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

(11) EP 3 165 625 A1

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

(43) Date of publication:
10.05.2017 Bulletin 2017/19

(21) Application number: **15814624.1**

(22) Date of filing: **02.06.2015**

(51) Int Cl.:
C22C 38/00 *(2006.01)* ***C22C 38/14*** *(2006.01)*
C22C 38/54 *(2006.01)* ***C21D 8/06*** *(2006.01)*
C21D 9/52 *(2006.01)*

(86) International application number:
PCT/JP2015/065863

(87) International publication number:
WO 2016/002413 (07.01.2016 Gazette 2016/01)

(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

(30) Priority: **01.07.2014 JP 2014136222**

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(54) WIRE MATERIAL FOR STEEL WIRE, AND STEEL WIRE

(57) An object of the present invention is to provide a wire rod for a steel wire, which is excellent in low cycle fatigue characteristics and is useful as a material for a high-strength steel wire such as a wire rope or a PC steel wire, and to provide a steel wire that can exhibit such characteristics. A wire rod for a steel wire of the present invention comprises by mass: C: 0.70 to 1.3%; Si: 0.1 to 1.5%; Mn: 0.1 to 1.5%; N: 0.001 to 0.006%; Al: 0.001 to 0.10%; Ti: 0.02 to 0.20%; B: 0.0005 to 0.010%; P: 0% or more and 0.030% or less; and S: 0% or more and 0.030% or less, with the balance being iron and inevitable impurities, wherein, the wire rod has pearlite as a main phase, an area ratio of proeutectoid ferrite is 1.0% or less, and an average thickness of the proeutectoid ferrite is 5 μm or less.

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Description

TECHNICAL FIELD

[0001] The present invention relates to a wire rod for a steel wire, which is a material for a high-strength steel wire used for a wire rope, a PC steel wire, and the like, and to such a steel wire.

BACKGROUND ART

[0002] In steel stranded wires to which bending stress is repetitively applied, such as a rope for elevators and a winding rope of cranes, the bending fatigue characteristics of an element wire are important factors to determine the design strength and life of a rope. In recent years, needs for reduction in weight of a rope are increasing along with the acceleration of elevators and the reduction in size of cranes, and a high-strength wire rod for a steel wire is demanded, which satisfies the needs and is excellent in the bending fatigue characteristics. The high-strength wire rod for a steel wire, which is excellent in the bending fatigue characteristics, is also useful as a material for a PC (Prestressed Concrete) steel wire. Specifically, such a wire rod for a steel wire is required not to generate low cycle fatigue that occurs in 10^4 to 10^5 repeating cycles.

[0003] Various techniques for improving the characteristics of a wire rod have been heretofore proposed. For example, Patent Literature 1 discloses a technique of improving the fatigue strength by finely precipitating a BN-based inclusion in steel.

[0004] Patent Literature 2 discloses a technique of obtaining a high-strength wire rod by directly performing a molten salt patenting treatment after hot rolling so that the structure of the wire rod is controlled to a pearlite structure having an area ratio of proeutectoid ferrite of 3% or less.

[0005] Further, Patent Literature 3 discloses a technique of obtaining a high-ductility wire rod by making the metallographic structure of the wire rod a 95% or more pearlite structure and controlling to predetermined ranges the maximum value and the average value of pearlite block grain sizes of the pearlite in a core part of a cross-section perpendicular to the axis direction of the wire rod. This technique also discloses that it is useful to adjust the volume ratio of proeutectoid ferrite to 2% or less for excellent wire drawability.

PRIOR ART DOCUMENT

PATENT LITERATURES

[0006]

Patent Literature 1: JP 2011-225990 A
Patent Literature 2: JP 2007-39800 A
Patent Literature 3: WO 2007/139234 A

SUMMARY OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

[0007] The characteristic to be an issue in the technique of Patent Literature 1 is high cycle fatigue that occurs near the fatigue limit of 10^7 repeating cycles, and the mechanism of the high cycle fatigue is different from that of the above-mentioned low cycle fatigue. In products that are exposed to outside air over a long period of time, such as a wire rope, a crack easily occurs on a surface layer part by the influence such as oxidation and intrusion of hydrogen on the surface layer part, and friction between element wires, and there is a possibility that breaking of a wire occurs much earlier than its intrinsic fatigue limit, resulting in a short life. Therefore, it is necessary to take measures to suppress development of a crack.

[0008] In the technique of Patent Literature 2, special equipment for performing the direct patenting treatment after hot rolling is required for acquisition of a high-strength wire rod, causing equipment investment to increase. Such equipment also has a drawback of being inferior in productivity and maintainability to so-called Stelmor cooling equipment that cools a wire rod while conveying it on a conveyor. In addition, a sufficient effect of improving the low cycle fatigue characteristics cannot be exhibited only with reduction in the area ratio of proeutectoid ferrite in a wire rod.

[0009] Further, a sufficient effect for the low cycle fatigue characteristics cannot be obtained only by defining the requirements described in Patent Literature 3.

[0010] The present invention has been made under the circumstances as described above, and an object of the present invention is to provide a wire rod for a steel wire, which is excellent in low cycle fatigue characteristics and is useful as a material for a high-strength steel wire such as a wire rope or a PC steel wire, and to provide a steel wire that can exhibit such characteristics.

MEANS FOR SOLVING THE PROBLEMS

[0011] A wire rod for a steel wire of the present invention, which can solve the above problems, comprises by mass: C: 0.70 to 1.3%; Si: 0.1 to 1.5%; Mn: 0.1 to 1.5%; N: 0.001 to 0.006%; Al: 0.001 to 0.10%; Ti: 0.02 to 0.20%; B: 0.0005 to 0.010%; P: 0% or more and 0.030% or less; and S: 0% or more and 0.030% or less, with the balance being iron and inevitable impurities, wherein, the wire rod has pearlite as a main phase, an area ratio of proeutectoid ferrite is 1.0% or less, and an average thickness of the proeutectoid ferrite is 5 μm or less.

[0012] The phrase "having pearlite as a main phase" means that 95 area% or more of the metallographic structure is a pearlite structure. The average thickness of proeutectoid ferrite means an average value of the thickness in the width direction of the proeutectoid ferrite when the proeutectoid ferrite is observed by an optical microscope.

[0013] It is also preferred that the wire rod for a steel wire of the present invention further comprises by mass:

(a) at least one of Cr: more than 0% and 1.0% or less, and V: more than 0% and 0.5% or less;
(b) at least one of Ni: more than 0% and 0.5% or less, and Nb: more than 0% and 0.5% or less;
(c) Co: more than 0% and 1.0% or less;
(d) at least one of Mo: more than 0% and 0.5% or less, and Cu: more than 0% and 0.5% or less; and the like.

