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# (54) STEEL WIRE MATERIAL

(57) A steel wire rod includes, as a chemical composition, C, Si, Mn, Cr, Al, N, P, S, and optionally includes one or more selected from the group consisting of Mo, V, Ti, Nb, and B, and a remainder of Fe and impurities; in which a metallographic structure includes a pearlite and an area ratio of the pearlite is 85% or more; the average lamellar spacing of the pearlite is 50 nm to 100 nm; and when the Si content is represented by [%Si] by mass%, the Cr content in a cementite in the pearlite is represented by [%Crθ] by mass%, and the Cr content in a ferrite in the pearlite is represented by [%Crα] by mass%, [%Si], [%Crθ], and [%Crα] satisfy the following expression "$([\%Cr\theta]/[\%Cr\alpha]) \geq (2.0+[\%Si]\times 10)$".

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## Description

[Technical Field of the Invention]

**[0001]** The present invention relates to a steel wire rod.

**[0002]** Priority is claimed on Japanese Patent Application No. 2014-114429, filed on June 2, 2014, the content of which is incorporated herein by reference.

[Related Art]

**[0003]** In an aluminum stranded cable used for a power line or the like, strands of steel wire are used as a core to reinforce the strength. This stranded cable is generally called "aluminum conductor steel-reinforced cable". Hereinafter, the aluminum conductor steel-reinforced cable will be abbreviated as "ACSR".

**[0004]** In many cases, steel wire used as a core of ACSR is produced by cold drawing a piano wire rod such as SWRS72B or SWRS82B specified in the JIS standard. In order to produce ACSR, as necessary, a heat treatment called patenting or aluminum plating treatment is performed before or during cold drawing.

**[0005]** In ACSR, not only aluminum wire but also steel wire as a core are electrically charged. Therefore, in a case where the electrical resistivity of steel wire increases, the total electrical resistivity of ACSR increases, and thus the amount of heat generated during power transmission is increased. As a result, the transmission efficiency decreases.

**[0006]** In addition, in a case where the strength of steel wire is low, it is necessary that the amount of steel wire having a higher electrical resistivity than aluminum is increased to reinforce the strength. However, since steel wire is also electrically conductive, as a result, the total electrical resistivity of ACSR is increased.

**[0007]** Therefore, steel wire having a low electrical resistivity and a high strength, and a steel wire rod having a low electrical resistivity and a high strength as a material of the steel wire, are required.

**[0008]** In general, the electrical resistivity of steel increases as the amounts of elements in the steel increase. Therefore, in steel disclosed in Patent Document 1, by reducing the amounts of major elements such as C, Mn, or Cr, the electrical resistivity is reduced. However, in this steel, the C content and the Si content in the steel are adjusted to be low in order to reduce the electrical resistivity and to improve cold forgeability. Therefore, the tensile strength is insufficient.

**[0009]** In addition, in a steel sheet for spring disclosed in Patent Document 2, by adjusting the C content, the Si content, and the Mn content in the steel to be lower than a value obtained from a predetermined expression, the electrical resistivity of the steel is reduced. However, since the metallographic structure is not optimized in this steel sheet for spring and does not include Cr, the tensile strength cannot be increased. Therefore, a balance between the securing of strength and the reduction in electrical resistivity is not sufficient.

**[0010]** Further, in hypereutectoid steel wire having high strength and high toughness disclosed in Patent Document 3, by specifying the contents of elements such as C, Si, or Mn in the steel and a metallographic structure thereof, the tensile strength and drawability are secured. However, in the hypereutectoid steel wire having high strength and high toughness, the Si content is 0.5% or more, and a metallographic structure is not optimized to reduce the electrical resistivity. Therefore, the electrical resistivity is high.

**[0011]** Patent Document 4 discloses a high carbon steel wire rod in which the spheroidizing heat treatment time is reduced by increasing the Cr content in a carbide. However, in this high carbon steel wire rod, the Cr content in the carbide is 6.0 mass% or more. Therefore, a reduction in electrical resistivity and an increase in tensile strength cannot be achieved at the same time.

[Prior Art Document]

[Patent Document]

**[0012]**

[Patent Document 1] Japanese Unexamined Patent Application, First Publication No. 2003-226938
[Patent Document 2] Japanese Unexamined Patent Application, First Publication No. 2004-156120
[Patent Document 3] Japanese Unexamined Patent Application, First Publication No. H6-271937
[Patent Document 4] PCT International Publication No. WO 2012/144630

[Disclosure of the Invention]

[Problems to be Solved by the Invention]

**[0013]** The present invention has been made in consideration of the above-described circumstances, and an object thereof is to provide a steel wire rod having a high strength and a low electrical resistivity.

[Means for Solving the Problem]

**[0014]** In a steel wire rod according to the present invention, in particular, the Si content which increases the electrical resistivity is limited, and the Cr content in cementite in pearlite is increased within a range where the electrical resistivity and the tensile strength are well-balanced, and conversely, the Cr content in ferrite in pearlite is reduced. As a result, an increase in electrical resistivity is prevented. In addition, in the steel wire rod according to the present invention, by reducing the average lamellar spacing of pearlite, the tensile strength is increased, and the reduction in the electrical resistivity and the improvement of the tensile strength are achieved at the same time.

**[0015]** The steel wire rod according to the present invention is a material before performing cold drawing, and includes a hot rolled wire rod and a steel obtained by performing a heat treatment on the hot rolled wire rod.

**[0016]** In order to solve the above-described problems and to obtain a steel wire rod having a high strength and a low electrical resistivity, the present inventors performed a detailed investigation and study of the chemical composition, the metallographic structure, and the distribution state of alloy elements in the steel wire rod. As a result, the following findings (a) to (c) were made.

(a) The electrical resistivity of the steel wire rod at room temperature does not substantially change due to cold drawing. Therefore, components of the steel wire rod, a metallographic structure before cold drawing, and a state where alloy elements are present in the steel wire rod have large effects on the electrical resistivity and the tensile strength after cold drawing.

(b) In a case where the Si content and the Cr content are increased, the strength of the steel wire rod increases due to solid solution strengthening. However, an increase in the Si content causes a significant increase in the electrical resistivity. On the other hand, an increase in the Cr content also causes an increase in the electrical resistivity, but Cr has a smaller effect than Si. In addition, when Cr is solid soluted in ferrite, Cr increases the electrical resistivity. Therefore, by increasing the Cr content in cementite and decreasing the Cr content in ferrite, an increase in electrical resistivity can be suppressed. In other words, by increasing the Cr content in cementite in pearlite and decreasing the Cr content in ferrite in pearlite, an increase in the electrical resistivity can be suppressed.

In addition, by controlling the Cr content in cementite according to the Si content contributing to solid solution strengthening, the improvement of the tensile strength and the reduction in the electrical resistivity can be achieved at the same time with high efficiency.

Hereinafter, "the Cr content in cementite in pearlite" will also be referred to simply as "the Cr content in cementite", and "the Cr content in ferrite in pearlite" will also be referred to simply as "the Cr content in ferrite".

(c) In order to achieve the improvement of the tensile strength of the steel wire rod and the reduction in the electrical resistivity of the steel wire rod at the same time, it is effective that the metallographic structure of the steel wire rod includes pearlite. Further, when the metallographic structure of the steel wire rod is pearlite having a lamellar structure of ferrite and cementite, the tensile strength can be improved by reducing the average lamellar spacing. On the other hand, the average lamellar spacing of pearlite has little effect on the electrical resistivity. Therefore, in order to achieve the improvement of the tensile strength and the reduction in the electrical resistivity at the same time, it is preferable that the average lamellar spacing is reduced.

**[0017]** The present invention has been made based on the above findings, and the scope thereof is as follows.

(1) According to an aspect of the present invention, a steel wire rod includes, as a chemical composition, by mass%, C: 0.8% to 1.1%, Si: 0.02% to 0.30%, Mn: 0.1% to 0.6%, Cr: 0.3% to 1.5%, Al: 0.01% to 0.05%, N: limited to 0.008% or less, P: limited to 0.03% or less, S: limited to 0.02% or less, and optionally includes one or more selected from the group consisting of Mo: 0.20% or less, V: 0.15% or less, Ti: 0.050% or less, Nb: 0.050% or less, and B: 0.0030% or less, and a remainder of Fe and impurities; in which a metallographic structure includes a pearlite and an area ratio of the pearlite is 85% or more; an average lamellar spacing of the pearlite is 50 nm to 100 nm; and when the Si content is represented by [%Si] by mass%, the Cr content in a cementite in the pearlite is represented by [%Cr$\theta$] by mass%, and the Cr content in a ferrite in the pearlite is represented by [%Cr$\alpha$] by mass%, [%Si], [%Cr$\theta$], and [%Cr$\alpha$] satisfy the following expression (a),

$$([\%Cr\theta]/[\%Cr\alpha])\geq(2.0+[\%Si]\times 10)\ ...\qquad (a).$$

(2) The steel wire rod according to (1) may include, as the chemical composition, by mass%, one or more selected from the group consisting of Mo: 0.02% to 0.20%, V: 0.02% to 0.15%, Ti: 0.002% to 0.050%, Nb: 0.002% to 0.050%, and B: 0.0003% to 0.0030%.

