 0.01°C/sec. or more as a practical range. It is noted that in the first cooling, the cooling rate may be changed as long as the average cooling rate is 3°C/sec. or less.

(c) Second cooling

Average cooling rate of the second cooling: 5 to 30°C/sec.

[0049] The second cooling is started at a temperature in a range of 700 to 750°C and ended at a temperature of at least 600°C. If the average cooling rate in the second cooling is less than 5°C/sec., it becomes difficult to set an average lamellar spacing of the pearlite at 0.20 μm or less. The average cooling rate in the second cooling is preferably 7°C/sec. or more, and more preferably 10°C/sec. or more. If the average cooling rate in the second cooling is more than 30°C/sec., microstructures such as bainite and/or martensite, are generated, which makes it difficult to set the total area ratio of the proeutectoid ferrite and the pearlite at 90% or more. The average cooling rate in the second cooling is preferably 28°C/sec. or less, and more preferably 25°C/sec. or less. It is noted that in the second cooling, the cooling rate may be changed as long as the average cooling rate is in a range of 5 to 30°C/sec.

[0050] The term "at least 600°C" as used herein means that the highest end temperature of the second cooling performed at the above-mentioned average cooling rate is 600°C. The reason for setting the highest end temperature to "600°C" is that the forms of the metal microstructure specified by the present disclosure, such as an average lamellar spacing of the pearlite and the total area ratio of the proeutectoid ferrite and the pearlite, are almost determined by the cooling step to 600°C and hardly influenced by the cooling rate of lower than 600°C. Therefore, the end temperature of the second cooling is not limited to 600°C, but may be room temperature, like Examples to be mentioned later. Alternatively, for example, the second cooling may be performed by setting the end temperature of the second cooling at 400°C, and then the usual cooling down to room temperature, such as allowing the steel to cool, may be performed. In general, the average cooling rate for allowing the steel to cool often becomes lower than the average cooling rate of the second cooling mentioned above.

[0051] By using the mechanical structure steel for cold-working according to the embodiment of the present invention, the spheroidizing annealing is performed for a short time, for example, for approximately 1 to 3 hours, in a temperature range of Ac_1 to approximately Ac_1 + 30°C. Consequently, the spheroidization degree can be at a target spheroidization degree or less as mentioned later, and further the hardness of the steel can be at a target hardness or lower as mentioned later. Ac_1 is a value calculated from the following formula:

$$Ac_1\ (^\circ C) = 723 - 10.7\ (\%Mn) - 16.9\ (\%Ni) + 29.1\ (\%Si) + 16.9\ (\%Cr)$$

where (% element name) in the formula means a content of each element in percent by mass.

Examples

[0052] The embodiments of the present invention will be more specifically described by way of Examples. The embodiments of the present invention are not limited by the following Examples, and it is possible to implement the embodiments with modifications within the range that can meet the gist of the present disclosure as described above and below, all of these modifications being within the technical scope of the present disclosure.

[0053] Steels having the chemical component composition shown in Table 1 below were used and rolled to produce a wire rod with ϕ17.0 mm. Further, the wire rod was then subjected to machining to produce a test specimen for working Formastor that had a size of ϕ8.0 mm × 12.0 mm. The obtained test specimen for the working Formastor was used to perform a working heat treatment test by a working Formastor tester on the conditions mentioned in Table 2. The working conditions mentioned in Table 2 simulate rolling conditions imposed on the actual device. Note that in Table 2, the working temperature corresponds to the finish rolling temperature.

[Table 1]

Steel type	Chemical composition (% by mass) *Balance being iron and inevitable impurities								Cr+Cu+Ni+Mc (Formula (X))
	C	Si	Mn	P	S	Al	N	Others	
A	0.25	0.22	0.40	0.013	0.024	0.022	0.005	-	0
B	0.07	0.19	0.44	0.009	0.035	0.042	0.002	Cr: 0.15	0.15
C	0.09	0.22	0.51	0.016	0.019	0.050	0.002	-	0
D	0.10	0.09	0.33	0.018	0.011	0.018	0.003	-	0
E	0.10	0.18	0.72	0.012	0.022	0.027	0.010	Cu: 0.22 Ni:0.13	0.35
F	0.12	0.41	1.12	0.012	0.025	0.073	0.005	-	0
G	0.14	0.36	0.68	0.020	0.029	0.026	0.004	B: 0.0032	0
H	0.15	0.47	0.23	0.008	0.016	0.082	0.012	-	0
I	0.18	0.32	1.66	0.015	0.024	0.054	0.013	-	0
J	0.19	0.25	1.44	0.026	0.012	0.025	0.006	Ni: 0.15	0.15
K	0.22	0.24	0.92	0.014	0.036	0.017	0.007	Mo: 0.21	0.21
L	0.25	0.06	0.85	0.017	0.043	0.038	0.010	Cr: 0.36	0.36
M	0.27	0.12	1.10	0.010	0.024	0.023	0.005	-	0
N	0.29	0.18	1.57	0.023	0.018	0.019	0.007	-	0
O	0.15	0.33	2.08	0.025	0.031	0.085	0.004	-	0
P	0.21	0.34	0.78	0.009	0.042	0.042	0.008	Cr: 1.07	1.07
Q	0.26	0.20	0.43	0.012	0.022	0.025	0.004	-	0
R	0.16	0.18	0.44	0.016	0.023	0.026	0.003	-	0
S	0.17	0.22	0.70	0.015	0.020	0.031	0.007	Cr: 0.13 B: 0.0019 Ti: 0.033	0.13