[0014] In the wire rod for a steel wire of the present invention, a content of a solid solution B is preferred to be 0.0003% by mass or more.

[0015] The present invention also encompasses a steel wire comprising the above-mentioned chemical composition, wherein 100000 cycle fatigue strength σ satisfies a relationship of formula (1) below with tensile strength TS:

$$\sigma > 0.45\ \mathrm{TS} \qquad (1).$$

EFFECTS OF THE INVENTION

[0016] According to the present invention, the area ratio of proeutectoid ferrite of a steel wire rod before a wire drawing process is reduced and the thickness of the proeutectoid ferrite is decreased to improve the bending fatigue strength of a steel wire after cold working (a wire drawing process), allowing the steel wire to exhibit excellent fatigue characteristics. Particularly, the steel wire exhibits excellent characteristics against low cycle fatigue caused by repetitive stress load of about 10^4 to 10^5 cycles.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017]

Fig. 1 is a schematic diagram illustratively showing an execution state of a four point bending fatigue test.
Fig. 2 is a diagram-replacing micrograph showing an example of proeutectoid ferrite grains observed.

MODE FOR CARRYING OUT THE INVENTION

[0018] The present inventors have earnestly searched for a factor that affects the low cycle fatigue characteristics in a steel wire rod of a metallographic structure having pearlite as a main phase. As a result, the present inventors have found that proeutectoid ferrite (hereinafter, may be abbreviated as "proeutectoid α) slightly precipitated in a pearlite structure accelerates development of a fatigue crack. In high-carbon steel that has a carbon content of 0.70% or more, plate-shaped proeutectoid α is precipitated in a prior austenite grain boundary as shown in Fig. 2 described later; however, the present inventors have found that excellent low cycle fatigue characteristics can be exhibited by making the area ratio of the proeutectoid α 1.0% or less and reducing the thickness of the proeutectoid α, and thus have complete the present invention.

[0019] In the steel wire rod having a pearlite structure as a main phase, a void is generated in an interface between the proeutectoid α and the pearlite to accelerate the development of a fatigue crack. Therefore, it is important to minimize the area ratio of the proeutectoid α as much as possible so that the amount of the interface is reduced. In addition, the reduction in the area ratio of the proeutectoid α also gives an effect of suppressing a longitudinal crack during a torsion test. When a longitudinal crack is generated, the steel wire cannot endure a wire stranding process, and therefore the steel wire having a longitudinal crack is determined to be defective. In view of these effects, it is necessary to make the area ratio of the proeutectoid α a ratio of 1.0% or less relative to the whole metallographic structure. The area ratio of the proeutectoid α is preferably 0.8% or less, more preferably 0.6% or less.

[0020] In order to reduce the area ratio of the proeutectoid α, addition of B is effective. B exhibits the effect of reducing the area ratio of the proeutectoid α when B exists as a solid solution B, and with regard to the portion that B is precipitated as a compound such as BN, the effect is lost. Therefore, it is necessary in the steel wire rod of the present invention to control the amounts of N and B in appropriate ranges, and it is preferred to produce the steel wire rod under production conditions in which BN is hardly precipitated.

[0021] On the other hand, an increase in thickness of the proeutectoid α causes concentration of stress to a void generated in an interface to enlarge the void, so that the development of a fatigue crack is encouraged to deteriorate the fatigue strength. The proeutectoid α small in thickness is deformed by a wire drawing process to be rendered harmless, while the proeutectoid α large in thickness remains even after a wire drawing process to deteriorate bending fatigue strength (hereinafter, may be simply referred to as "fatigue strength"). Specifically, the average thickness of the proeutectoid α is necessary to be 5 μm or less. The average thickness of the proeutectoid α is preferably 4 μm or less, more preferably 3 μm or less.

[0022] In order to decrease the average thickness of the proeutectoid α, it is effective to finely disperse Ti inclusions, e.g., TiC, in steel, especially in the vicinity of a grain boundary so that many precipitation nuclei of the proeutectoid α are produced, and to suppress the growth of the nuclei. For achievement of the above, it is necessary to control the amount of Ti in a steel wire rod in an appropriate range, and further, it is preferred to produce a steel wire rod under manufacturing conditions which facilitates fine precipitation of Ti-based inclusions such as TiC.

[0023] In the steel wire rod according to the present invention, it is necessary to also appropriately adjust the chemical composition of the steel wire rod so as to exhibit the basic characteristics of the steel wire rod when the steel wire rod is applied. The chemical composition including the amounts of the above-mentioned B, N and Ti is as follows. It is to be noted that "%" in the chemical composition is "% by mass" in any case.

(C: 0.70 to 1.3%)

[0024] C is an element effective for enhancing the strength, and a wire rod (steel wire rod) before cold working and a steel wire after cold working are improved in the strength with the increasing amount of C. The amount of C also affects the precipitation amount of the proeutectoid α, and when the amount of C is small, the precipitation of the proeutectoid α cannot be sufficiently suppressed. Therefore, the amount of C is determined to be 0.70% or more. The amount of C is preferably 0.74% or more, more preferably 0.78% or more. An excessive amount of C, however, causes precipitation of proeutectoid cementite (hereinafter, may be abbreviated as "proeutectoid θ") to lead to breaking of a wire during a wire drawing process. Therefore, the amount of C is determined to be 1.3% or less. The amount of C is preferably 1.2% or less, more preferably 1.1% or less.

(Si: 0.1 to 1.5%)

[0025] Si has an action as a deoxidizing agent, and also has an action of improving the strength of a wire rod. For effective exhibition of these actions, the amount of Si is determined to be 0.1% or more. The amount of Si is preferably 0.15% or more, more preferably 0.20% or more. On the other hand, an excessive amount of Si deteriorates cold wire drawability to cause the increase in the ratio of breaking of a wire. Therefore, the amount of Si is determined to be 1.5% or less. The amount of Si is preferably 1.4% or less, more preferably 1.3% or less.

(Mn: 0.1 to 1.5%)

[0026] Mn particularly has, in addition to a deoxidizing action as with Si, an action of fixing S in steel as MnS to enhance toughness and ductility of steel. For effective exhibition of these actions, the amount of Mn is set to 0.1% or more. The amount of Mn is preferably 0.15% or more, more preferably 0.20% or more. Mn is, however, an element that is easily segregated, and excessive addition thereof may possibly cause excessive increase of hardenability at a Mn segregated portion to produce a supercooled structure such martensite. Therefore, the amount of Mn is determined to be 1.5% or less. The amount of Mn is preferably 1.4% or less, more preferably 1.3% or less.