(3) In the steel wire rod according to (1) or (2), a tensile strength TS of the steel wire rod may be 1350 MPa or more, and an absolute value of the tensile strength TS of the steel wire rod may be 64 times or more an absolute value of an electrical resistivity ρ expressed in units of $\mu\Omega\cdot$cm of the steel wire rod.

[Effects of the Invention]

**[0018]** According to the aspects (1) to (3), a steel wire rod having a high strength and a low electrical resistivity can be provided. In particular, the steel wire rod according to the aspect is suitable as a material of steel wire which is used for reinforcing the strength of a power line and reduces power loss.

**[0019]** In addition, steel wire, which is obtained by cold drawing the steel wire rod according to the aspect and optionally performing the aluminum plating treatment after cold drawing, has a high strength and a low electrical resistivity. Therefore, when ACSR is produced using this steel wire, a predetermined strength can be secured and the electrical resistivity can be further reduced in the ACSR. Therefore, the contribution to the industry is remarkable.

[Embodiment of the Invention]

**[0020]** A steel wire rod according to an embodiment will be described.

**[0021]** First, the reason for limiting a chemical composition of the steel wire rod according to the embodiment will be described. In the following description, % represents mass%.

C: 0.8% to 1.1%

**[0022]** C is an element which is effective for allowing a metallographic structure of the steel wire rod to include pearlite and to thereby improve the tensile strength.

**[0023]** In a case where the C content is less than 0.8%, it is difficult to stably impart a high tensile strength of, for example, 1350 MPa to the steel wire rod. Therefore, the lower limit of the C content is set to 0.8%. In order to obtain more uniform pearlite and to improve the tensile strength, the C content is preferably 0.9% or more and more preferably 1.0% or more.

**[0024]** On the other hand, when the C content is excessively high, the steel wire rod is hardened, and it causes deterioration in drawability. In particular, when the C content is higher than 1.1%, since it is difficult to industrially stably suppress the formation of cementite precipitating along a prior austenite grain boundary, that is, proeutectoid cementite, drawability deteriorates significantly. Therefore, the upper limit of the C content is set to 1.1%.

Si: 0.02% to 0.30%,

**[0025]** Si is an element which is effective for improving the strength of the steel wire rod by solid solution strengthening and is also necessary as a deoxidizer.

**[0026]** When the Si content is less than 0.02%, these effects are not sufficient. Therefore, the lower limit of the Si content is set to 0.02%. In addition, in order to secure the strength by solid solution strengthening and to exhibits the deoxidation effect more stably, the Si content is preferably 0.05% or more.

**[0027]** On the other hand, when the Si content increases, the electrical resistivity increases. In particular, when the Si content is higher than 0.30%, the improvement of the tensile strength and the reduction in the electrical resistivity cannot be achieved at the same time. Therefore, the upper limit of the Si content is set to 0.30%. In order to obtain a lower electrical resistivity, the Si content is preferably 0.20% or less and more preferably 0.10% or less.

Mn: 0.1% to 0.6%

**[0028]** Mn is an element which has effects of improving the strength of the steel wire rod and preventing hot brittleness by fixing S as MnS in the steel wire rod.

**[0029]** When the Mn content is less than 0.1%, these effects are not sufficient. Therefore, the lower limit of the Mn content is set to 0.1%. Further, in order to secure the strength and further prevent hot brittleness, the Mn content is preferably 0.2% or more and is more preferably 0.3% or more.

**[0030]** On the other hand, when the Mn content increases, the electrical resistivity increases. In particular, when the Mn content is higher than 0.6%, the improvement of the tensile strength and the reduction in the electrical resistivity cannot be achieved at the same time. Therefore, the upper limit of the Mn content is set to 0.6%. In order to obtain a lower electrical resistivity, the Mn content is preferably 0.5% or less and is more preferably 0.4% or less.

Cr: 0.3% to 1.5%

**[0031]** Cr has an effect of reducing the average lamellar spacing of pearlite to improve the tensile strength of the steel wire rod. In addition, when Cr is solid soluted in ferrite in pearlite, Cr increases the electrical resistivity. Therefore, an effect of suppressing an increase in electrical resistivity can be obtained by increasing the Cr content in cementite such that the Cr content in ferrite is relatively reduced.

**[0032]** When the Cr content is lower than 0.3%, a sufficient tensile strength of the steel wire rod cannot be secured, and the Cr content in cementite cannot be increased. Therefore, in order to achieve the improvement of the tensile strength and the reduction in the electrical resistivity at the same time, it is necessary that the Cr content is 0.3% or more. In order to obtain a higher tensile strength, the Cr content is preferably 0.4% or more and more preferably 0.5% or more.

**[0033]** On the other hand, when the Cr content is higher than 1.5%, the drawability of the steel wire rod deteriorates. Therefore, the upper limit of the Cr content is set to 1.5%. In order to further suppress deterioration in drawability, the Cr content is preferably 1.0% or less and more preferably 0.8% or less.

Al: 0.01% to 0.05%

**[0034]** Al is an element which has a deoxidation effect and is necessary to reduce the oxygen content in the steel wire rod.

**[0035]** When the Al content is lower than 0.01%, this effect is not sufficient. Therefore, the lower limit of the Al content is set to 0.01%. In order to improve the deoxidation effect, the Al content is preferably 0.02% or more.

**[0036]** On the other hand, Al is an element which forms a hard oxide-based inclusion and deteriorates the ductility of the steel wire rod. In particular, when the Al content is higher than 0.05%, a coarse oxide-based inclusion is likely to be formed. Therefore, the drawability of the steel wire rod deteriorates significantly. Therefore, the upper limit of the Al content is set to 0.05%. In order to further limit deterioration in the drawability of the steel wire rod, the Al content is preferably 0.04% or less and more preferably 0.03% or less.

**[0037]** In the steel wire rod according to the embodiment, it is necessary to limit N, P, and S as described below.

N: 0.008% or less

**[0038]** N is an element which is pinned to dislocations in the steel to deteriorate drawability during cold drawing. In particular, when the N content is higher than 0.008%, the drawability deteriorates significantly. Accordingly, the N content is limited to 0.008% or less. The N content is preferably 0.005% or less and more preferably 0.004% or less.

**[0039]** In addition, the lower limit of the N content may be 0%. However, in consideration of the current refining technique and the production costs, the lower limit of the N content is preferably 0.0001%.

P: 0.03% or less

**[0040]** P is an element which segregates in a grain boundary and deteriorates drawability. In particular, when the P content is higher than 0.03%, the drawability deteriorates significantly. Accordingly, the P content is limited to 0.03% or less. The P content is preferably 0.02% or less and more preferably 0.01% or less.

**[0041]** In addition, the lower limit of the P content may be 0%. However, in consideration of the current refining technique and the production costs, the lower limit of the P content is preferably 0.001%.

S: 0.02% or less

**[0042]** As in P, S is an element which deteriorates drawability. In particular, when the S content is higher than 0.02%, the drawability deteriorates significantly. Accordingly, the S content is limited to 0.02% or less. The S content is preferably 0.01% or less.

**[0043]** In addition, the lower limit of the S content may be 0%. However, in consideration of the current refining technique and the production costs, the lower limit of the S content is preferably 0.001%.

**[0044]** Hereinabove, the basic chemical composition of the steel wire rod according to the embodiment has been described, and the remainder thereof includes iron and impurities. Here, "impurities" described in the expression "the remainder of Fe and impurities" refer to elements which are unavoidably incorporated from raw materials such as ore or scrap or unavoidably incorporated in various production environments, when the steel is industrially produced.

**[0045]** However, in addition to the base elements, the steel wire rod according to the embodiment optionally includes one or more elements selected from the group consisting of Mo, V, Ti, Nb, and B instead of a portion of Fe in the remainder.

Mo: 0.20% or less

**[0046]** The addition of Mo is optional, and the lower limit of the Mo content is 0%.

**[0047]** However, due to the addition of Mo, an effect of improving a balance between the tensile strength and the electrical resistivity of the steel wire rod can be stably obtained. In order to obtain this effect, it is preferable that 0.02% or more of Mo is added. More preferably, the Mo content is 0.05% or more.