(continued)

Steel type	Chemical composition (% by mass) *Balance being iron and inevitable impurities								Cr+Cu+Ni+Mc (Formula (X))
	C	Si	Mn	P	S	Al	N	Others	
T	0.23	0.20	0.82	0.011	0.017	0.029	0.005	Cr: 0.16 B: 0.0012 Ti: 0.022	0.16
U	0.24	0.29	0.88	0.008	0.016	0.040	0.009	Ti: 0.061	0

[0054] The test specimens obtained after performing the working heat treatment test on the conditions mentioned in Table 2 were evaluated for their microstructures in the ways (1) to (3) below. Further, after the working heat treatment test, the test specimens subjected to the spheroidizing annealing were measured for the spheroidization degree and the hardness in the ways (4) and (5) below, respectively. In either measurement, the test specimen provided after the working heat treatment or the spheroidizing annealing was cut at a plane (axial central section) passing through the central axis of the test specimen and oriented in parallel to the central axis thereof. The cut test specimen is sometimes called a "longitudinal section sample". The longitudinal section sample was embedded in resin so that the section of the center axis of the test specimen can be observed. Regarding the test specimens respectively obtained after the working heat treatment and after the spheroidizing annealing, the position of D/4 ("D/4 position") from the side surface toward the center of the test specimen was subjected to the measurement of the properties below, where D is a diameter of the cylindrical test specimen.

(1) Measurement of Microstructure Area Ratio

[0055] The axial central section of the longitudinal section sample was polished to a mirror finish, and then etched with nital to expose its microstructure. Then, in the microstructure at the D/4 position, a region of 220 μm × 165 μm was photographed for each of five fields of view with an optical microscope at a magnification of 400X. Then, on each of the obtained images, ten lines were drawn in each of the longitudinal and lateral directions at equal intervals in a grid pattern to form 100 intersection points. Among the 100 intersection points, the number of points where proeutectoid ferrite or pearlite exists was measured on each image. The total area ratios (%) of such microstructures in the respective five fields of view were determined to calculate an average of them over the five fields of view.

(2) Measurement of bcc-Fe Average Grain Size

[0056] A bcc-Fe average grain size was measured using an Electron Back Scattering Pattern (EBSP) analyzer and a Field-Emission Scanning Electron Microscope (FE-SEM). The "crystal grain" was defined by specifying boundaries where a misorientation (oblique angle) exceeded 15°, i.e., high angle grain boundaries as grain boundaries, and then the bcc-Fe average grain size was determined. At this time, the measuring was performed with the measurement region set at 200 μm × 400 μm and the measurement step set at intervals of 1.0 μm. Any measured point where a confidence index indicative of the reliability of a measurement orientation was 0.1 or less was excluded from an analysis target. A sample where a martensite microstructure was precipitated in the metal microstructure did not obtain an appropriate bcc-Fe average grain size and thus was not measured.

(3) Measurement of Pearlite Lamellar Spacing

[0057] Fig. 1(a) shows a schematic diagram of a pearlite lamellar microstructure 1, and Fig. 1(b) shows an enlarged view of the pearlite lamellar microstructure 1. As shown in Fig. 1(b), the pearlite lamellar microstructure 1 is a microstructure in which a lamellar ferrite 3 and a lamellar cementite 2 are alternately arranged side by side in a layer shape (in a lamellar shape) . The lamellar spacing specified by the present disclosure is a distance between the adjacent lamellar cementites 2.