(N: 0.001 to 0.006%)

[0027] N chemically combines with B in steel to form BN, so that the effect of B is lost. Further, N in a solid solution state causes deterioration of torsion characteristics due to strain aging during wire drawing, and causes a longitudinal crack in significant cases. For prevention of these adverse effects, the amount of N is set to 0.006% or less. The amount of N is preferably 0.005% or less, more preferably 0.004% or less. On the other hand, a small amount of N gives an effect of refining crystal grains by a nitride such as TiN or AlN to enhance ductility of a wire rod. For exhibition of such an effect, the amount of N is set to 0.001% or more. The amount of N is preferably 0.0015% or more, more preferably 0.0020% or more.

(Al: 0.001 to 0.10%)

[0028] Al is an effective deoxidizing element. Al also has an effect of forming a nitride such as AlN to refine crystal grains. For effective exhibition of such an effect, the amount of Al is set to 0.001% or more. The amount of Al is preferably 0.002% or more, more preferably 0.003% or more. On the other hand, excessive addition of Al forms an oxide such as Al_2O_3 to increase breaking of a wire during wire drawing. From the viewpoint described above, the amount of Al is set to 0.10% or less. The amount of Al is preferably 0.09% or less, more preferably 0.08% or less.

(Ti: 0.02 to 0.20%)

[0029] Ti has an action of forming a carbide such as TiC to reduce the grain size (thickness) of the proeutectoid α. Further, Ti also has an action of chemically combining with N in steel to form a nitride such as TiN, so that Ti prevents the deterioration of torsion characteristics caused by N. For effective exhibition of those effects, the amount of Ti is set to 0.02% or more. The amount of Ti is preferably 0.03% or more, more preferably 0.04% or more. On the other hand, an excessive amount of Ti causes precipitation of large amounts of Ti inclusions such as TiC and TiN to increase breaking of a wire during wire drawing. Therefore, the amount of Ti is set to 0.20% or less. The amount of Ti is preferably 0.15% or less, more preferably 0.10% or less.

(B: 0.0005 to 0.010%, preferably 0.0003% or more as a solid solution B)

[0030] B has an action of preventing production of the proeutectoid α so that the area ratio of the proeutectoid α is reduced. However, when a compound such as BN is formed, such an action is not exhibited. For effective exhibition of the effect of B, it is necessary to set the amount of B to 0.0005% or more. The lower limit of the amount of B is preferably 0.0007% or more, more preferably 0.001% or more. On the other hand, an excessive amount of B causes precipitation of a Fe-B compound as a compound of B and Fe, e.g., FeB_2 to cause a crack during hot rolling. Therefore, it is necessary to set the amount of B to 0.010% or less. The amount of B is preferably 0.008% or less, more preferably 0.006% or less. In addition, B is contained as a solid solution B in steel in an amount of preferably 0.0003% or more, more preferably 0.0005% or more.

(P: 0% or more and 0.030% or less)

[0031] P is segregated in a prior austenite grain boundary to embrittle the grain boundary, so that the fatigue strength is deteriorated. Therefore, the less the content of P, the more preferable it is. Thus, the amount of P is set to 0.030% or less. The amount of P is preferably 0.025% or less, more preferably 0.020% or less. The amount of P may be 0%, but P is generally contained in an amount of 0.001% or more.

(S: 0% or more and 0.030% or less)

[0032] S is segregated in a prior austenite grain boundary as with P to embrittle the grain boundary, so that the fatigue strength is deteriorated. Therefore, the less the content of S, the more preferable it is. Thus, the amount of S is set to 0.030% or less. The amount of S is preferably 0.025% or less, more preferably 0.020% or less. The amount of S may be 0%, but S is generally contained in an amount of 0.001% or more.
[0033] The basic components of the wire rod of the present invention are as described above, and the balance is substantially iron. However, inclusion of inevitable impurities in steel, which are brought depending on the state of a raw material, a material, manufacturing equipment or the like, is naturally accepted.
[0034] It is also preferred that the wire rod of the present invention further contain, as necessary, for further improvement of characteristics such as strength, toughness and ductility:

(a) at least one of Cr: more than 0% and 1.0% or less, and V: more than 0% and 0.5% or less;
(b) at least one of Ni: more than 0% and 0.5% or less, and Nb: more than 0% and 0.5% or less;
(c) Co: more than 0% and 1.0% or less;

(d) at least one of Mo: more than 0% and 0.5% or less, and Cu: more than 0% and 0.5% or less; and the like.

(At least one of Cr: more than 0% and 1.0% or less, and V: more than 0% and 0.5% or less)

[0035] Cr and V are elements useful for enhancing the strength (tensile strength) of a wire rod, and one or two in combination of these elements may be contained.

[0036] Particularly, Cr has an action of reducing the lamellar spacing of pearlite to enhance the strength and toughness of a wire rod. For effective exhibition of such an action, the amount of Cr is preferably 0.05% or more. The amount of Cr is more preferably 0.10% or more, further preferably 0.15% or more. On the other hand, an excessive amount of Cr increases hardenability to increase a risk of generating a supercooled structure during hot rolling. Therefore, the amount of Cr is preferably set to 1.0% or less. The amount of Cr is more preferably 0.8% or less, further preferably 0.6% or less.

[0037] V has an effect of forming a carbonitride to improve the strength of a wire rod. In addition, V not only forms a nitride with an excessive solid solution N after precipitation of AlN as with Nb to contribute to refining of crystal grains, but also has an effect of suppressing aging embrittlement by fixation of the solid solution N. For effective exhibition of such actions, the amount of V is preferably 0.01% or more, more preferably 0.02% or more, further preferably 0.03% or more. V is, however, an expensive element, and even excessive addition of V only causes saturation of the effect of V, leading to economical waste. Therefore, the amount of V is preferably 0.5% or less, more preferably 0.4% or less, further preferably 0.2% or less.

(At least one of Ni: more than 0% and 0.5% or less, and Nb: more than 0% and 0.5% or less)

[0038] Ni and Nb are elements useful for enhancing the toughness of a steel wire, and one or two in combination of these elements may be contained.

[0039] Particularly, Ni is an element that enhances the toughness of a steel wire after wire drawing. For effective exhibition of such an action, the amount of Ni is preferably 0.05% or more, more preferably 0.1% or more, further preferably 0.2% or more. However, even excessive addition of Ni only causes saturation of the effect of Ni, leading to economical waste. Therefore, the amount of Ni is preferably 0.5% or less, more preferably 0.4% or less, further preferably 0.3% or less.