**[0048]** On the other hand, when the Mo content is higher than 0.20%, a martensite structure is likely to be formed in the steel, and the drawability may deteriorate. Therefore, the upper limit of the Mo content is preferably 0.20%. More preferably, the upper limit of the Mo content is 0.10%.

V: 0.15% or less

**[0049]** The addition of V is optional, and the lower limit of the V content is 0%.

**[0050]** However, V has an effect of forming a carbide or a carbonitride in the steel wire rod to reduce the pearlite block size. Therefore, due to the addition of V, the drawability can be improved. In order to obtain this effect, it is preferable that 0.02% or more of V is added. More preferably, the V content is 0.05% or more.

**[0051]** On the other hand, when the V content is higher than 0.15%, a coarse carbide or carbonitride is likely to be formed in the steel wire rod, and the drawability may deteriorate. Therefore, the upper limit of the V content is preferably 0.15%. More preferably, the upper limit of the V content is 0.08%.

Ti: 0.050% or less

**[0052]** The addition of Ti is optional, and the lower limit of the Ti content is 0%.

**[0053]** However, Ti has an effect of forming a carbide or a carbonitride in the steel wire rod to reduce the pearlite block size. Therefore, due to the addition of Ti, the drawability can be improved. In order to obtain this effect, it is preferable that 0.002% or more of Ti is added. More preferably, the Ti content is 0.005% or more.

**[0054]** On the other hand, when the Ti content is higher than 0.050%, a coarse carbide or carbonitride is likely to be formed in the steel wire rod, and the drawability may deteriorate. Therefore, the upper limit of the Ti content is preferably 0.050%. More preferably, the upper limit of the Ti content is 0.030%.

Nb: 0.050% or less

**[0055]** The addition of Nb is optional, and the lower limit of the Nb content is 0%.

**[0056]** However, Nb has an effect of forming a carbide or a carbonitride in the steel wire rod to reduce the pearlite block size. Therefore, due to the addition of Nb, the drawability can be improved. In order to obtain this effect, it is preferable that 0.002% or more of Nb is added. More preferably, the Nb content is 0.005% or more.

**[0057]** On the other hand, when the Nb content is higher than 0.050%, a coarse carbide or carbonitride is likely to be formed in the steel wire rod, and the drawability may deteriorate. Therefore, the upper limit of the Nb content is preferably 0.050%. More preferably, the upper limit of the Nb content is 0.020%.

B: 0.0030% or less

**[0058]** The addition of B is optional, and the lower limit of the B content is 0%.

**[0059]** However, B has an effect of binding to N, which is solid soluted in the steel wire rod, to form BN and to thereby reduce solid solution N. Therefore, due to the addition of B, the drawability can be improved. In order to obtain this effect, it is preferable that 0.0003% or more of B is added. More preferably, the B content is 0.0007% or more.

**[0060]** On the other hand, when the B content is higher than 0.0030%, a coarse carbide is likely to be formed in the steel wire rod, and the drawability may deteriorate. Therefore, the upper limit of the B content is preferably 0.0030%. More preferably, the upper limit of the B content is 0.0020%.

**[0061]** Next, a metallographic structure of the steel wire rod according to the embodiment will be described.

**[0062]** The metallographic structure of the steel wire rod according to the embodiment includes pearlite in which ferrite and cementite form a layered lamellar structure. The main metallographic structure of the steel wire rod according to the embodiment is pearlite. Here, "main metallographic structure" refers to a metallographic structure having an area ratio of 85% or more in a C cross section which is perpendicular to a longitudinal direction of the steel wire rod or in a L cross section which is parallel to the longitudinal direction of the steel wire rod. The area ratio of pearlite can be obtained by subtracting an area ratio of a non-pearlite structure from 100%. The area ratio of pearlite is 85% or more and is preferably 90% or more and more preferably 95% or more. The area ratio of pearlite may be 100%.

**[0063]** The remainder in the metallographic structure of the steel wire rod according to the embodiment, that is, a microstructure other than pearlite is a non-pearlite structure including proeutectoid ferrite, bainite, degenerate-pearlite, proeutectoid cementite, or the like. When the area ratio of the non-pearlite structure is higher than 15%, the drawability deteriorates. Therefore, the area ratio of the non-pearlite structure is 15% or less. The area ratio of the non-pearlite structure is preferably 10% or less and more preferably 5% or less. The area ratio of the non-pearlite structure may be 0%.

**[0064]** The area ratio of pearlite can be obtained as follows.

**[0065]** For example, as shown in Examples described below, a C cross section of a sample of the steel wire rod, which is perpendicular to a longitudinal direction of the steel wire rod, is mirror polished and then is etched with nital.

**[0066]** Next, an arbitrary area of the sample etched with nital was imaged using a SEM at a magnification to 5000-fold in ten visual fields. Here, the area per visual field is $3.6\times10^{-4}$ $mm^2$.

**[0067]** Using a SEM image obtained from each of the visual fields, the area ratio of pearlite per visual field can be obtained using a typical image analysis method.

**[0068]** By averaging the obtained area ratios of pearlite in the ten visual fields, the area ratio of pearlite in the steel wire rod can be obtained.

Average Lamellar Spacing of Pearlite: 50 nm to 100 nm

**[0069]** The tensile strength of the steel wire rod can be improved by reducing the average lamellar spacing of the pearlite, as above described. The average lamellar spacing has little effect on the electrical resistivity. Therefore, in order to achieve the improvement of the tensile strength of the steel wire rod and the reduction in the electrical resistivity at the same time, it is necessary to reduce the average lamellar spacing. When the average lamellar spacing of pearlite is higher 100 nm, the effect of improving the tensile strength is not sufficient. Therefore, in the steel wire rod according to the embodiment, in order to obtain this effect, the average lamellar spacing of pearlite is set to 100 nm or less. The average lamellar spacing of pearlite is preferably 75 nm or less.

**[0070]** On the other hand, in order to adjust the average lamellar spacing of pearlite to be less than 50 nm, it is necessary that the transformation is completed at a low temperature. However, when the transformation is completed at a low temperature, the area ratio of the non-pearlite structure such as bainite is higher than 15%, and the drawability of the steel wire rod deteriorates. Therefore, the average lamellar spacing of pearlite is set to 50 nm or more. The average lamellar spacing of pearlite is preferably 55 nm or more.

**[0071]** The average lamellar spacing of pearlite can be measured as follows. For example, as shown in Examples described below, a C cross section of a sample of the steel wire rod is polished and is etched such that pearlite appears. Next, the C cross section on which pearlite appears is imaged with a scanning electron microscope (SEM) in multiple visual fields to obtain metallographic structure images of the sample. Using the obtained metallographic structure images, the average lamellar spacing of pearlite can be measured.

**[0072]** Specifically, the measurement can be performed using the following method. First, metallographic structure images in ten visual fields are obtained using a SEM. In the obtained metallographic structure image in each of the ten visual fields, plural positions where five lamellar spacings can be measured are selected in a range of the visual field where lamellar orientations are aligned. At each of the selected multiple positions, a straight line perpendicular to lamellar is drawn to measure the length of five lamellar spacings. Next, two positions in order from the smallest length of five spacings are selected from the selected multiple positions. At each of the selected two positions, the measured length of five lamellar spacings is divided by 5 to obtain the lamellar spacing at the position. That is, the lamellar spacings at two positions can be obtained from each visual field. The average value of lamellar spacings obtained as described above at 20 positions in total in the ten visual fields can be obtained as "the average lamellar spacing of pearlite" of the sample.

**[0073]** As described above, in order to improve the tensile strength of the steel wire rod, it is effective to reduce the average lamellar spacing of pearlite. In order to reduce the average lamellar spacing of pearlite as described above, it is preferable that pearlitic transformation is completed at a low temperature of about 600°C after setting a cooling rate in a cooling process after hot rolling to be 50 °C/sec or faster.

**[0074]** In pearlite, electricity flows mainly through a ferrite portion. In addition, when Cr is solid soluted in ferrite in pearlite, Cr has an effect of increasing the electrical resistivity. Therefore, if the Cr content in ferrite in pearlite can be reduced, the electrical resistivity can also be reduced. That is, by concentrating Cr into cementite in pearlite such that the Cr content in ferrite in pearlite is relatively reduced, an increase in the electrical resistivity of the steel wire rod can be suppressed. Cr is an element which is likely to be concentrated into cementite in pearlite. Therefore, by controlling heat treatment conditions, the Cr content in cementite in pearlite can be increased, and the Cr content in ferrite in pearlite can be reduced.

