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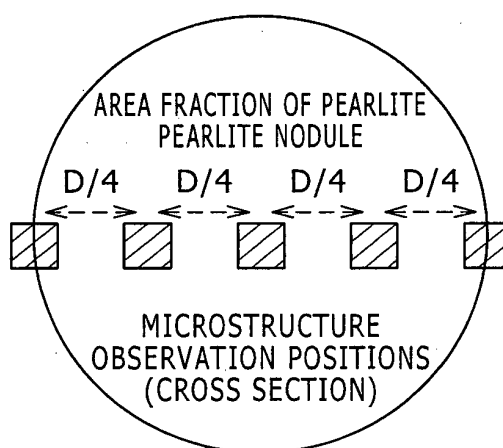
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(54) **STEEL WIRE ROD WITH EXCELLENT SHAVABILITY FOR HIGH-STRENGTH SPRING, AND HIGH-STRENGTH SPRING**

(57) This steel wire rod for a high-strength spring is a hot-rolled steel wire rod which has a prescribed chemical composition and a texture such that the area fraction of pearlite is 90% or more; and the average grain size number of pearlite nodules, namely Pave, satisfies the relationship (1) $6.0 \leq Pave \leq 12.0$. In the hot-rolled steel wire rod, the total decarburized depth of the surface layer is 0.20 mm or less, and the content of Cr-based alloy carbides is 7.5% or lower relative to the mass of the steel wire rod. The wire rod for a high strength spring and a high-strength spring obtained using the same as the raw material exhibit excellent shavability and ensure excellent discharge of shavings and excellent SV processing which is not accompanied with the breaking of wire.

FIG. 2



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Description

Technical Field

[0001] The present invention relates to a steel wire rod for a high-strength spring that is usable as material for the high-strength springs (especially, valve spring) used in parts of vehicles, including a clutch, an engine, a fuel injector, a suspension mechanism, and the like, and also to a high-strength spring using the steel wire rod for a high-strength spring. More particularly, the present invention is directed to a steel wire rod for a high-strength spring that can exhibit excellent shavability in a shaving process.

Background Art

[0002] Springs applied under the environment described above are used with a high stress applied thereto over a long time of period. For this reason, such springs are required to have high fatigue resistance. In order to improve the fatigue resistance, it is required to impart the excellent surface properties to the spring, and to appropriately control inclusions in the spring. Regarding the surface properties, the spring molded is subjected to a planarization process and a hardening process by shot peening, nitriding, or the like. When a flaw on the order of several tens of micrometers in size remains or occurs in the spring, a break might be caused starting from the surface flaw in use of the spring.

[0003] Thus, a shaving process (hereinafter referred to as a "SV process") is performed to remove a decarburized part of a surface layer of the wire rod having been rolled, and a fine flaw on the surface layer of the wire rod. The SV process is a process which involves cutting the surface layer of the wire rod over its entire periphery in a depth direction by about several hundreds of micrometers using a chipper die. A wire rod having unsatisfactory SV workability (shavability) might be broken in the SV process, which disadvantageously results in a crack of the chipper die, an uneven surface of the wire rod, a shorter life time of a tool, and the like. Further, a breaker is provided for improving the discharge of shavings produced by minutely cutting the wire rod. In cutting the wire rod having the unsatisfactory SV workability, the shavings might be stuck in the breaker, excessively increasing a load on motor for driving the breaker. As a result, the device might sometimes stop, which decreases the yield of products or wire rods.

[0004] Improvement of the SV workability of a wire rod can significantly increase the yield of the wire rods and improve the quality of the wire rod. The mainstream techniques for improving the SV workability include control of the microstructure of the wire rod, control of the composition of inclusions, and the like. Various types of such techniques have been already proposed.

[0005] For example, Patent Literature (PTL) 1 has proposed that the shavability of a wire rod is improved by making austenite crystal grain size coarse. However, in order to achieve a spring steel with high fatigue strength, the steel needs to be formed of fine crystal grains. Moreover, taking into consideration the productivity, including the SV workability, wire-drawing workability, and the like, the crystal grains of the wire rod preferably have a fine grain size.

[0006] As disclosed in PTL 2, the composition of an oxide-based inclusion, and the size and distribution density of the oxide-based inclusion existing in the surface layer can be defined to improve the SV workability. However, the alloy-based carbide or nitride which significantly influences the ductility and toughness of the microstructure tends to cause the reduction in the SV workability at present.