[0040] Nb not only forms a nitride as with Ti and Al to contribute to refining of crystal grains for improvement of the toughness of a steel wire, but also has an effect of suppressing aging embrittlement by fixation of a solid solution N. For effective exhibition of such actions, the amount of Nb is preferably 0.01% or more, more preferably 0.03% or more, further preferably 0.05% or more. Nb is, however, an expensive element, and even excessive addition of Nb only causes saturation of the effect of Nb, leading to economical waste. Therefore, the amount of Nb is preferably 0.5% or less, more preferably 0.4% or less, further preferably 0.3% or less.

(Co: more than 0% and 1.0% or less)

[0041] Co has an action of reducing production of proeutectoid cementite to make the structure a uniform pearlite structure, particularly when the amount of C is high. For effective exhibition of such an action, the amount of Co is preferably 0.05% or more, more preferably 0.1% or more, further preferably 0.2% or more. However, even excessive addition of Co only causes saturation of the effect of Co, leading to economical waste. Therefore, the amount of Co is preferably 1.0% or less, more preferably 0.8% or less, further preferably 0.6% or less.

(At least one of Mo: more than 0% and 0.5% or less, and Cu: more than 0% and 0.5% or less)

[0042] Mo is an element that improves corrosion resistance of a steel wire. For effective exhibition of such an action, the amount of Mo is preferably 0.05% or more, more preferably 0.1% or more, further preferably 0.2% or more. An excessive amount of Mo, however, easily causes generation of a supercooled structure during hot rolling and also deteriorates the ductility. Therefore, the amount of Mo is preferably 0.5% or less, more preferably 0.4% or less, further preferably 0.3% or less.

[0043] Cu is an element that improves corrosion resistance of a steel wire as with Mo. For effective exhibition of such an action, the amount of Cu is preferably 0.05% or more, more preferably 0.08% or more, further preferably 0.10% or more. An excessive amount of Cu, however, causes reaction of Cu with S to segregate CuS in a grain boundary portion, so that a flaw is generated during a manufacturing process of a wire rod. For avoidance of such an adverse effect, the amount of Cu is preferably 0.5% or less, more preferably 0.4% or less, further preferably 0.3% or less.

[0044] One or two in combination of Mo and Cu may be contained.

[0045] Next described is a method that enables manufacturing of the wire rod for a steel wire according to the present invention.

[0046] A wire rod before cold wire drawing is generally manufactured by melting, bloom rolling, and hot rolling of steel obtained by appropriately controlling the chemical components thereof, further followed by a patenting treatment as necessary. It is important to appropriately control the precipitation behavior of TiC or BN in addition to appropriate control of the content of Ti, B and N to the above-mentioned ranges, for manufacturing the wire rod of the present invention while satisfying the requirements (metallographic structure, area ratio of proeutectoid α, and average thickness of proeutectoid α) defined in the present invention.

[0047] First, it is preferred that a slab cast is heated to 1200°C or higher in bloom rolling to decompose coarse TiC precipitated during casting. A heating temperature lower than 1200°C causes coarse TiC to remain in a wire rod so that the thickness of proeutectoid α cannot be sufficiently reduced, resulting in deterioration of the fatigue strength. The heating temperature is more preferably 1250°C or higher, further preferably 1300°C or higher. An excessively high heating temperature, however, causes melting of a wire rod, and therefore the heating temperature is generally set to up to about 1400°C.

[0048] It is preferred that in subsequent hot rolling, the billet be heated to a temperature range of 1000°C or higher to sufficiently decompose coarse BN in the billet followed by sufficient cooling with water after the rolling, and the placing temperature of the rolled material (wire rod) is controlled to 800 to 1000°C at a laying head. A placing temperature exceeding 1000°C causes precipitation of a large amount of BN in a wire rod during cooling on a conveyor after the placing so that a solid solution B may not possibly be sufficiently secured. The placing temperature is more preferably 980°C or lower, further preferably 950°C or lower. A placing temperature lower than 800°C causes increase in deformation resistance of a wire rod so that a placing defect in a laying head, e.g., unavailable coiling and the like, may occur. Therefore, the placing temperature is preferably 800°C or higher. The placing temperature is more preferably 820°C or higher, further preferably 850°C or higher.

[0049] When hot rolling is performed, it is preferred that the strain rate at final 4 passes of the rolling is set to 0.5 sec^{-1} or more, and crystal grains are refined by dynamic recrystallization, so that fine TiC is precipitated. The strain rate of less than 0.5 sec^{-1} does not allow sufficient refining of TiC so that the average thickness of proeutectoid α cannot be sufficiently reduced. The strain rate at this time is more preferably 0.8 sec^{-1} or more, further preferably 1.0 sec^{-1} or more. However, in terms of equipment load, generally, the strain rate is preferably set to 5 sec^{-1} or less. A strain rate $V\varepsilon$ can be represented by the following formula (2), with a sectional area $S_0(m^2)$ of a wire rod before entry into the first roll that is a roll 4 passes before the final pass, a sectional area $S_4(m^2)$ after passing the final pass, and the total passing time (rolling time) t (sec) of the 4 passes:

$$V\varepsilon = \{\ln (S_0/S_4)\}/t \qquad (2).$$

[0050] After the placing, the wire rod is cooled on a cooling conveyor to cause pearlite transformation during the cooling. It is preferred that the wire rod is rapidly cooled by setting the average cooling rate before the start of the pearlite transformation to 5°C/sec or more. A low average cooling rate at this time easily causes precipitation of proeutectoid α at a high temperature to coarsen the proeutectoid α, so that the thickness of the proeutectoid α may not possibly be sufficiently reduced. Further, in some cases, an average cooling rate of less than 5°C/sec causes local precipitation of a structure in which the lamellar spacing is extremely coarse, which is so-called coarse pearlite, so that the wire drawability is deteriorated. The start of the pearlite transformation may be obtained by measuring the temperature of the wire rod and determining a changing point (inflection point) caused by transformation heating in a cooling curve. The average cooling rate is more preferably 10°C/sec or more, further preferably 15°C/sec or more. The upper limit of the average cooling rate is preferably 100°C/sec or less, more preferably 50°C/sec or less.

[0051] The wire rod obtained as described above can be used as a steel wire after directly performing a wire drawing process (cold working) on the wire rod, while a patenting treatment may be performed on the wire rod before the wire drawing process. Such a patenting treatment before the wire drawing process can enhance the strength of the wire rod and reduce the variation in strength.