**[0075]** In addition, Si is an element contributing to solid solution strengthening. Therefore, when the Si content in the steel wire rod increases, the strength of the steel wire rod can be improved. On the other hand, however, when the Si content in the steel wire rod increases, the electrical resistivity increases. Therefore, according as the Si content increases, a high tensile strength and a low electrical resistivity can be achieved at the same time by increasing the Cr content in cementite in pearlite.

**[0076]** In the steel wire rod according to the embodiment, in order to obtain these effects, it is important that the Si content, the Cr content in cementite in pearlite, and the Cr content in ferrite in pearlite satisfy the following expression (1), by mass%. Here, in the following expression (1), the Si content is represented by [%Si] by mass%, the Cr content in cementite in pearlite is represented by [%Crθ] by mass%, and the Cr content in ferrite in pearlite is represented by [%Crα].

$$([\%Cr\theta]/[\%Cr\alpha]) \geq (2.0+[\%Si]\times 10) \ ... \qquad (1)$$

**[0077]** In the steel wire rod according to the embodiment, by controlling the Cr content in cementite in pearlite according to the Si content contributing to solid solution strengthening such that the expression (1) is satisfied, the improvement of the tensile strength and the reduction in the electrical resistivity can be achieved at the same time.

**[0078]** The Cr content in cementite in pearlite, that is, [%Crθ] in the expression (1) can be obtained, for example, by chemically analyzing a residue extracted by electrolysis. Specifically, the Cr content in cementite in pearlite can be obtained using the following method. First, the steel wire rod according to the embodiment is cut into a size which is suitable for electrolysis, and electrolysis is performed at a current density of 250 to 350 A/m$^2$ using a 10% AA electrolytic solution as general conditions of electrolytic polishing so as to extract a solution. Next, the extracted solution was filtered through a filter having a mesh size of 0.2 μm to obtain a residue. The filtrate, that is, the residue can be obtained by performing a general chemical analysis thereon. Here, as the general chemical analysis, for example, a method of dissolving the residue in an acidic solution and analyzing the solution using ICP atomic emission spectroscopy is included. In the steel wire rod according to the embodiment, metal elements included in cementite in pearlite are Fe, Mn, and Cr. Among these, Fe and Cr are less likely to be extracted from a microstructure other than cementite, and Mn is more likely to form MnS rather than cementite. Therefore, the Cr content in cementite in pearlite, that is, [%Crθ] can be calculated using the following expression (2). Here, in the following expression (2), the Cr content in the residue, the Fe content in the residue, and the Mn content in the residue are represented by [%Residue Cr], [%Residue Fe], and [%Residue Mn] by mass%, respectively, and the S content in the steel wire rod is represented by [%S] by mass%.

$$[\%Cr\theta]=100\times[\%\text{Residue Cr}]/\{[\%\text{Residue Fe}]+[\%\text{Residue Mn}]+[\%\text{Residue Cr}]-[\%S]\times(55/32)\} \ ... \qquad (2)$$

**[0079]** In addition, in order to achieve the improvement of the tensile strength and the reduction in the electrical resistivity, it is preferable that the Cr content in cementite in pearlite is 0.80% to 5.80% by mass%.

**[0080]** Defining that C is less likely to be solid soluted in ferrite, the Cr content in ferrite in pearlite can be calculated based on, for example, the Cr content in the steel wire rod, that is, [%Cr], the Cr content in cementite in pearlite, that is, [%Crθ], and the volume fraction of cementite obtained from the C content, that is, [ϕθ]. Specifically, since C is less likely to be solid soluted in ferrite, it is generally known that the volume fraction of cementite in pearlite can be obtained from the following expression (3). In the following expression (3), the C content is represented by [%C] by mass%, and the volume fraction of cementite in pearlite is represented by [ϕθ0].

**[0081]** In the following expression (3), the coefficient 0.149 can be obtained from 6.69 mass% of C in the composition of cementite and 7.68 g/cm$^3$ of the density of cementite.

$$[\phi\theta]=[\%C]\times 0.149 \ ... \qquad (3)$$

**[0082]** Next, the volume fraction of ferrite in pearlite, that is, [ϕα] is obtained from the following expression (4).

$$[\phi\alpha]=1.0-[\phi\theta] \ ... \qquad (4)$$

**[0083]** In this way, the Cr content in ferrite in pearlite, that is, [%Crα] can be calculated using the following expression (5).

$$[\%\mathrm{Cr}\alpha]=\{[\%\mathrm{Cr}]-([\%\mathrm{Cr}\theta]\times[\phi\theta])\}/[\phi\alpha] \quad \ldots \quad (5)$$

**[0084]** As described above, in order to suppress an increase in the electrical resistivity of the steel wire rod, it is effective to concentrate Cr into cementite. In this way, in order to concentrate Cr into cementite, it is preferable that a wire rod is held at the temperature range after the pearlitic transformation from austenite is completed, and Cr is concentrated into cementite. However, after the pearlitic transformation is completed, when the holding time at the temperature range increases, cementite in pearlite is spheroidized, and the strength of the steel wire rod may deteriorate.

**[0085]** It is preferable that the tensile strength TS of the steel wire rod according to the embodiment is 1350 MPa or more. In addition, an absolute value of the tensile strength TS of the steel wire rod is 64 times or more an absolute value of an electrical resistivity p expressed in units of μΩ·cm.

**[0086]** When the steel wire rod according to the embodiment is applied to a core of ACSR, if the strength of the steel wire rod is low, it may be necessary that the amount of the steel wire rod is increased to reinforce the strength. In this case, it is assumed that the total electrical resistivity of ACSR is increased. Therefore, the tensile strength TS of the steel wire rod according to the embodiment is preferably 1350 MPa or more, more preferably 1400 MPa or more, and still more preferably 1500 MPa or more. By setting the tensile strength TS of the steel wire rod to 1350 MPa or more, for example, in a case where the diameter of the steel wire rod is 11 mm to 5 mm, when the cold drawing is performed at a true strain of 1.6 as a general drawing amount, the tensile strength of the steel wire rod after cold drawing can be set to 1900 MPa or more.

**[0087]** In addition, in the steel wire rod according to the embodiment, from the viewpoint of realizing a high strength and a low electrical resistivity of the steel wire rod at the same time, it is preferable that a relationship between the absolute value of the tensile strength TS and the absolute value of the electrical resistivity p expressed in units of μΩ·cm satisfies the following numerical value range.

**[0088]** Regarding a wire rod which is produced under general hot rolling conditions by using steel having a chemical composition of SWRS72B or SWRS82B specified in JIS G 3502 as a core of general ACSR, the absolute value of the tensile strength TS thereof is about 55 times the absolute value of the electrical resistivity p. The unit of tensile strength of the wire rod is MPa, and the unit of electrical resistivity is μΩ·cm.

**[0089]** Therefore, as described above, with reference to a case where the absolute value of the tensile strength TS of the wire rod is 55 times the absolute value of the electrical resistivity p expressed in units of μΩ·cm, that is, when the value of the tensile strength TS which is 55 times the absolute value of the electrical resistivity p is set as a reference value, it is preferable that the absolute value of the tensile strength TS of the steel wire rod according to the embodiment is 64 times or more the absolute value of the electrical resistivity ρ thereof expressed in units of μΩ·cm so as to be 15% or more of the reference value. In addition, it is more preferable that the absolute value of the tensile strength TS of the steel wire rod according to the embodiment is 67 times the absolute value of the electrical resistivity ρ thereof expressed in units of μΩ·cm so as to be 20% or more of the reference value.

**[0090]** In this way, by setting the tensile strength TS of the steel wire rod to 1350 MPa or more and setting the absolute value of the tensile strength TS of the steel wire rod to be 64 times the absolute value of the electrical resistivity ρ expressed in units of μΩ·cm, the strength of the steel wire rod can be increased, and the electrical resistivity can be reduced. As a result, in a case where the steel wire rod is applied to a core of ACSR, the reinforcement number can be reduced. Further, an increase in the total electrical resistivity of ACSR can be suppressed, the heat generation during power transmission can be suppressed, and a stable transmission efficiency can be secured.

**[0091]** In the steel wire rod according to the embodiment, the absolute value of the electrical resistivity p expressed in units of μΩ·cm is not particularly limited. That is, in the steel wire rod according to the embodiment, it is preferable that the absolute value of the tensile strength TS and the absolute value of the electrical resistivity ρ thereof expressed in units of μΩ·cm satisfy the following expression (6).

$$\text{Absolute Value of Tensile Strength TS} \geq \text{Absolute Value of Electrical resistivity } \rho\times 64 \quad \ldots \quad (6)$$

**[0092]** By setting a steel wire rod so as to satisfy the expression (6), the tensile strength of the steel wire rod can be secured to be significantly higher than that in the prior art. As a result, when the steel wire rod is applied to a core of ACSR to reinforce the strength, the reinforcement number can be reduced, and an increase in the total electrical resistivity of ACSR can be suppressed.