[0007] On the other hand, PTL 3 has proposed that the SV workability is improved by defining the mechanical characteristics of steel. In the technique, however, the amount of added alloys is so much that a spring steel includes precipitation of alloy-based carbides or nitrides in a large amount. As a result, the spring steel can satisfy only the mechanical characteristics, but cannot improve the SV workability.

Citation List

Patent Document

[0008]

PTL 1: Japanese Unexamined Patent Publication No. 2000-256785

PTL 2: Japanese Unexamined Patent Publication No. 2010-222604

PTL3: Japanese Unexamined Patent Publication No. 2000-239797

Summary of Invention

Technical Problem

[0009] In particular, spring valves are required to have a high fatigue strength and a high fatigue life. In order to satisfy these characteristics, a spring needs to have good surface properties. The SV process is performed on the spring so as to remove a decarburized layer or surface flaw of a rolled rod. The SV process includes a skin pass step of enhancing the circularity of the rolled rod to prevent side cutting, and a shaving step of shaving using a chipper die. It is necessary that cooling conditions for rolling on a conveyor are properly controlled to prevent a rolled rod microstructure from containing a supercooled phase (bainite, martensite).

[0010] The shaving process with the chipper die requires that the overall length of a coil having a weight of 2 tons can be shaved with a stable surface quality, for example, with no mark made by the die. For this reason, the rolled rod microstructure needs to have excellent shavability. For example, the rolled rod microstructure does not contain a supercooled phase that might cause break of a wire. Additionally, the chipper die needs to be less likely to be cracked, and a load on a tool should be small. Shavings generated when shaving the wire rod with the chipper die are discharged by being cut finely by a breaker. Thus, the shavings needs to be easily cut by the breaker, that is, the wire rod needs to have excellent discharge of shavings.

[0011] The present invention has been made in order to solve such problems in the related art. The object of the present invention is to provide a wire rod for a high-strength spring that can exhibit the excellent SV workability without any break of the wire in an SV process, while having excellent shavability and discharging property of shavings, and also to provide a high-strength spring obtained by using such a wiring rod for a high-strength spring as material.

Solution to Problem

[0012] The present invention has achieved the objects described above, and provides a steel wire rod for a high-strength spring, which is a steel wire rod having been hot-rolled. The steel wire rod includes as a chemical composition: C in a content of 0.4% or more and less than 1.2%; Si in a content of 1.5% to 3.0%; Mn in a content of 0.5% to 1.5%; Cr in a content of 0.02% to 0.5%; and Al in a content of 0.010% or less, in mass percent, with the remainder being iron and inevitable impurities, wherein the steel wire rod has a phase with an area fraction of pearlite of 90% or more, an average grain size number P_{ave} of pearlite nodules satisfies the following formula (1), a total decarburized depth of the surface layer is 0.20 mm or less, and a content of Cr-based alloy carbides is 7.5% or less relative to a mass of the steel wire rod:

$$6.0 \leq P_{ave} \leq 12.0 \quad \dots \quad (1).$$

[0013] The steel wire rod for a high-strength spring according to the present invention further effectively includes: at least one of (a) V in a content of 0.5% or less (excluding 0%), and Nb in a content of 0.5% or less (excluding 0%); (b) Mo in a content of 0.5% or less (excluding 0%); (c) Ni in a content of 1.0% or less (excluding 0%); (d) Cu in a content of 0.5% or less (excluding 0%); and (e) B in a content of 0.010% or less (excluding 0%), as necessary. Accordingly, the characteristics of the steel wire rod for a high-strength spring can be improved depending on the components included therein.

[0014] The present invention includes a high-strength spring obtained from the steel wire rod for a high-strength spring described above.

Advantageous Effects of Invention

[0015] The present invention optimizes the manufacturing conditions by appropriately adjusting the chemical composition so as to form a microstructure having an area fraction of pearlite of 90% or more, to set an average grain size number P_{ave} of pearlite nodules in a predetermined range, and to control the total decarburized depth of the surface layer and the content of Cr-based alloy carbides. Accordingly, the present invention can achieve the steel wire rod for a high-strength spring that can exhibit the excellent SV workability without any break of the wire in the SV process, while having excellent shavability and discharging property of shavings. Such a steel wire rod for a high-strength spring is very useful as the material for manufacturing a high-strength spring.