[0058] The axial central section of the longitudinal section sample was polished to a mirror finish, and then etched with picral to expose its microstructure. Thereafter, the microstructure was observed at the D/4 position using the FE-SEM to photograph a region of 42 μm × 28 μm at a magnification of 3000X or a region of 25 μm × 17 μm at a magnification of 5000 X for each of the five fields of view in total. At this time, the photographing was performed to cause an image of each field of view to include at least one pearlite . A pearlite having the finest lamellar spacing (i.e., the narrowest lamellar spacing) in each field of view of the photographed image was selected and set as a measurement target. One line segment 4 was drawn in the pearlite as the measurement target so as to be perpendicular to the layered microstructure (i.e., perpendicular to the direction in which each layer extends) . Each of a starting point and an ending point of the line segment 4 was positioned at the center of the thickness of the lamellar cementite. A length L of the line segment 4 and the number n of lamellar cementites 2 included in the line segment 4 (in other words, the number of layers n of the lamellar cementites 2 intersecting the line segment 4) were measured. Note that the number n also includes the lamellar cementites where the starting point and the ending point of the line segment are positioned. By using formula (2), the lamellar spacing λ was calculated from the length L and the number n. The lamellar spacings λ in the respective fields of view were determined to calculate an average of them over the five fields of view. Fig. 1(b) indicates an example of n = 5, but the embodiment is not limited thereto. In the present specification, the line segment 4 was drawn such that the number n of the lamellar cementites 2 intersecting the line segment 4 was 5 or more when calculating the lamellar spacing λ.

$$\lambda = L/(n-1) \qquad (2)$$

[0059] The measurement was not performed on the sample in which a martensite microstructure was precipitated in the metal microstructure, and the total area ratio of the proeutectoid ferrite and the pearlite was less than 90%, because the lamellar spacing in such a sample was difficult to calculate.

(4) Measurement of Spheroidization Degree After Spheroidizing Annealing

[0060] Regarding the longitudinal section sample of each test specimen obtained after the spheroidizing annealing, the axial central section thereof was polished to a mirror finish and then etched with picral to expose its microstructure. Then, the microstructure at the D/4 position of each sample was observed for each of five fields of view with an optical microscope at a magnification of 400X. The spheroidization degree of each field of view was evaluated as any of No. 1 to No. 4 based on the accompanied drawings or JIS G3539:1991, and an average of the spheroidization degrees over the five fields of view was calculated. This means that the smaller the spheroidization degree is, the better the spheroidized microstructure becomes.

(5) Measurement of Hardness After Spheroidizing Annealing

[0061] Regarding the longitudinal section sample of each test specimen obtained after the spheroidizing annealing, the axial central section thereof was polished to a mirror finish. Then, the hardness of the D/4 position of the longitudinal section sample was measured. The hardness was measured under a load of 1 kgf by using a Vickers hardness tester. The measurement was performed at five different points located at D/4 position to thereby calculate its average (HV).

Examples

[0062] The steels of the types A to U shown in Table 1 were used and subjected to the working Formastor test by changing the working temperature (corresponding to a finish rolling temperature) and the cooling rate as shown in Table 2 below. In this way, working Formastor test specimens having different pre-microstructures were produced. In the steel type O, the Mn content exceeded 1.7%, and hence the steel type O did not fall within the scope of the present invention in the present application. In the steel type P, the Ti content exceeded 0.1%, and hence the steel type P did not fall within the scope of the present invention in the present application. In the steel types A to O and Q to U, [Cr%] + [Cu%] + [Ni%] + [Mo%] was 0.75% by mass or less, which satisfy the above-mentioned formula (X). In the steel type P, [Cr%] + [Cu%] + [Ni%] + [Mo%] exceeded 0.75% by mass, and therefore does not satisfy the formula (X).

[0063] In the working conditions shown in Table 2, in test specimens except for Test Nos. 10, 20, 43, and 44, the "first cooling" was started from the working temperature and ended at the first-cooling end temperature in a temperature of 700 to 750°C, while the "second cooling" was started at the first-cooling end temperature of the "first cooling" and ended at room temperature. In Test Nos. 10, 20, and 44, since cooling was performed at a certain average cooling rate from the working temperature at the start of the first cooling to the end temperature of the second cooling, the "first cooling" and the "second cooling" were not distinguished. Note that in Test No. 44, the cooling was performed at an average cooling rate of 40.0°C/sec. from 850°C to 300°C, and then the test specimen was allowed to cool to room temperature. In Test No. 43, the cooling was performed by setting the end temperature of the "first cooling" at 650°C, and setting the end temperature of the "second cooling" at 550°C, and then the test specimen was allowed to cool to room temperature.