**[0093]** In addition, the lower the electrical resistivity ρ of the steel wire rod according to the embodiment, the better, and the higher the tensile strength TS, the better.

**[0094]** By satisfying the chemical composition and the metallographic structure as described above, a steel wire rod in which the improvement of the strength and the reduction in the electrical resistivity can be achieved at the same time can be obtained. In order to obtain the above-described steel wire rod, the steel wire rod may be produced using a production method described below. Next, a preferable method of producing the steel wire rod according to the embodiment will be described.

**[0095]** The steel wire rod according to the embodiment can be produced as follows. The method of producing the steel wire rod described below is an example of a method of obtaining the steel wire rod according to the embodiment. The present invention is not limited to the following procedure and method, and any method which can realize the configuration of the present invention can be adopted.

**[0096]** First, steel having the above-described chemical composition is melted and continuously cast to produce a billet, and the billet is hot rolled. After continuous casting, blooming may be performed. When the obtained billet is hot rolled, the central part of the billet is heated to 1000°C to 1100°C using a general method, and the finishing temperature is set to be 900°C to 1000°C. After finish rolling, the hot rolled wire rod is primarily cooled to 700°C or less by using a combination of water cooling and wind cooling with air. During this primary cooling, the average cooling rate is preferably 50 °C/sec or faster. After the primary cooling, in order to complete pearlitic transformation, the wire rod is secondarily cooled to 590°C to 620°C by being immersed into a nitrate molten salt at 500°C to 530°C. After the secondary cooling, the wire rod is held in the molten salt at 550°C to 570°C for 30 seconds to 50 seconds. As a result, Cr can be concentrated into cementite. Next, water is sprayed to the wire rod so as to remove the molten salt, the wire rod is tertiarily cooled to room temperature, and is wound. In addition, the winding may be performed immediately after primary cooling or secondary cooling.

**[0097]** In addition, during this secondary cooling, the average cooling rate is preferably 30 °C/sec or faster. In addition, when the wire rod is held after secondary cooling, it is preferable that the wire rod is held in a range of 600°C to 550°C for 30 seconds to 50 seconds. For example, a lead bath or a fluidized bed furnace may be used. In a case where a lead bath is used, the wire rod is not necessarily cooled to 700°C during primary cooling and secondary cooling and holding may be performed in the same lead bath. In this case, it is preferable that the wire rod is held in a lead bath at 550°C to 600°C for 35 seconds to 60 seconds.

**[0098]** As a method of cooling and holding the wire rod after finish rolling, cooling and holding can be performed using only a lead bath. For example, when the temperature of the wire rod after finish rolling is in a range of 900°C to 700°C, in a case where the wire rod is immersed into a lead bath at 640°C to 500°C, the average cooling rate of the wire rod is 100 °C/sec to 200 °C/sec.

**[0099]** In addition, when the temperature of the wire rod after finish rolling is in a range of 700°C to 620°C, in a case where the temperature of a lead bath is 590°C to 600°C, the average cooling rate of the wire rod is 40 °C/sec to 50 °C/sec, in a case where the temperature of a lead bath is 550°C to 560°C, the average cooling rate of the wire rod is 60 °C/sec to 70 °C/sec, and in a case where the temperature of a lead bath is 490°C to 500°C, the average cooling rate of the wire rod is 90 °C/sec to 100 °C/sec.

**[0100]** In addition, the finishing temperature during the hot rolling refers to the surface temperature of the steel wire rod immediately after finish rolling. Further, the average cooling rate during cooling after finish rolling refers to the cooling rate of the surface of the steel wire rod.

[Examples]

**[0101]** Hereinafter, the effects of the steel wire rod according to the embodiment will be described in more detail using examples of the steel wire rod according to the present invention. However, conditions of the examples are merely exemplary to confirm the feasibility and the effects of the present invention, and the present invention is not limited to these examples. The conditions can be appropriately changed within a range where the gist of the present invention can be adapted without departing from the scope of the present invention as long as the object of the present invention can be accomplished. Therefore, the present invention can employ various conditions, and these conditions are included in the technical features of the present invention.

**[0102]** 50kg of each of steels A to Y having a chemical composition shown in Table 1 were melted in vacuum melting furnace and were cast into ingots. The chemical composition of Steel V satisfy SWRS82B of the JIS standard.

**[0103]** Each of the ingots was heated at 1250°C for 1 hour and was hot-forged under a condition of a finishing temperature 950°C or more until the diameter reached 15 mm. Next, the ingot was naturally cooled to room temperature to obtain a hot-forged material. This hot-forged material was cut to obtain a cut material having a diameter of 10 mm and a length of 1000 mm.

**[0104]** Next, each of the obtained cut materials was heated in a nitrogen atmosphere at 1050°C for 15 minutes such that the temperature of the center of the cut material was 1000°C or more. Next, the cut material was hot rolled under a condition of a finishing temperature of 950°C to 1000°C until the diameter thereof reached 7 mm. As a result, a wire rod was obtained. Further, in a state where the temperature of the wire rod was 900°C or more, the wire rod was immersed into a lead bath under conditions shown in Table 2 and was held. Next, the wire rod was taken out from the lead bath and was naturally cooled to room temperature. As a result, a steel wire rod was obtained.

**[0105]** When the temperature of the wire rod after finish rolling was in a range of 900°C to 700°C, in a case where the temperature of the lead bath was 640°C to 500°C, the average cooling rate of the wire rod was 100 °C/sec to 200 °C/sec.

**[0106]** In addition, when the temperature of the wire rod after finish rolling was in a range of 700°C to 620°C, in a case where the temperature of a lead bath was 590°C to 600°C, the average cooling rate of the wire rod was 40 °C/sec to 50 °C/sec, in a case where the temperature of a lead bath was 550°C to 560°C, the average cooling rate of the wire rod was 60 °C/sec to 70 °C/sec, and in a case where the temperature of a lead bath was 490°C to 500°C, the average cooling rate of the wire rod was 90 °C/sec to 100 °C/sec.

**[0107]** For comparison, some of the obtained cut materials were hot rolled to obtain wire rods until the diameters thereof reached 7 mm. Next, these wire rods were cooled to room temperature by naturally cooling in the air or by blowing wind to them using a fan without immersing them in a molten salt or a lead bath. As a result, steel wire rods were obtained. When the wire rod is naturally cooled in the air, in a case where the temperature of the wire rod after finish rolling was 900°C to 700°C, the average cooling rate was 7 °C/sec to 8 °C/sec, and in a case where the temperature of the wire rod after finish rolling was 700°C to 620°C, the average cooling rate was 4 °C/sec to 5 °C/sec. When the wire rod is cooled by blowing wind thereto using a fan, in a case where the temperature of the wire rod after finish rolling was 900°C to 700°C, the average cooling rate was 12 °C/sec to 14 °C/sec, and in a case where the temperature of the wire rod after finish rolling was 700°C to 620°C, the average cooling rate was 6 °C/sec to 7 °C/sec.

**[0108]** The steel wire rods of Test Nos. 1 to 48 which were produced under the above-described respective conditions were evaluated by performing the following tests.

**[0109]** Regarding each of the steel wire rods, a C cross section perpendicular to a longitudinal direction of the steel wire rod was mirror polished and was etched with nital.

**[0110]** In order to obtain an area ratio of pearlite, an arbitrary area of the sample etched with nital was imaged using a SEM at a magnification to 5000-fold in ten visual fields. The area per visual field was $3.6\times10^{-4}$ mm$^2$.

**[0111]** Next, the area ratio of pearlite was obtained from each of the images of the visual fields using a typical image analysis method. The obtained average value of the area ratios of pearlite in the ten visual fields was set as the area ratio of pearlite in the steel wire rod.

**[0112]** In order to obtain an average lamellar spacing of pearlite, an arbitrary area of the sample etched with nital was imaged using a SEM at a magnification to 10000-fold in ten visual fields. The area per visual field was $9.0\times10^{-5}$ mm$^2$.

**[0113]** Next, in each of the images of the visual fields, a range where lamellar orientations of pearlite are aligned was selected. Next, at each of a position having the smallest lamellar spacing and a position having the second smallest lamellar spacing where five lamellar spacings can be measured, a straight line perpendicular to lamellar was drawn to measure the length of five lamellar spacings. Then, the obtained length of the five lamellar spacings was divided by 5. As a result, the lamellar spacing of pearlite at each position was obtained. The obtained average value of lamellar spacings at 20 positions in total in the ten visual fields was set as the average lamellar spacing of pearlite of the steel wire rod.