Brief Description of Drawings

[0016]

[Fig. 1] Fig. 1 is an explanatory diagram showing a sampling method (ring division positions) of samples for evaluation.
 [Fig. 2] Fig. 2 is an exemplary cross-sectional view showing a microstructure observation position of a wire rod.
 [Fig. 3] Fig. 3 is an exemplary cross-sectional view showing surface decarbonization observation position of the wire rod.
 [Fig. 4] Fig. 4 is a graph showing variations in current through a breaker in a test No. 2 (example of the invention).
 [Fig. 5] Fig. 5 is a graph showing variations in breaker current in a test No. 27 (comparative example).

Description of Embodiments

[0017] The inventors have studied the characteristics of steel wire rods for a high-strength spring to achieve the above objects from various points of view. As a result, it has been revealed that a chemical composition and microstructure of a rolled rod, the grain size number of pearlite nodules, a decarburized depth of a surface layer, and a Cr-based alloy carbide content of the rolled rod surface layer are appropriately controlled to provide a steel wire rod that can drastically improve the SV workability without any break of the wire in an SV process, while having excellent shavability and discharging property of shavings. The shavability and the discharge property of shavings are hereinafter referred to as the "SV workability". Now, requirements specified by the invention will be described.

[Microstructure with area fraction of pearlite of 90% or more]

[0018] The steel wire rod (steel wire rod obtained after hot-rolling: rolled wire rod) of the invention has a microstructure with an area fraction of pearlite of 90 % or more. The rolled wire rod having the microstructure with an area fraction of pearlite of 90% or more means a rolled wire rod in which an area fraction of ferrite and supercooled phases formed of bainite and martensite that occupy a cross section of the rolled wire rod is 10% or less. The rolled wire rod having an area fraction of pearlite of 90% or more can be subjected to the SV processing while having no break of the wire during the SV processing. In contrast, if a rolled wire rod has a supercooled phase containing bainite, martensite, and the like at an area fraction of 10% or more, the rolled wire rod will have the reduced ductility/toughness, and as a result, might degrade the SV workability, for example, might be broken in the SV processing.

[0019] Ferrite does not reduce the SV workability so much as the supercooled phases of bainite, martensite, or the like, and may be partly contained in the wire rod microstructure. If the ferrite content of the steel wire rod is excessive, however, the microstructure of the wire rod becomes heterogeneous, which is not preferable in terms of the SV workability. From this aspect, in the steel wire rod of the invention, an area fraction of pearlite is preferably 90 area% or more. The area fraction of pearlite is more preferably 92 area% or more (most preferably, 95 area% or more).

[Average grain size number of pearlite nodules P_{ave} : $6.0 \leq P_{ave} \leq 12.0$]

[0020] An average grain size number of pearlite nodules (hereinafter sometimes referred to as a "pearlite nodule size") P_{ave} significantly affects the ductility of the rolled wire rod. A rolled wire rod with a small pearlite nodule size has poor ductility, which might cause a break of the wire in the SV processing. As the pearlite nodule size becomes larger, the ductility of the wire is improved. However, to make the pearlite nodules much finer, a rolling temperature in the hot rolling is required to be excessively reduced, and cooling equipment with an excessive heating capacity is necessary for rapid cooling. Thus, this is difficult to implement in real life. From this aspect, the average pearlite nodule size P_{ave} is set to satisfy the following formula:

$$6.0 \leq P_{ave} \leq 12.0, \text{ preferably, } 7.0 \leq P_{ave} \leq 11.0.$$

[Total decarburized depth of surface layer: 0.20 mm or less]

[0021] A decarburized surface layer is normally removed by the SV process. However, when the decarburized surface layer is deep, the ductility of shavings generated in the SV process becomes higher, which results in deterioration of separability of shavings by the chip breaker and reduction in discharge of the shavings, thereby degrading the SV workability. Further, the deep decarburized surface layer is likely to remain even after the SV process, which drastically reduces a fatigue strength of a spring. Accordingly, the total decarburized depth of the surface layer is set to 0.20 mm

or less, and preferably 0.15 mm or less (more preferably, 0.10 mm or less).