[Table 2]

Test No.	Steel type	Working conditions				
		Heating	First cooling		Second cooling	
		Working temperature (°C)	Average cooling rate (°C/sec.)	End temperature (°C)	Average cooling rate (°C/sec.)	End temperature (°C)
1	A	950	2.5	710	10.0	Room temperature
2	A	1,000	1.0	740	7.0	Room temperature
3	A	1,000	1.5	730	20.0	Room temperature
4	A	1,050	2.5	700	15.0	Room temperature
5	A	1,050	3.0	720	5.0	Room temperature
6	A	1,100	0.1	740	10.0	Room temperature
7	A	1,150	1.0	730	25.0	Room temperature
8	A	1,150	2.0	730	7.0	Room temperature
9	A	900	2.5	700	15.0	Room temperature
10	A	1,000	2.0		2.0	Room temperature
11	A	1,050	10.0	700	10.0	Room temperature
12	A	1200	0.1	740	10.0	Room temperature
13	B	1,050	1.0	720	5.0	Room temperature
14	B	1,100	0.5	750	3.0	Room temperature
15	C	1,000	0.1	740	10.0	Room temperature
16	C	1,100	2.0	730	5.0	Room temperature
17	D	1,150	0.1	730	25.0	Room temperature
18	D	1,250	2.5	740	7.0	Room temperature
19	E	950	1.5	740	20.0	Room temperature
20	E	1,100	5.0	-	5.0	Room temperature

(continued)

Test No.	Steel type	Working conditions				
		Heating	First cooling		Second cooling	
		Working temperature (°C)	Average cooling rate (°C/sec.)	End temperature (°C)	Average cooling rate (°C/sec.)	End temperature (°C)
21	F	1,000	3.0	720	10.0	Room temperature
22	F	1,000	2.0	720	50.0	Room temperature
23	G	1,050	0.1	710	30.0	Room temperature
24	G	1,150	2.0	700	15.0	Room temperature
25	H	900	2.0	710	20.0	Room temperature
26	H	1,100	1.5	720	15.0	Room temperature
27	I	950	3.0	740	5.0	Room temperature
28	I	1,050	10.0	730	15.0	Room temperature
29	J	950	1.5	740	10.0	Room temperature
30	J	1,150	2.5	730	10.0	Room temperature
31	K	950	3.0	700	20.0	Room temperature
32	K	1,000	0.1	750	7.0	Room temperature
33	L	1,050	20.0	720	7.0	Room temperature
34	L	1,100	1.5	740	50.0	Room temperature
35	M	1,050	1.0	700	30.0	Room temperature
36	M	1,150	1.0	740	7.0	Room temperature
37	N	1,000	3.0	710	25.0	Room temperature
38	N	1,150	2.5	720	10.0	Room temperature
39	O	950	2.5	720	30.0	Room temperature
40	O	1,150	0.1	740	5.0	Room temperature

(continued)

Test No.	Steel type	Working conditions				
		Heating	First cooling		Second cooling	
		Working temperature (°C)	Average cooling rate (°C/sec.)	End temperature (°C)	Average cooling rate (°C/sec.)	End temperature (°C)
41	P	1,000	0.5	740	10.0	Room temperature
42	P	1,050	2.0	700	25.0	Room temperature
43	Q	850	15.0	650	0.5	550
44	R	850	40.0	-	40.0	300
45	S	1,000	2.5	720	10.0	Room temperature
46	S	1,100	2.0	710	15.0	Room temperature
47	T	1,050	2.0	730	15.0	Room temperature
48	T	1,100	1.0	720	7.0	Room temperature
49	U	950	1.0	740	10.0	Room temperature
50	U	1,100	3.0	700	7.0	Room temperature

[0064] Each of the above working Formastor test specimens was cut into four equal pieces at the section perpendicular to its central axis. One of these pieces was used as a sample for examination of the microstructure, and another of these pieces was used as a sample for spheroidizing annealing. The spheroidizing annealing was performed by sealing each test specimen in a vacuum and applying heat treatment in an atmospheric furnace. In the spheroidizing annealing, the test specimen was subjected to soaking by holding its temperature at 730°C for 2 hours, then cooled to 710°C at an average cooling rate of 30°C/hr, and subsequently cooled to 680°C at an average cooling rate of 10°C/hr, followed by allowed the test specimen to cool to the room temperature.

[0065] Table 3 shows the microstructure of each test specimen before the spheroidizing annealing and the spheroidization degree and hardness thereof after the spheroidizing annealing, which were evaluated in the above ways (1) to (5). The required spheroidization degree for the test specimen differs depending on its C content. The spheroidization degree to be targeted (mentioned as "target spheroidization degree" in Table 3) was a value determined by formula (3) below. The required spheroidization degree differs depending on the contents of C, Si and Mn in each test specimen. Further, the hardness to be targeted (mentioned as "target hardness" in Table 3) was a value determined by formula (4) below.

$$\text{Target Spheroidization Degree} = 5 \times [\text{C\%}] + 1.5 \qquad (3)$$

$$\text{Target Hardness} = 88.4 \times \text{Ceq} + 86.0 \qquad (4)$$

in which Ceq = [C%] + 0.2 × [Si%] + 0.2 × [Mn%], where [C%], [Si%] and [Mn%] indicate contents of C, Si and Mn in percent by mass, respectively.