**[0114]** Each of the steel wire rods was cut into a diameter of 6 mm, and electrolysis is performed at a current density of 250 to 350 A/m$^2$ using a 10% AA electrolytic solution as general conditions of electrolytic polishing so as to extract a solution. Here, the 10% AA electrolytic solution was a methanol solution including 10 vol% of acetyl acetone and 1 mass% of tetramethylammonium chloride. Next, the extracted solution was filtered through a filter having a mesh size of 0.2 μm to obtain a residue, and this residue was dissolved in an acidic solution. By analyzing this solution using ICP atomic emission spectroscopy, the Cr content in the residue [%Residue Cr], the Fe content in the residue [%Residue Fe], and the Mn content in the residue [%Residue Mn] were obtained. The Cr content in cementite in pearlite, that is, [%Crθ] was calculated using the following expression (A). In this case, the following conditions were defined: "metal elements in cementite were substantially Fe, Mn, and Cr"; "Fe and Cr were not extracted from a microstructure other than cementite"; and "in a case where S is included in the steel, Mn formed MnS prior to cementite". Here, in the following expression (A), the Cr content, the Fe content, and the Mn content in the residue are represented by [%Residue Cr], [%Residue Fe], and [%Residue Mn] by mass%, respectively, and the S content in the steel wire rod is represented by [%S] by mass%.

$$[\%\mathrm{Cr}\theta]=100\times[\%\mathrm{Residue\ Cr}]/\{[\%\mathrm{Residue\ Fe}]+[\%\mathrm{Residue\ Mn}]+[\%\mathrm{Residue\ Cr}]-[\%\mathrm{S}]\times(55/32)\} \quad \ldots \quad (\mathrm{A})$$

**[0115]** In addition, the Cr content in ferrite was calculated as follows. First, the volume fraction [ϕθ] of cementite in pearlite was obtained from the following expression (B), and the volume fraction [$\phi\alpha$] of ferrite in pearlite was obtained from the following expression (C). Next, the Cr content in ferrite [%Crα] was calculated from the following expression (D).

**[0116]** In addition, in the following expression (B), the total C content in the steel wire rod is represented by [%C] by mass%. In the following expression (D), the total Cr content in the steel wire rod is represented by [%Cr] by mass%.

$$[\phi\theta]=[\%C]\times 0.153 \quad \ldots \quad (B)$$

$$[\phi\alpha]=1.0-[\phi\theta] \quad \ldots \quad (C)$$

$$[\%Cr\alpha]=\{[\%Cr]-([\%Cr\theta]\times[\phi\theta])\}/[\phi\alpha] \quad \ldots \quad (D)$$

**[0117]** From the central part of the C cross section of each of the steel wire rods, two tensile test pieces having a parallel body with a diameter of 3.2 mm (a circle having a radius of 1.6 mm around the center of the C cross section) and a length of 18 mm were obtained by cutting. Using these tensile test pieces, a tensile test was performed at room temperature using a method according to JIS Z 2241 to measure the tensile strengths TS thereof, and the measured average value of the tensile strengths TS was set as the tensile strength TS of the steel wire rod. Here, the unit of the tensile strength TS is MPa.

**[0118]** As a test piece for measuring the electrical resistivity p, a rectangular test piece having a size of 3.0 mm×4.0 mm×60 mm was obtained from the central part of each of the steel wire rods, and the electrical resistivity of the test piece was measured using a typical four-terminal method at a temperature of 20°C. The unit of the obtained electrical resistivity ρ is μΩ·cm.

**[0119]** The obtained evaluation results are shown in Tables 3 and 4. Here, in Tables 3 and 4, [%Crθ] and [%Crα] represent "the Cr content in cementite in pearlite" and "the Cr content in ferrite in pearlite" by mass%, respectively.

**[0120]** In addition, in Tables 3 and 4, a case where the expression (1) was satisfied was determined as "pass" and shown as "O", and a case where the expression (1) was not satisfied was determined as "fail" and shown as "X".

**[0121]** In addition, the tensile strength TS of the steel wire rod expressed in units of MPa, the absolute value of the electrical resistivity p expressed in units of μΩ·cm, and a value which is 64 times the absolute value of the electrical resistivity p are shown in Tables 3 and 4.

**[0122]** In addition, in Tables 3 and 4, a case where the absolute value of the tensile strength TS was 64 times or more the absolute value of the electrical resistivity ρ expressed in units of μΩ·cm was determined as "good" and shown as "O", and a case where the absolute value of the tensile strength TS was less than 64 times than the absolute value of the electrical resistivity ρ was determined as "bad" and shown as "X".

**[0123]** In Tables 3 and 4, Test Nos. 1, 3, 6, 7, 9 to 11, 14, 17, 18, 20 to 22, 24, 26, 27, 30, 33, 34, 36, and 44 to 47 did not satisfy at least one of the technical features specified in the present invention including the chemical composition, the metallographic structure, the average lamellar spacing of pearlite, the relationship between the Si content, the Cr content in cementite in pearlite, and the Cr content in ferrite in pearlite. In addition, in Test Nos. 45 and 47, the drawability was low.

**[0124]** On the other hand, Test Nos. 2, 4, 5, 8, 12, 13, 15, 16, 19, 23, 25, 28, 29, 31, 32, 35, 37 to 43, and 48 satisfied all of the technical features specified in the present invention including the chemical composition, the metallographic structure, the average lamellar spacing of pearlite, the relationship between the Si content, the Cr content in cementite in pearlite, and the Cr content in ferrite in pearlite.

**[0125]** [Table 1]

## Table 1

| STEEL No. | CHEMICAL COMPOSITION (mass%) | | | | | | | | | | | | | NOTE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Al | N | P | S | Mo | V | Ti | Nb | B | |
| <u>A</u> | <u>0.73</u> | 0.21 | 0.42 | 0.52 | 0.019 | 0.0031 | 0.011 | 0.008 | - | - | - | - | - | COMPARATIVE EXAMPLE |
| B | 0.81 | 0.18 | 0.41 | 0.51 | 0.016 | 0.0035 | 0.013 | 0.007 | - | - | - | - | - | EXAMPLE |
| C | 0.98 | 0.19 | 0.39 | 0.49 | 0.021 | 0.0068 | 0.022 | 0.009 | - | - | - | - | - | EXAMPLE |
| D | 1.08 | 0.20 | 0.41 | 0.52 | 0.015 | 0.0041 | 0.014 | 0.006 | - | - | - | - | - | EXAMPLE |
| E | 0.98 | 0.04 | 0.41 | 0.52 | 0.012 | 0.0027 | 0.012 | 0.006 | - | - | - | - | - | EXAMPLE |
| F | 0.98 | 0.09 | 0.38 | 0.51 | 0.019 | 0.0037 | 0.009 | 0.007 | - | - | - | - | - | EXAMPLE |
| G | 0.98 | 0.30 | 0.40 | 0.49 | 0.021 | 0.0031 | 0.015 | 0.008 | - | - | - | - | - | EXAMPLE |
| <u>H</u> | 0.97 | <u>0.34</u> | 0.39 | 0.49 | 0.014 | 0.0042 | 0.012 | 0.007 | - | - | - | - | - | COMPARATIVE EXAMPLE |
| I | 0.92 | 0.21 | 0.59 | 0.51 | 0.021 | 0.0041 | 0.011 | 0.005 | - | - | - | - | - | EXAMPLE |
| <u>J</u> | 0.93 | 0.19 | <u>0.66</u> | 0.51 | 0.012 | 0.0038 | 0.010 | 0.004 | - | - | - | - | - | COMPARATIVE EXAMPLE |
| <u>K</u> | 1.01 | 0.18 | 0.42 | <u>0.26</u> | 0.024 | 0.0032 | 0.016 | 0.005 | - | - | - | - | - | COMPARATIVE EXAMPLE |
| L | 1.00 | 0.21 | 0.42 | 0.33 | 0.018 | 0.0028 | 0.017 | 0.008 | - | - | - | - | - | EXAMPLE |
| M | 0.93 | 0.08 | 0.29 | 0.81 | 0.022 | 0.0047 | 0.012 | 0.009 | - | - | - | - | - | EXAMPLE |
| N | 0.91 | 0.09 | 0.30 | 1.48 | 0.017 | 0.0031 | 0.009 | 0.006 | - | - | - | - | - | EXAMPLE |
| O | 1.03 | 0.11 | 0.28 | 0.42 | 0.017 | 0.0033 | 0.013 | 0.007 | 0.07 | - | - | - | - | EXAMPLE |
| P | 0.98 | 0.10 | 0.38 | 0.51 | 0.022 | 0.0031 | 0.010 | 0.006 | - | 0.08 | - | - | - | EXAMPLE |
| Q | 0.97 | 0.09 | 0.37 | 0.52 | 0.014 | 0.0030 | 0.012 | 0.005 | - | - | 0.028 | - | - | EXAMPLE |
| R | 0.99 | 0.11 | 0.40 | 0.53 | 0.021 | 0.0038 | 0.011 | 0.008 | - | - | - | 0.015 | - | EXAMPLE |
| S | 1.02 | 0.09 | 0.26 | 0.38 | 0.021 | 0.0031 | 0.014 | 0.007 | 0.06 | - | 0.015 | - | - | EXAMPLE |
| T | 0.98 | 0.09 | 0.41 | 0.49 | 0.024 | 0.0029 | 0.016 | 0.006 | - | - | - | - | 0.0016 | EXAMPLE |
| U | 0.98 | 0.08 | 0.39 | 0.52 | 0.018 | 0.0027 | 0.014 | 0.008 | - | - | 0.025 | - | 0.0014 | EXAMPLE |
| <u>V</u> | 0.82 | 0.21 | <u>0.72</u> | <u>-</u> | 0.021 | 0.0031 | 0.015 | 0.009 | - | - | - | - | - | COMPARATIVE EXAMPLE |
| <u>W</u> | <u>1.18</u> | 0.22 | 0.41 | 0.43 | 0.025 | 0.0030 | 0.010 | 0.007 | - | - | - | - | - | COMPARATIVE EXAMPLE |
| <u>X</u> | 0.92 | 0.21 | 0.49 | <u>1.58</u> | 0.024 | 0.0028 | 0.011 | 0.006 | - | - | - | - | - | COMPARATIVE EXAMPLE |
| <u>Y</u> | 0.95 | 0.22 | 0.47 | 0.48 | <u>0.059</u> | 0.0035 | 0.012 | 0.007 | - | - | - | - | - | COMPARATIVE EXAMPLE |