[0052] When the degree of the wire drawing process is predicted to be large as in the case of manufacturing a steel wire having a small diameter, it is also useful to perform a patenting treatment after drawing a wire from a rolled material to some extent, to return the structure of the wire rod to an unprocessed pearlite structure, followed by a further wire drawing process. At this time, the proeutectoid α obtained during hot rolling is lost due to the patenting treatment, while when finely precipitated TiC and a sufficient amount of a solid solution B are secured, an appropriate area ratio and an appropriate average thickness of proeutectoid α can be obtained by common patenting treatment conditions.

[0053] The heating temperature during the patenting treatment (hereinafter, this temperature may be referred to as a "reheating temperature") is preferably about 900 to 1000°C, more preferably 920°C or higher and 980°C or lower. The reheating temperature is preferably 900°C or higher from the viewpoints of preventing a carbide from remaining in a non-solid solution state and completely austenitizing the structure, while an excessively high reheating temperature causes, in some cases, coarsening of TiC, and reduction of a solid solution B caused by reaction thereof with N, so that a predetermined area ratio and a predetermined average thickness of proeutectoid α cannot be obtained. The holding temperature at the patenting treatment is preferably about 530 to 600°C, more preferably 550°C or higher and 580°C or lower.

[0054] In the wire rod of the present invention, the amount of proeutectoid α that causes generation and development of a fatigue crack is sufficiently reduced, and the thickness of the proeutectoid α is controlled to be small. Therefore, a steel wire obtained by performing cold working on the wire rod, and products such as a wire rope and a PC steel wire, which partially or wholly include the steel wire, are excellent in fatigue characteristics compared to a general product. Generally, the tensile strength and the fatigue strength are in a proportional relationship, while a steel wire manufactured from the wire rod of the present invention is characterized by that 100000 cycle fatigue strength σ satisfies the relationship of the following formula (1) with tensile strength TS, and the present invention encompasses such a steel wire. Further, the present invention encompasses a product such as a wire rope that is manufactured by using such a steel wire for a partial or whole part of the wire rope.

$$\sigma > 0.45TS \quad (1)$$

[0055] The present application claims the benefit of the right of priority based on the Japanese Patent Application No. 2014-136222 filed on July 1, 2014. The entire contents of the specification of the Japanese Patent Application No. 2014-136222 are incorporated herein by reference.

EXAMPLES

[0056] Hereinafter, the present invention will be described more specifically with reference to examples. The present invention is not limited by the following examples, but can be naturally carried out by adding appropriate modifications thereto within a range that is suitable for the gist described above and below, and the modifications are included in the technical range of the present invention.

[0057] Steel ingots each having the chemical composition shown in Table 1 below were subjected to bloom rolling and hot rolling under the conditions shown in Table 2 below to process the ingots into wire rod coils, and a part of the coils was further subjected to a patenting treatment under the conditions shown in Table 3 below. It means that one having a rolling wire diameter shown in Table 2 below different from a patenting wire diameter shown in Table 3 below was subjected to a heat treatment after intermediate wire drawing.

[Table 1]

Steel type	Chemical composition [mass%], balance being iron and inevitable impurities															
	C	Si	Mn	Al	P	S	N	Ti	B	Cr	V	Mo	Cu	Co	Ni	Nb
A	0.97	0.40	0.30	0.035	0.010	0.010	0.0042	0.06	0.0018	0.20	-	-	-	-	-	-
B	0.92	0.90	0.50	0.040	0.011	0.006	0.0037	0.02	0.0010	-	-	-	-	-	-	-
C	0.82	0.20	0.70	0.030	0.008	0.008	0.0053	0.08	0.0020	-	-	-	-	-	-	-
D	0.88	0.40	0.75	0.033	0.010	0.010	0.0044	0.07	0.0015	-	0.09	-	-	-	-	-
E	0.80	0.25	0.50	0.002	0.010	0.011	0.0032	0.09	0.0030	-	-	-	-	-	-	-
F	0.97	0.62	0.51	0.060	0.007	0.010	0.0046	0.05	0.0020	-	-	-	-	-	-	0.10
G	0.84	0.43	1.20	0.040	0.010	0.020	0.0051	0.10	0.0025	-	-	-	-	-	-	-
H	1.10	0.60	0.70	0.030	0.020	0.008	0.0048	0.09	0.0022	-	-	-	-	-	0.05	-
I	0.90	0.50	0.81	0.090	0.007	0.010	0.0052	0.09	0.0017	-	-	-	0.07	-	-	-
J	0.75	0.40	0.60	0.050	0.008	0.012	0.0031	0.05	0.0035	-	-	0.10	-	-	-	-
K	0.85	0.24	0.61	0.020	0.006	0.008	0.0042	0.16	0.0055	-	-	-	-	0.20	-	-
L	1.30	0.69	0.51	0.003	0.010	0.007	0.0058	0.20	0.0005	-	-	-	-	-	-	-
M	0.80	0.25	0.50	0.020	0.015	0.011	0.0036	0.08	0.0007	-	-	-	-	-	-	-
N	0.93	1.43	1.50	0.030	0.010	0.010	0.0052	0.02	0.0090	-	-	-	-	-	-	-
O	0.70	0.20	0.80	0.050	0.008	0.013	0.0047	0.07	0.0080	-	-	-	-	-	-	-
P	0.65	0.39	0.68	0.070	0.010	0.010	0.0018	0.05	0.0012	-	-	-	-	-	-	-
Q	1.40	0.40	0.58	0.060	0.008	0.011	0.0037	0.03	0.0024	-	-	-	-	-	-	-
R	0.96	0.61	0.59	0.050	0.008	0.011	0.0044	0.01	0.0055	-	-	-	-	-	-	-
S	0.89	0.69	0.70	0.080	0.008	0.010	0.0053	0.25	0.0023	-	-	-	-	-	-	-
T	0.84	0.50	0.50	0.040	0.010	0.007	0.0055	0.04	0.0150	-	-	-	-	-	-	-
U	0.92	0.40	0.80	0.080	0.015	0.010	0.0041	0.05	0.0003	-	-	-	-	-	-	-

[Table 2]