[Table 3]

Test No.	Microstructure before annealing					Microstructure after annealing			
	Area ratio of proeutectoid ferrite and pearlite (%)	bcc-Fe average grain size (μm)	Area ratio Af of proeutectoid ferrite (%)	Value (A) on the right side of formula (1)	Average pearlite lamellar spacing (μm)	Spheroidization degree	Target spheroidization degree	Hardness (HV)	Target hardness (HV)
1	100	16.7	83	57	0.15	2.20	2.75	116	119
2	100	18.2	74	57	0.18	2.40	2.75	117	119
3	100	19.6	80	57	0.13	2.20	2.75	116	119
4	100	21.2	77	57	0.13	2.40	2.75	114	119
5	100	22.5	72	57	0.20	2.60	2.75	118	119
6	100	25.0	83	57	0.16	2.60	2.75	116	119
7	100	28.2	72	57	0.11	2.40	2.75	115	119
8	100	29.3	65	57	0.19	2.60	2.75	118	119
9	100	12.4	80	57	0.13	1.80	2.75	121	119
10	100	17.9	84	57	0.23	3.20	2.75	119	119
11	100	23.0	53	57	0.15	2.40	2.75	122	119
12	100	33.6	72	57	0.14	3.40	2.75	117	119
13	100	21.6	95	75	0.19	1.60	1.85	100	103
14	100	25.2	92	75	0.22	2.80	1.85	101	103
15	100	20.5	93	73	0.16	1.40	1.95	104	107
16	100	25.8	92	73	0.18	1.60	1.95	103	107
17	100	29.6	92	72	0.10	2.00	2.00	99	102
18	100	36.6	85	72	0.17	3.00	2.00	101	102
19	100	15.3	83	72	0.20	1.60	2.00	110	111
20	100	26.1	65	72	0.11	1.80	2.00	114	111
21	100	17.4	88	70	0.15	1.60	2.10	122	124
22	54	-	40	70	-	1.40	2.10	136	124

(continued)

Test No.	Microstructure before annealing					Microstructure after annealing			
	Area ratio of proeutectoid ferrite and pearlite (%)	bcc-Fe average grain size (μm)	Area ratio Af of proeutectoid ferrite (%)	Value (A) on the right side of formula (1)	Average pearlite lamellar spacing (μm)	Spheroidization degree	Target spheroidization degree	Hardness (HV)	Target hardness (HV)
23	92	23.9	90	68	0.10	1.80	2.20	116	117
24	100	28.7	77	68	0.14	2.00	2.20	114	117
25	100	11.2	86	67	0.12	1.40	2.25	115	112
26	100	27.4	83	67	0.14	2.20	2.25	108	112
27	100	16.6	74	64	0.19	2.20	2.40	133	137
28	100	22.7	55	64	0.13	2.40	2.40	141	137
29	100	17.3	86	63	0.16	2.20	2.45	129	133
30	100	27.9	66	63	0.15	2.40	2.45	130	133
31	100	15.9	82	60	0.14	2.00	2.60	124	126
32	100	18.2	69	60	0.17	2.40	2.60	126	126
33	100	23.1	49	57	0.17	2.20	2.75	128	124
34	0	-	0	57	-	1.40	2.75	142	124
35	95	20.3	84	55	0.11	2.40	2.85	127	131
36	100	29.0	61	55	0.16	2.80	2.85	128	131
37	100	20.3	71	53	0.12	2.60	2.95	139	143
38	100	19.1	63	53	0.15	2.60	2.95	143	143
39	100	16.3	78	67	0.10	1.60	2.25	147	142
40	100	29.5	69	67	0.18	2.20	2.25	145	142
41	100	19.1	79	61	0.16	2.20	2.55	127	124
42	100	22.2	83	61	0.12	2.20	2.55	126	124
43	100	11.4	54	56	0.14	1.80	2.80	125	120
44	47	-	38	66	-	1.40	2.30	123	111

(continued)

Test No.	Microstructure before annealing					Microstructure after annealing			
	Area ratio of proeutectoid ferrite and pearlite (%)	bcc-Fe average grain size (μm)	Area ratio Af of proeutectoid ferrite (%)	Value (A) on the right side of formula (1)	Average pearlite lamellar spacing (μm)	Spheroidization degree	Target spheroidization degree	Hardness (HV)	Target hardness (HV)
45	100	17.1	75	65	0.17	1.80	2.35	113	117
46	100	23.5	69	65	0.17	2.00	2.35	114	117
47	100	20.8	67	59	0.16	2.20	2.65	122	124
48	100	24.0	63	59	0.19	2.60	2.65	120	124
49	100	16.2	70	58	0.15	2.20	2.70	123	128
50	100	21.6	61	58	0.18	2.40	2.70	126	128

[0066] From the results shown in Table 3, the following consideration can be made. Test Nos. 1 to 8, 13, 15 to 17, 19, 21, 23, 24, 26, 27, 29 to 32, 35 to 38, and 45 to 50 shown in Table 3 are examples that satisfied all the requirements specified by the embodiment of the present invention. After the spheroidizing annealing, these tests achieved the target spheroidization degree as well as and further could achieve the target hardness even if the spheroidizing annealing is the short-time spheroidizing annealing.