UNDERLINED NUMERICAL VALUES REPRESENT THAT THEY ARE OUT OF THE RANGE OF THE PRESENT INVENTION.

**[0126]** [Table 2]

Table 2

| CONDITION No. | BATH TEMPERATURE (°C) | HOLDING TIME (sec) |
|---|---|---|
| I | 640 | 45 |
| II | 600 | 35 |
| III | 560 | 45 |
| IV | 500 | 60 |
| V | 600 | 20 |
| VI | 600 | 60 |
| VII | 600 | 180 |
| VIII | NATURALLY COOLING IN AIR | |
| IX | WIND COOLING USING FAN | |

**[0127]** [Table 3]

Table 3

| TEST No. | STEEL No. | CONDITION No. | AREA RATIO OF PEARLITE (%) | AVERAGE LAMELLAR SPACING OF PEARLITE (nm) | [%Cr θ] (mass%) | [%Cr α] (mass%) | [%Cr θ]/[%Cr α] IN LEFT SIDE OF EXPRESSION (1) (-) | 2.0+[%Si]*10 IN RIGHT SIDE OF EXPRESSION (1) (-) | LEFT SIDE ≥ RIGHTSIDE IN EXPRESSION 1 (-) | TENSILE STRENGTH TS (MPa) | ELECTRIC RESISTIVITY ρ (μΩ·cm) | 64 TIMES ABSOLUTE VALUE OF ρ (-) | ABSOLUTE VALUE OF TS≥64 TIMES ABSOLUTE VALUE OF ρ (-) | NOTE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | II | 92 | 108 | 1.56 | 0.39 | 4.0 | 4.1 | × | 1261 | 19.9 | 1274 | × | COMPARATIVE EXAMPLE |
| 2 | B | II | 96 | 92 | 1.54 | 0.36 | 4.3 | 3.8 | ○ | 1358 | 20.2 | 1293 | ○ | EXAMPLE |
| 3 | C | I | 97 | 105 | 1.69 | 0.28 | 6.0 | 3.9 | ○ | 1275 | 20.2 | 1293 | × | COMPARATIVE EXAMPLE |
| 4 | C | II | 96 | 68 | 1.37 | 0.34 | 4.0 | 3.9 | ○ | 1441 | 21.4 | 1370 | ○ | EXAMPLE |
| 5 | C | III | 90 | 59 | 1.36 | 0.34 | 4.0 | 3.9 | ○ | 1479 | 21.8 | 1395 | ○ | EXAMPLE |
| 6 | C | IV | 35 | -*1 | 0.79 | 0.44 | 1.8 | 3.9 | × | 1327 | 21.5 | 1376 | × | COMPARATIVE EXAMPLE |
| 7 | C | V | 96 | 67 | 1.05 | 0.39 | 2.7 | 3.9 | × | 1414 | 22.4 | 1434 | × | COMPARATIVE EXAMPLE |
| 8 | C | VI | 95 | 69 | 1.56 | 0.30 | 5.2 | 3.9 | ○ | 1418 | 21.2 | 1357 | ○ | EXAMPLE |
| 9 | C | VII | 92 | 102 | 1.95 | 0.23 | 8.5 | 3.9 | ○ | 1321 | 21.1 | 1350 | × | COMPARATIVE EXAMPLE |
| 10 | C | VIII | 95 | 163 | 2.33 | 0.17 | 13.7 | 3.9 | ○ | 1124 | 19.7 | 1261 | × | COMPARATIVE EXAMPLE |
| 11 | C | IX | 97 | 139 | 2.20 | 0.19 | 11.6 | 3.9 | ○ | 1181 | 19.9 | 1274 | × | COMPARATIVE EXAMPLE |
| 12 | D | VI | 95 | 52 | 1.63 | 0.30 | 5.4 | 4.0 | ○ | 1565 | 22.9 | 1466 | ○ | EXAMPLE |
| 13 | E | II | 97 | 71 | 1.53 | 0.34 | 4.5 | 2.4 | ○ | 1411 | 20.8 | 1331 | ○ | EXAMPLE |
| 14 | F | I | 97 | 111 | 1.69 | 0.30 | 5.6 | 2.9 | ○ | 1246 | 19.7 | 1261 | × | COMPARATIVE EXAMPLE |
| 15 | F | II | 95 | 70 | 1.31 | 0.37 | 3.5 | 2.9 | ○ | 1417 | 21.2 | 1357 | ○ | EXAMPLE |
| 16 | F | III | 91 | 62 | 1.18 | 0.39 | 3.0 | 2.9 | ○ | 1460 | 21.7 | 1389 | ○ | EXAMPLE |
| 17 | F | IV | 42 | -*1 | 0.79 | 0.46 | 1.7 | 2.9 | × | 1284 | 20.8 | 1331 | × | COMPARATIVE EXAMPLE |
| 18 | F | V | 96 | 70 | 1.13 | 0.40 | 2.8 | 2.9 | × | 1402 | 22.1 | 1414 | × | COMPARATIVE EXAMPLE |
| 19 | F | VI | 94 | 72 | 1.56 | 0.32 | 4.9 | 2.9 | ○ | 1405 | 21.0 | 1344 | ○ | EXAMPLE |
| 20 | F | VII | 92 | 105 | 1.82 | 0.28 | 6.5 | 2.9 | ○ | 1317 | 20.8 | 1331 | × | COMPARATIVE EXAMPLE |
| 21 | F | VIII | 94 | 171 | 2.33 | 0.19 | 12.3 | 2.9 | ○ | 1078 | 19.1 | 1222 | × | COMPARATIVE EXAMPLE |
| 22 | F | IX | 96 | 143 | 2.14 | 0.22 | 9.7 | 2.9 | ○ | 1160 | 19.4 | 1242 | × | COMPARATIVE EXAMPLE |

UNDERLINED NUMERICAL VALUES REPRESENT THAT THEY ARE OUT OF THE RANGE OF THE PRESENT INVENTION.
*1 SINCE BAINITE WAS A MAIN MICROSTRUCTURE, THE AVERAGE LAMELLAR SPACING OF PEARLITE WAS NOT ABLE TO BE MEASURED.