Test No.	Steel type	Bloom rolling	Hot rolling				
		Heating temperature (°C)	Heating temperature (°C)	Strain rate (sec^{-1})	Placing temperature (°C)	Average cooling rate (°C/sec)	Rolling wire diameter (mm)
1	A	1250	1100	0.7	900	15	5.5
2	B	1300	1100	0.7	900	13	6.0
3	C	1200	1100	0.8	900	13	6.0
4	C	1100	1100	0.8	900	13	6.0
5	C	1200	900	0.8	870	13	6.0
6	C	1200	1100	0.3	1000	13	6.0
7	C	1200	1100	0.8	700	Placing defect	
8	C	1200	1100	0.8	1100	13	6.0
9	C	1200	1100	0.8	950	4	6.0
10	D	1250	1000	0.6	850	10	8.0
11	E	1250	1000	1.1	900	8	10.0
12	F	1250	1150	1.3	820	15	5.5
13	G	1250	1150	0.7	850	7	11.0
14	H	1250	1000	0.8	880	6	13.0
15	I	1250	1000	1.1	850	7	12.0
16	J	1250	1150	0.5	900	7	12.0
17	K	1300	1100	1.0	900	6	14.0
18	L	1250	1100	0.7	900	6	14.0
19	M	1300	1100	0.9	870	10	8.0
20	N	1300	1150	1.2	880	13	6.0
21	O	1300	1150	1.2	940	13	6.0
22	P	1250	1100	0.7	820	10	8.0
23	Q	1250	1100	0.6	820	10	8.0
24	R	1250	1100	0.5	850	10	8.0
25	S	1250	1100	0.8	880	10	8.0
26	T	1250	Wire breaking during rolling				
27	U	1250	1100	0.8	880	11	7.0

[Table 3]

Test No.	Steel type	Patenting conditions		
		Reheating temperature (°C)	Retention temperature (°C)	Wire diameter (mm)
1	A	-	-	-
2	B	-	-	-
3	C	950	580	6.0
4	C	950	580	6.0

(continued)

Test No.	Steel type	Patenting conditions		
		Reheating temperature (°C)	Retention temperature (°C)	Wire diameter (mm)
5	C	950	580	6.0
6	C	950	580	6.0
7	C	-	-	-
8	C	950	580	6.0
9	C	1000	580	6.0
10	D	950	570	8.0
11	E	950	570	10.0
12	F	950	590	3.0
13	G	950	580	11.0
14	H	1000	550	13.0
15	I	950	560	12.0
16	J	950	560	12.0
17	K	1000	540	14.0
18	L	1000	540	14.0
19	M	950	570	8.0
20	N	950	580	4.0
21	O	950	580	4.0
22	P	950	580	8.0
23	Q	950	580	8.0
24	R	950	580	8.0
25	S	950	580	8.0
26	T	-	-	-
27	U	950	580	7.0

[0058] A sample obtained from each of the wire rods before finish wire drawing was used for a tensile test, evaluation of the metallographic structure (area ratio of proeutectoid α, area ratio of pearlite, and average thickness of proeutectoid α), and measurement of the amount of a solid solution B which were conducted by the following methods.

(Tensile test)

[0059] The tensile strength TS of the obtained sample was measured in accordance with JIS Z 2241 (2011). The results are shown in Table 4 below.

(Evaluation of area ratio of proeutectoid α)

[0060] The obtained sample was embedded in a resin or the like, subjected to mirror polishing, and observed by an optical microscope with a mixed liquid of trinitrophenol and ethanol used as a corrosive liquid, to measure the area ratio of proeutectoid α by image analysis. A part that emerges white by the corrosive liquid is proeutectoid α. When the diameter of a wire rod was defined as D, a D/4 part on a transverse section of the wire rod was regarded as a representative structure, and the structure was imaged with a magnification of 400 to evaluate total 5 visual fields. The "area ratio of proeutectoid α" shown in Table 4 below shows the average value of the visual fields. The transverse section herein indicates a surface perpendicular to the longitudinal direction of the wire rod.

[0061] The area ratio of pearlite was also measured by this method. It means that one indicated by "P" in the item of the metallographic structure of Table 4 below has a pearlite structure of 95 area% or more, i.e., pearlite as a main phase. While, it means that one indicated by "P + α" or "P + θ" in the item of the metallographic structure has a pearlite structure of less than 95 area%, and has a mixed structure of pearlite with ferrite (α) or cementite (θ).

(Evaluation of average thickness of proeutectoid α)

[0062] A specimen subjected to mirror polishing in the same manner as in the above sample was structurally observed by a SEM (Scanning Electron Microscope), the thickness of 10 proeutectoid α grains observed was measured, and the average value of the thickness of the grains was obtained to calculate the thickness per grain. The measurement was conducted at a D/4 part on a transverse section in the same manner as in the above sample. The results are shown in Table 4 below.

(Measurement of amount of solid solution B)

[0063] The amount of a solid solution B was evaluated by an electrolytic extraction residue measurement. The electrolytic extraction residue measurement was conducted by using a 10% acetylacetone solution, and the amount of a compound type B in a residue was measured with a mesh having an opening of 0.1 μm by a bromoester method. The amount of a solid solution B was obtained by subtracting the amount of the compound type B from the whole amount of B in steel. The results are shown in Table 4 below. The specimen used for the bromoester method was 3 g. Since the amount of a solid solution B does not change without a heat history of 900°C or higher, the examination may be conducted with a steel wire after cold working.

[0064] Next, the obtained wired rod coils were subjected to a wire drawing process to produce a steel wire (wire), and a tensile test, evaluation of the torsion characteristics, and evaluation of the fatigue characteristics were conducted. Table 5 below shows an area reduction ratio during the wire drawing process and a wire diameter of a steel wire obtained by the wire drawing process.

(Tensile test)

[0065] The tensile strength TS and yield point YP of the steel wires were measured in accordance with JIS Z 2241 (2011). The results are shown in Table 5 below. A value obtained by multiplying the tensile strength TS by 0.45 is also shown in Table 5 below.

(Evaluation of torsion characteristics)

[0066] The torsion characteristics were evaluated on the basis of a torsion value required before breaking (number of times of torsion before breaking) by conducting a torsion test. The torsion value in Table 5 below is the average value of N = 5 wires. At this time, the torsion rate was set to 52 times/min, and the tensile force was set to 500 gf (4.9N). The torsion value was normalized by converting the distance between chucks (length of the sample wire) to 100 times of the wire diameter d (100d). In addition, a longitudinal crack was discriminated from a normal fracture surface by fracture surface observation, and one having even one longitudinal crack in 5 wires was described as "yes" in the item of the longitudinal crack in the following Table 5.

(Evaluation of fatigue characteristics)

[0067] The fatigue characteristics were evaluated by conducting a repetitive four point bending fatigue test with a jig having 4 supporting points. In Fig. 1, a numeral 1 is a test piece (wire rod), a numeral 2 is a direction to which a repetitive stress is applied, and a circle represents a supporting point. The test was conducted by one side bending, and the difference between the maximum stress and the minimum stress was defined as stress amplitude. Bending was repeated 100000 cycles with various types of stress amplitude, and in a test of N = 3 wires, one that had no broken wire (breaking of a wire) was determined to be acceptable, while one that had even one broken wire was determined to be unacceptable. The maximum stress amplitude of the specimen determined to be acceptable was defined as 100000 cycle fatigue strength σ. The 100000 cycle fatigue strength σ is shown in Table 5 below. The stress wave form was a sine wave, and the frequency was set to 10 Hz.