[0067] Meanwhile, Test Nos. 9 to 12, 14, 18, 20, 22, 25, 28, 33, 34, and 39 to 44 shown in Table 3 are examples that did not satisfy any one of the requirements specified by the embodiment of the present invention. After the spheroidizing annealing, these tests did not achieve at least one of the target spheroidization degree and the target hardness.

[0068] Test No. 9 used steel type A shown in Table 1 that satisfied the composition of the embodiment of the present invention.

[0069] However, in this test, the working temperature, corresponding to the finish rolling temperature, was low. Thus, the bcc-Fe average grain size became small, and the hardness of the steel after the spheroidizing annealing still remained hard.

[0070] Test No. 10 used steel type A shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the second cooling was low. Thus, an average pearlite lamellar spacing became large, and the spheroidization degree after the spheroidizing annealing was unsatisfactory.

[0071] Test No. 11 used steel type A shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the first cooling was high. Thus, the area ratio of the proeutectoid ferrite in the steel became small, and the hardness of the steel after the spheroidizing annealing still remained hard.

[0072] Test No. 12 used steel type A shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the working temperature was high. Thus, the bcc-Fe average grain size of the steel became large, and the spheroidization degree after the spheroidizing annealing became large (that is, the spheroidized microstructure was unsatisfactory).

[0073] Test No. 14 used steel type B shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the second cooling was low. Thus, the average pearlite lamellar spacing became large, and the spheroidization degree after the spheroidizing annealing became large (that is, the spheroidized microstructure was unsatisfactory).

[0074] Test No. 18 used steel type D shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the working temperature was high. Thus, the bcc-Fe average grain size became large, and the spheroidization degree of the steel after the spheroidizing annealing became large (that is, the spheroidized microstructure was unsatisfactory).

[0075] Test No. 20 used steel type E shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the first cooling was high. Thus, the area ratio of the proeutectoid ferrite in the steel became small, and the hardness of the steel after the spheroidizing annealing still remained hard.

[0076] Test No. 22 used steel type F shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the second cooling was high. Thus, the martensite microstructure was precipitated, whereby the total area ratio of the proeutectoid ferrite and the pearlite and the area ratio of the proeutectoid ferrite became small. As a result, the hardness of the steel after the spheroidizing annealing still remained hard.

[0077] Test No. 25 used steel type H shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the working temperature was low. Thus, the bcc-Fe average grain size of the steel became small, and the hardness of the steel after the spheroidizing annealing still remained hard.

[0078] Test No. 28 used steel type I shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the first cooling was high. Thus, the area ratio of the proeutectoid ferrite in the steel became small, and the hardness of the steel after the spheroidizing annealing still remained hard.

[0079] Test No. 33 used steel type L shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the first cooling was high. Thus, the area ratio of the proeutectoid ferrite in the steel became small, and the hardness of the steel after the spheroidizing annealing still remained hard.

[0080] Test No. 34 used steel type L shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the cooling rate of the second cooling was high. Thus, the martensite microstructure was precipitated, whereby the total area ratio of the proeutectoid ferrite and the pearlite and the area ratio of the proeutectoid ferrite became small. As a result, the hardness of the steel after the spheroidizing annealing still remained hard.

[0081] Test Nos. 39 and 40 used steel type O shown in Table 1 in which the Mn content was large. Thus, the hardness of the steel after the spheroidizing annealing still remained hard.

[0082] Test Nos. 41 and 42 used steel type P shown in Table 1 in which the Cr content was large and which did not satisfy the formula (X). Thus, the hardness of the steel after the spheroidizing annealing still remained hard.

[0083] Test No. 43 used steel type Q shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the working temperature was low and the cooling rate of the first cooling was high. Thus, the bcc-Fe average grain size became small, and the martensite microstructure was precipitated, so that the area ratio of the proeutectoid ferrite was reduced. As a result, the hardness of the steel after the spheroidizing annealing still remained hard.

[0084] Test No. 44 used steel type R shown in Table 1 that satisfied the composition of the embodiment of the present invention. However, in this test, the working temperature was low, the cooling rate of the first cooling was high, and the cooling rate of the second cooling was high. Thus, the bcc-Fe average grain size of the steel became small, the area ratio of the proeutectoid ferrite was reduced, and further the martensite microstructure was precipitated, so that the total area ratio of the proeutectoid ferrite and the pearlite was reduced. As a result, the hardness of the steel after the spheroidizing annealing still remained hard.