**[0128]** [Table 4]

Table 4

| TEST No. | STEEL No. | CONDITION No. | AREA RATIO OF PEARLITE (%) | AVERAGE LAMELLAR SPACING OF PEARLITE (nm) | [%Cr θ] (mass%) | [%Cr α] (mass%) | [%Cr θ]/[%Cr α] IN LEFT SIDE OF EXPRESSION (1) (-) | 2.0+[%Si]*10 IN RIGHT SIDE OF EXPRESSION (1) (-) | LEFT SIDE ≥ RIGHTSIDE IN EXPRESSION 1 (-) | TENSILE STRENGTH TS (MPa) | ELECTRIC RESISTIVITY ρ (μΩ·cm) | 64 TIMES ABSOLUTE VALUE OF ρ (-) | ABSOLUTE VALUE OF TS≥64 TIMES ABSOLUTE VALUE OF ρ (-) | NOTE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | G | VI | 95 | 68 | 1.63 | 0.29 | 5.6 | 5.0 | ○ | 1455 | 22.2 | 1421 | ○ | EXAMPLE |
| 24 | H | II | 93 | 68 | 1.46 | 0.32 | 4.6 | 5.4 | × | 1447 | 23.1 | 1478 | × | COMPARATIVE EXAMPLE |
| 25 | I | VI | 97 | 74 | 1.56 | 0.34 | 4.6 | 4.1 | ○ | 1412 | 21.5 | 1376 | ○ | EXAMPLE |
| 26 | J | VI | 95 | 74 | 1.60 | 0.33 | 4.8 | 3.9 | ○ | 1399 | 22.0 | 1408 | × | COMPARATIVE EXAMPLE |
| 27 | K | II | 96 | 71 | 0.72 | 0.18 | 4.0 | 3.8 | ○ | 1408 | 22.2 | 1421 | × | COMPARATIVE EXAMPLE |
| 28 | L | II | 95 | 67 | 0.98 | 0.21 | 4.7 | 4.1 | ○ | 1473 | 22.2 | 1421 | ○ | EXAMPLE |
| 29 | L | III | 89 | 61 | 0.92 | 0.22 | 4.2 | 4.1 | ○ | 1527 | 22.6 | 1446 | ○ | EXAMPLE |
| 30 | L | IV | 38 | -*1 | 0.66 | 0.27 | 2.4 | 4.1 | × | 1285 | 22.1 | 1414 | × | COMPARATIVE EXAMPLE |
| 31 | M | II | 96 | 67 | 2.33 | 0.56 | 4.2 | 2.8 | ○ | 1444 | 21.6 | 1382 | ○ | EXAMPLE |
| 32 | M | VI | 95 | 68 | 2.58 | 0.52 | 5.0 | 2.8 | ○ | 1436 | 21.2 | 1357 | ○ | EXAMPLE |
| 33 | M | IX | 96 | 115 | 3.82 | 0.31 | 12.3 | 2.8 | ○ | 1242 | 20.8 | 1331 | × | COMPARATIVE EXAMPLE |
| 34 | N | I | 94 | 103 | 6.21 | 0.72 | 8.6 | 2.9 | ○ | 1281 | 21.0 | 1344 | × | COMPARATIVE EXAMPLE |
| 35 | N | VI | 87 | 67 | 5.62 | 0.81 | 6.9 | 2.9 | ○ | 1477 | 21.9 | 1402 | ○ | EXAMPLE |
| 36 | N | VIII | 93 | 132 | 7.93 | 0.44 | 18.0 | 2.9 | ○ | 1209 | 20.7 | 1325 | × | COMPARATIVE EXAMPLE |
| 37 | O | VI | 94 | 54 | 1.44 | 0.23 | 6.3 | 3.1 | ○ | 1588 | 21.8 | 1395 | ○ | EXAMPLE |
| 38 | P | II | 96 | 60 | 1.50 | 0.34 | 4.4 | 3.0 | ○ | 1566 | 22.1 | 1414 | ○ | EXAMPLE |
| 39 | Q | II | 96 | 61 | 1.50 | 0.35 | 4.3 | 2.9 | ○ | 1528 | 21.9 | 1402 | ○ | EXAMPLE |
| 40 | R | II | 94 | 61 | 1.50 | 0.36 | 4.2 | 3.1 | ○ | 1524 | 21.8 | 1395 | ○ | EXAMPLE |
| 41 | S | VI | 93 | 55 | 1.58 | 0.16 | 9.9 | 2.9 | ○ | 1575 | 21.9 | 1402 | ○ | EXAMPLE |
| 42 | T | II | 95 | 62 | 1.44 | 0.32 | 4.5 | 2.9 | ○ | 1520 | 21.9 | 1402 | ○ | EXAMPLE |
| 43 | U | II | 94 | 56 | 1.46 | 0.35 | 4.2 | 2.8 | ○ | 1531 | 22.1 | 1414 | ○ | EXAMPLE |
| 44 | V | IX | 93 | 153 | - | - | - | 4.1 | × | 1108 | 20.1 | 1286 | × | COMPARATIVE EXAMPLE |
| 45 | W | VI | 88 | 54 | 1.38 | 0.23 | 6.1 | 4.2 | ○ | 1624 | 24.5 | 1568 | ○ | COMPARATIVE EXAMPLE |
| 46 | X | II | 47 | -*2 | 3.60 | 1.26 | 2.9 | 4.1 | × | 1327 | 22.4 | 1434 | × | COMPARATIVE EXAMPLE |
| 47 | Y | VI | 95 | 58 | 1.64 | 0.29 | 5.7 | 4.2 | ○ | 1518 | 22.3 | 1427 | ○ | COMPARATIVE EXAMPLE |
| 48 | D | II | 96 | 52 | 1.42 | 0.35 | 4.1 | 4.0 | ○ | 1572 | 24.8 | 1587 | × | EXAMPLE |

UNDERLINED NUMERICAL VALUES REPRESENT THAT THEY ARE OUT OF THE RANGE OF THE PRESENT INVENTION.
*1 SINCE BAINITE WAS A MAIN MICROSTRUCTURE, THE AVERAGE LAMELLAR SPACING OF PEARLITE WAS NOT ABLE TO BE MEASURED.
*2 SINCE MARTENSITE WAS A MAIN MICROSTRUCTURE, THE AVERAGE LAMELLAR SPACING OF PEARLITE WAS NOT ABLE TO BE MEASURED.

[Industrial Applicability]

**[0129]** According to the present invention, a steel wire rod having a high strength and a low electrical resistivity can be obtained, which remarkably contributes to the industry.

## Claims

1. A steel wire rod comprising, as a chemical composition, by mass%,
C: 0.8% to 1.1%,
Si: 0.02% to 0.30%,
Mn: 0.1% to 0.6%,
Cr: 0.3% to 1.5%,
Al: 0.01% to 0.05%,
N: limited to 0.008% or less,
P: limited to 0.03% or less,
S: limited to 0.02% or less, and
optionally including one or more selected from the group consisting of Mo: 0.20% or less,
V: 0.15% or less,
Ti: 0.050% or less,
Nb: 0.050% or less, and
B: 0.0030% or less, and
a remainder of Fe and impurities;
wherein a metallographic structure includes a pearlite and an area ratio of the pearlite is 85% or more;
an average lamellar spacing of the pearlite is 50 nm to 100 nm, and
when the Si content is represented by [%Si] by mass%, the Cr content in a cementite in the pearlite is represented by [%Crθ] by mass%, and the Cr content in a ferrite in the pearlite is represented by [%Crα] by mass%, [%Si], [%Crθ], and [%Crα] satisfy the following expression (1),

$$([\%Cr\theta]/[\%Cr\alpha]) \geq (2.0+[\%Si]\times 10)\ \ldots \qquad (1).$$

2. The steel wire rod according to claim 1 comprising, as the chemical composition, by mass%,
one or more selected from the group consisting of
Mo: 0.02% to 0.20%,
V: 0.02% to 0.15%,
Ti: 0.002% to 0.050%,
Nb: 0.002% to 0.050%, and
B: 0.0003% to 0.0030%.

3. The steel wire rod according to claim 1 or 2,
wherein a tensile strength TS of the steel wire rod is 1350 MPa or more, and
an absolute value of the tensile strength TS of the steel wire rod is 64 times or more an absolute value of an electrical resistivity ρ expressed in units of μΩ·cm of the steel wire rod.

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2015/065897

A. CLASSIFICATION OF SUBJECT MATTER
*C22C38/00*(2006.01)i, *C21D8/06*(2006.01)i, *C21D9/52*(2006.01)i, *C22C38/32*(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)
C22C38/00-38/60, 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. |
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| A | JP 6-322480 A (Sumitomo Metal Industries, Ltd.), 22 November 1994 (22.11.1994), examples; paragraph [0047] & US 5458699 A & EP 624658 A1 | 1-3 |

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

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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 21 August 2015 (21.08.15) | 01 September 2015 (01.09.15) |

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

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**INTERNATIONAL SEARCH REPORT**

International application No. PCT/JP2015/065897

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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## REFERENCES CITED IN THE DESCRIPTION

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