[Table 4]

Test No.	Steel type	Steel wire rod				
		Average thickness of proeutectoid α (μm)	Area ratio of proeutectoid α (%)	Solid solution B (ppm by mass)	Metallographic structure	TS (MPa)
1	A	1	0.3	7	P	1205
2	B	2	0.4	5	P	1212
3	C	4	0.3	10	P	1252
4	C	6	0.8	8	P	1252
5	C	3	1.4	2	P	1237
6	C	10	0.6	3	P	1267
7	C	-				
8	C	8	0.7	5	P	1260
9	C	7	0.7	6	P	1240
10	D	5	0.5	5	P	1271
11	E	4	0.6	3	P	1241
12	F	2	0.5	6	P	1383
13	G	4	0.4	5	P	1277
14	H	5	0.2	4	P	1321
15	I	4	0.1	5	P	1259
16	J	1	0.2	5	P	1225
17	K	2	0.1	6	P	1279
18	L	4	0.3	6	P	1301
19	M	3	0.5	7	P	1261
20	N	1	0.2	5	P	1257
21	O	5	0.5	3	P	1357
22	P	12	7.2	7	P+α	1067
23	Q	2	0.3	6	P+θ	1403
24	R	8	0.4	6	P	1256
25	S	4	0.5	8	P	1240
26	T	-				
27	U	4	2.4	1	P	1301

[Table 5]

Test No.	Steel type	Wire (steel wire)							
		Wire diameter (mm)	Area reduction rate (%)	TS (MPa)	YP (MPa)	Torsion value (times/100d)	Longitudinal crack	Fatigue strength (MPa)	0.45TS (MPa)
1	A	1.5	92.6	2307	1846	34	-	1050	1038
2	B	1.7	92.0	2277	1822	34	-	1100	1025
3	C	1.7	92.0	2352	1882	32	-	1100	1058
4	C	1.7	92.0	2352	1882	27	-	800	1058
5	C	1.7	92.0	2324	1859	11	Yes	500	1046
6	C	1.7	92.0	2380	1904	32	-	800	1071
7	C	-							
8	C	1.7	92.0	2367	1894	32	-	700	1065
9	C	1.7	92.0	2299	1811	21	-	700	1035
10	D	2.3	91.7	2370	1896	42	-	1100	1067
11	E	2.7	92.7	2388	1911	31	-	1100	1075
12	F	1.1	86.6	2283	1827	46	-	1050	1028
13	G	3.3	91.0	2332	1866	36	-	1100	1049
14	H	5.1	84.6	2054	1643	44	-	1000	924
15	I	3.3	92.4	2370	1896	32	-	1100	1067
16	J	3.2	92.9	2372	1898	31	-	1200	1067
17	K	5.2	86.2	1907	1526	33	-	1000	858
18	L	7.0	75.0	1820	1456	32	-	900	819
19	M	3.0	85.9	2059	1647	43	-	1100	927
20	N	1.3	89.4	2205	1764	37	-	1100	992
21	O	1.3	89.4	2381	1905	21	-	1200	1071
22	P	2.7	88.6	1697	1358	5	Yes	400	764
23	Q	Breaking of wire							
24	R	3.0	85.9	2051	1641	18	-	600	923

(continued)

Test No.	Steel type	Wire (steel wire)							
		Wire diameter (mm)	Area reduction rate (%)	TS (MPa)	YP (MPa)	Torsion value (times/100d)	Longitudinal crack	Fatigue strength (MPa)	0.45TS (MPa)
25	S	Breaking of wire							
26	T	-							
27	U	2.7	85.1	2031	1625	7	Yes	500	914

[0068] These results lead to the following considerations.

[0069] As to Test Nos. 1 to 3 and 10 to 21, both the chemical composition and the metallographic structure (area ratio of pearlite, area ratio of proeutectoid α, and average thickness of proeutectoid α) were within the ranges defined in the present invention, and therefore a steel wire (wire) was obtained, which had a tensile strength exceeding the tensile strength of the "piano wire B" described in JIS G 3522 (1991) (in the specification, 1620 to 1770 MPa in a wire having a wire diameter of 7.0 mm, for example), while achieving a fatigue strength satisfying the relationship of the above formula (1).

[0070] On the other hand, Test Nos. 4 to 9 and 22 to 27 are examples that did not satisfy any of the requirements of the present invention. Among them, Test No. 4 was low in the heating temperature during bloom rolling as shown in Table 2, causing precipitation of coarse TiC to increase the average thickness of the proeutectoid α as shown in Table 4 so that the fatigue strength was deteriorated.

[0071] Test No. 5 was low in the heating temperature during hot rolling as shown in Table 2, causing the increase in the area ratio of the proeutectoid α as shown in Table 4 while the solid solution B was reduced, so that the fatigue strength was deteriorated.

[0072] Test No. 6 was low in the strain rate during finish rolling as shown in Table 2, causing precipitation of coarse TiC to increase the average thickness of the proeutectoid α as shown in Table 4 so that the fatigue strength was deteriorated.

[0073] Test No. 7 was low in the placing temperature after hot rolling as shown in Table 2, causing a placing defect so that a specimen could not be obtained.

[0074] Test No. 8 was high in the placing temperature after hot rolling as shown in Table 2, causing coarsening of TiC to increase the average thickness of the proeutectoid α as shown in Table 4 so that the fatigue strength was deteriorated.

[0075] Test No. 9 was low in the average cooling rate after placing as shown in Table 2, causing the increase in the average thickness of the proeutectoid α as shown in Table 4 so that the fatigue strength was deteriorated.

[0076] Test No. 22 is an example of use of a steel type P containing a small amount of C, in which both the area ratio and average thickness of the proeutectoid α increased as shown in Table 4 so that the torsion characteristics and the fatigue strength were deteriorated.

[0077] Test No. 23 is an example of use of a steel type Q containing a large amount of C, in which large amounts of proeutectoid cementite was precipitated to cause breaking of a wire during wire drawing.

[0078] Test No. 24 is an example of use of a steel type R containing a small amount of Ti, in which, due to small amounts of TiC, the average thickness of the proeutectoid α increased so that the fatigue strength was deteriorated.