[0085] Note that in Test Nos. 1 to 8, 13, 15 to 17, 19, 21, 23, 24, 26, 27, 29 to 32, 35 to 38, and 45 to 50 (that satisfied all requirements specified by the embodiment of the present invention), the second cooling was performed until room temperature. However, the second cooling may be performed until 600°C, and then the steel may be allowed to cool. In this case, the substantially same results can be expected to be obtained.

[0086] The present application claims priority to Japanese Patent Application No. 2015-166030 filed on August 25, 2015 and Japanese Patent Application No. 2016-124959 filed on June 23, 2016. The disclosures of Japanese patent applications Nos. 2015-166030 and 2016-124959 are incorporated herein by reference in its entirety.

Description of Reference Numerals

[0087]

1 Pearlite lamellar microstructure
2 Lamellar cementite
3 Lamellar ferrite
4 Line segment (which is perpendicular to the layered microstructure and has its starting point and ending point positioned at the center of the thickness of the lamellar cementite)

Claims

1. A mechanical structure steel for cold-working, comprising, in percent by mass:

C: 0.07% or more and less than 0.3%,
Si: 0.05 to 0.5%,
Mn: 0.2 to 1.7%,
P: more than 0% and 0.03% or less,
S: 0.001 to 0.05%,
Al: 0.01 to 0.1%, and
N: 0 to 0.015%, with the balance being iron and inevitable impurities, wherein
the steel has a metal microstructure comprising proeutectoid ferrite and pearlite, a total area ratio of the proeutectoid ferrite and the pearlite with respect to the entire microstructure is 90% or more, while an area ratio Af of the proeutectoid ferrite with respect to the entire microstructure satisfies a relationship of Af ≥ A where an A value is represented by formula (1) below,
an average circle equivalent diameter of a bcc-Fe crystal grain is in a range of 15 to 30 μm, and
a pearlite lamellar spacing is 0.20 μm or less on average:

$$A = (103 - 128 \times [C(\%)]) \times 0.80\ (\%) \qquad (1)$$

where [C(%)] in the formula (1) indicates the C content in percent by mass.

2. The mechanical structure steel for cold-working according to claim 1, further comprises, in percent by mass, one or more elements selected from the group consisting of:

Cr: more than 0% and 0.5% or less,
Cu: more than 0% and 0.25% or less,
Ni: more than 0% and 0.25% or less,
Mo: more than 0% and 0.25% or less, and
B: more than 0% and 0.01% or less, the mechanical structure steel satisfying formula (X) below:

$$[Cr\%] + [Cu\%] + [Ni\%] + [Mo\%] \leq 0.75 \qquad (X)$$

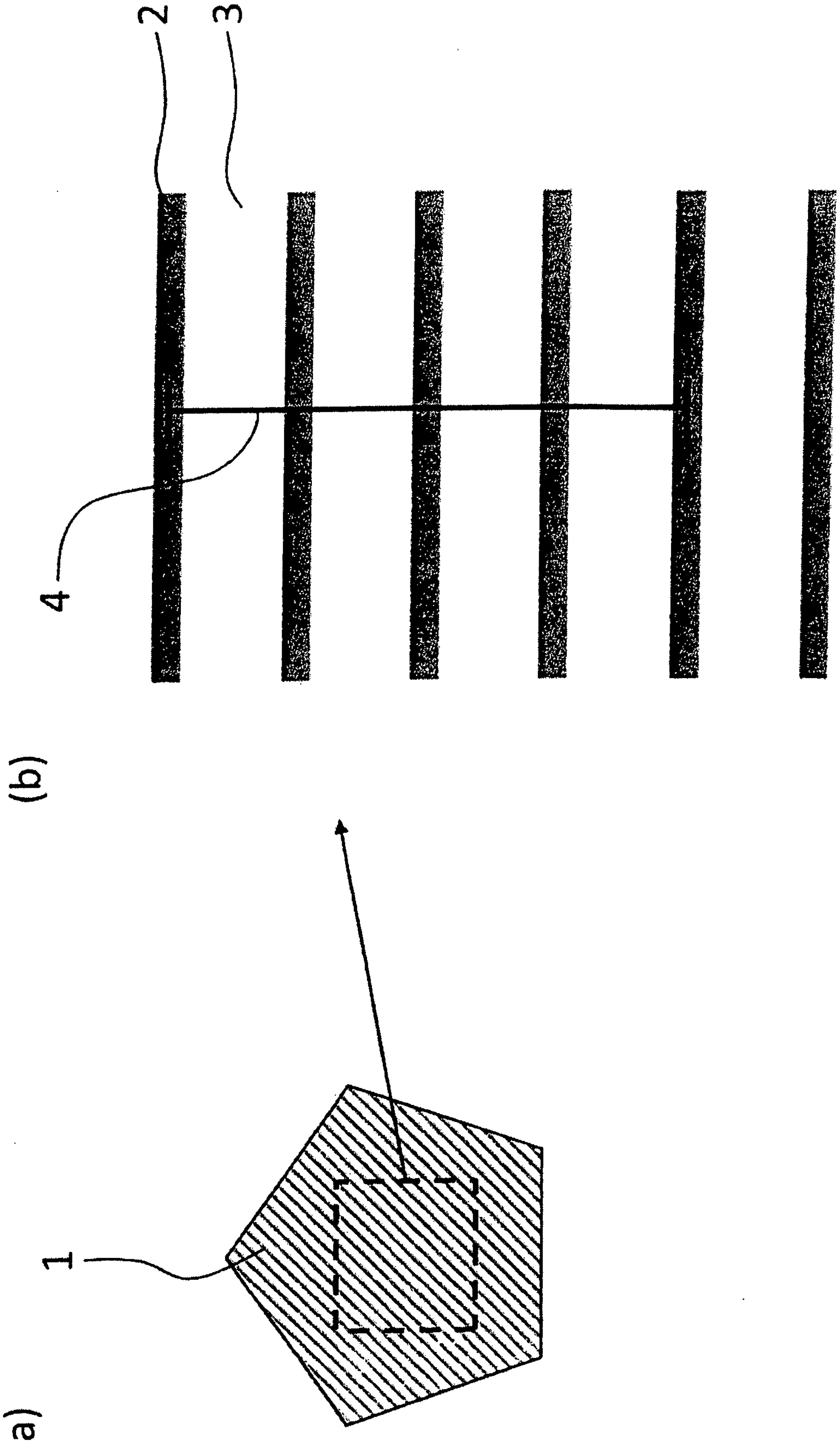
where [Cr%], [Cu%], [Ni%], and [Mo%] indicate the contents of Cr, Cu, Ni, and Mo in percent by mass, respectively.

3. The mechanical structure steel for cold-working according to claim 1 or 2, further comprises, in percent by mass: Ti: more than 0% and 0.1% or less.

4. A method for manufacturing the mechanical structure steel for cold-working according to any one of claims 1 to 3, the method comprising:

performing finish rolling at a temperature of 950°C or higher and 1,150°C or lower; and then
performing, in the following order, first cooling to a first-cooling end temperature of 700 to 750°C at an average cooling rate of 3°C/sec. or less and second cooling in a temperature range from the first-cooling end temperature to at least 600°C at an average cooling rate of 5 to 30°C/sec.

Fig. 1



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2016/073769

A. CLASSIFICATION OF SUBJECT MATTER
C22C38/00(2006.01)i, *C21D8/06*(2006.01)i, *C22C38/60*(2006.01)i

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)
C22C38/00-C22C38/60, C21D8/00-8/10

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

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2016
Kokai Jitsuyo Shinan Koho	1971-2016	Toroku Jitsuyo Shinan Koho	1994-2016

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.
X A	JP 2013-7089 A (Kobe Steel, Ltd.), 10 January 2013 (10.01.2013), 0001, 0016, 0024 to 0025, 0050 to 0057; tables 1 to 3 (Family: none)	1 2-4
A	JP 2000-212695 A (Nippon Steel Corp.), 02 August 2000 (02.08.2000), claims; 0001, 0027 to 0035, 0044 to 0046; tables 1 to 2; fig. 2 to 4 (Family: none)	1-4
A	JP 2013-7091 A (Kobe Steel, Ltd.), 10 January 2013 (10.01.2013), (Family: none)	1-4

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

* Special categories of cited documents:

"A"	document defining the general state of the art which is not considered to be of particular relevance
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"&"	document member of the same patent family

Date of the actual completion of the international search 12 October 2016 (12.10.16)	Date of mailing of the international search report 25 October 2016 (25.10.16)
Name and mailing address of the ISA/ Japan Patent Office 3-4-3,Kasumigaseki,Chiyoda-ku, Tokyo 100-8915,Japan	Authorized officer Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2016/073769

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	JP 2009-275252 A (Nippon Steel Corp.), 26 November 2009 (26.11.2009), (Family: none)	1-4
A	JP 2009-242916 A (Kobe Steel, Ltd.), 22 October 2009 (22.10.2009), (Family: none)	1-4
A	JP 9-53142 A (Sumitomo Metal Industries, Ltd.), 25 February 1997 (25.02.1997), (Family: none)	1-4
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- JP 4299744 B **[0008]**
- JP 2015166030 A **[0086]**
- JP 2016124959 A **[0086]**