[0079] Test No. 25 is an example of use of a steel type S containing a large amount of Ti, in which large amounts of Ti-based inclusions were precipitated to cause breaking of a wire during wire drawing.

[0080] Test No. 26 is an example of use of a steel type T containing a large amount of B, in which breaking of a wire occurred during hot rolling so that a specimen could not be obtained.

[0081] Test No. 27 is an example of use of a steel type U containing a small amount of B, in which the area ratio of the proeutectoid α increased so that the torsion characteristics and the fatigue strength were deteriorated.

[0082] Fig. 2 is a drawing-replacing micrograph showing an example of the proeutectoid α observed in Test No. 3 as an example. An oval 3 shown in Fig. 2 indicates a precipitation position of the proeutectoid α. From Fig. 2, it is understood that the proeutectoid α is precipitated in a plate shape and the "width direction" and "length direction" of grains can be easily discriminated.

Claims

1. A wire rod for a steel wire, comprising by mass:

C: 0.70 to 1.3%;
Si: 0.1 to 1.5%;
Mn: 0.1 to 1.5%;
N: 0.001 to 0.006%;
Al: 0.001 to 0.10%;
Ti: 0.02 to 0.20%;
B: 0.0005 to 0.010%;
P: 0% or more and 0.030% or less; and
S: 0% or more and 0.030% or less, with the balance being iron and inevitable impurities, wherein
the wire rod has pearlite as a main phase,
an area ratio of proeutectoid ferrite is 1.0% or less, and
an average thickness of the proeutectoid ferrite is 5 μm or less.

2. The wire rod for a steel wire according to claim 1, further comprising at least one selected from a group consisting of (a) to (d) below by mass:

(a) at least one of Cr: more than 0% and 1.0% or less, and V: more than 0% and 0.5% or less;
(b) at least one of Ni: more than 0% and 0.5% or less, and Nb: more than 0% and 0.5% or less;
(c) Co: more than 0% and 1.0% or less; and
(d) at least one of Mo: more than 0% and 0.5% or less, and Cu: more than 0% and 0.5% or less.

3. The wire rod for a steel wire according to claim 1 or 2, wherein a content of a solid solution B is 0.0003% by mass or more.

4. A steel wire comprising the chemical composition according to claim 1 or 2 wherein 100000 cycle fatigue strength σ satisfies a relationship of formula (1) below with tensile strength TS:

$$\sigma > 0.45\ \mathrm{TS} \quad (1).$$

Fig. 1

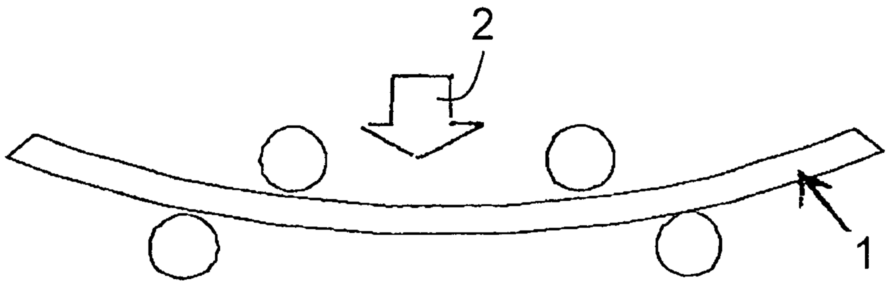
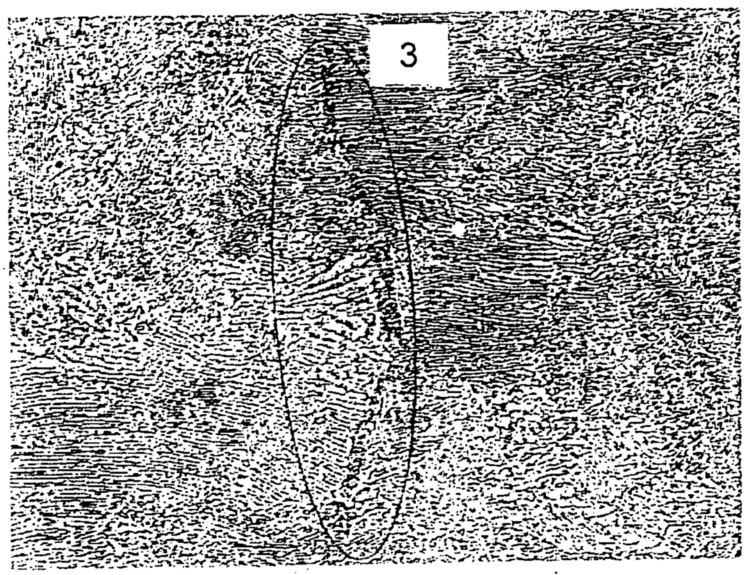


Fig. 2



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2015/065863

A. CLASSIFICATION OF SUBJECT MATTER
C22C38/00(2006.01)i, *C22C38/14*(2006.01)i, *C22C38/54*(2006.01)i, *C21D8/06*(2006.01)n, *C21D9/52*(2006.01)n

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C22C38/00, C22C38/14, C22C38/54, C21D8/06, C21D9/52

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	1996-2015
Kokai Jitsuyo Shinan Koho	1971-2015	Toroku Jitsuyo Shinan Koho	1994-2015

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.
Y	JP 2013-204069 A (Kobe Steel, Ltd.), 07 October 2013 (07.10.2013), claims; 0008, 0035, 0040 to 0042, 0045, 0048; tables 1 to 3 (Family: none)	1-4
Y	JP 11-199978 A (Kobe Steel, Ltd.), 27 July 1999 (27.07.1999), claims; 0001 to 0005, 0013, 0044, 0045; tables 1, 2 (Family: none)	1-4

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 August 2015 (19.08.15)	01 September 2015 (01.09.15)

Name and mailing address of the ISA/	Authorized officer
Japan Patent Office 3-4-3,Kasumigaseki,Chiyoda-ku, Tokyo 100-8915,Japan	Telephone No.

Form PCT/ISA/210 (second sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No. PCT/JP2015/065863

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 2005-232549 A (Kobe Steel, Ltd.), 02 September 2005 (02.09.2005), entire text; all drawings (Family: none)	1-4
A	WO 2008/093466 A1 (Nippon Steel Corp.), 07 August 2008 (07.08.2008), entire text; all drawings & JP 5169839 B2 & US 2010/0239884 A1 & EP 2062991 A1 & CN 101426943 A & KR 10-2009-0007707 A	1-4
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Form PCT/ISA/210 (continuation of second sheet) (July 2009)

REFERENCES CITED IN THE DESCRIPTION

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- JP 2014136222 A **[0055]**