[Content of Cr-based alloy carbides relative to mass of steel wire rod ≤ 7.5 mass%]

[0022] Cr-based alloy carbides are much harder than iron-based carbides. Thus, even a small amount of Cr-based alloy carbides causes cracks of a tip of a chipper blade, which reduces a life time of a chipper die and the discharge of shavings, thereby degrading the SV workability. Accordingly, an upper limit of the Cr-based alloy carbide content relative to the entire mass of steel wire rod is set to 7.5 mass%. The Cr-based alloy carbide content is preferably 5.0 % or less (more preferably, 4.0 % or less). The Cr-based alloy carbides of interest in the invention are carbides that basically contain Cr as a principal component. When the steel wire rod further contains a carbide formation element, such as V, Nb, or Mo, the Cr-based alloy carbides may contain a composite alloy carbide thereof. The Cr-based alloy carbides sometimes contain a very small amount of nitride or carbonitride.

[0023] To manufacture such a steel wire rod for a high-strength spring described above, manufacturing conditions also need to be appropriately controlled. The procedure for manufacturing the steel wire rod for a high-strength spring will be as follows. First, a steel billet having a predetermined chemical composition is hot-rolled into a desired wire diameter. An excessively high heating temperature in rolling makes the wire rod microstructure brittle due to an increase in grain size of a prior austenite, thereby reducing the SV workability. In contrast, an excessively low heating temperature increases a deformation resistance of the steel rod, causing a high load on a rolling machine, which leads to reduction of the productivity. Thus, the heating temperature before the rolling is preferably not less than 900°C nor more than 1100°C, and more preferably not less than 950°C nor more than 1050°C.

[0024] Subsequently, the steel wire rod having been hot-rolled is placed in the form of coil on a cooling conveyor. When the temperature at this time (placing temperature) exceeds 1100°C, the prior austenite grain size is increased to make the grains of the prior austenite coarse, which might cause the brittleness of the microstructure together with the grain coarsening of the pearlite nodules. On the other hand, when the placing temperature is below 860°C, the decarburized surface layer is more likely to be deep, which might increase the deformation resistance, leading to a defect in the winding shape. Accordingly, the placing temperature is preferably in a range of 860°C to 1100°C. The placing temperature can be controlled in such a range to thereby suppress the grain coarsening of the pearlite nodules and the formation of the decarburized surface layer. The placing temperature is more preferably in a range of not less than 900°C nor more than 1050°C.

[0025] After placing the steel wire rod on the conveyor, the rolled steel wire rod is cooled down to 600°C at an average cooling rate of 1.0°C/sec or more (preferably, 3.5°C/sec or more) and 10°C/sec or less (preferably, at 8°C/sec), which is an end temperature of pearlite transformation, whereby a rolled steel microstructure having a phase containing pearlite as a principal element is obtained while preventing the grain coarsening of the pearlite nodules. Sequentially, the steel wire rod is cooled in a temperature range decreasing from less than 600°C to 400°C at the average cooling rate of 3°C/sec or more (preferably, 3.5°C/sec or more) and 10°C/sec or less (preferably, 8°C/sec or less), and then continuously cooled to 400°C or less (preferably, 375°C or less), whereby the rolled steel wire rod with excellent SV workability can be obtained while preventing the precipitation of Cr-based alloy carbides in the phase containing pearlite as the principal element.

[0026] The steel wire rod for a high-strength spring in the invention needs to have its chemical composition controlled appropriately so as to exhibit the characteristics of a final product (specifically, a high-strength spring). The range of content of each of components (elements) in the chemical composition is specified for the following reason.

[C: 0.4% or more and less than 1.2%]

[0027] Carbon (C) element is effective for ensuring the strength basically required for steel and increasing the strength and settling resistance of a spring produced from the steel. For this reason, the carbon content needs to be 0.4% or more. The strength and settling resistance of the spring is improved as the carbon content is increased. However, if the carbon content is excessive, the coarse cementite will precipitate in a great amount, which reduces the ductility/toughness of the wire rod, thus adversely affecting the workability and characteristics of the spring. From this aspect, the carbon content needs to be less than 1.2%. The lower limit of carbon content is preferably 0.5% or more, and the upper limit of carbon content is preferably 1.0% or less.

[Si: 1.5% to 3.0%]

[0028] Silicon (Si) element is necessary for deoxidation of the steel and also for ensuring the strength, hardness, and settling resistance of the spring. To exhibit these effects, the Si content needs to be 1.5% or more. If the Si content is excessive, however, the steel is hardened, and additionally, the ductility/toughness of the steel wire rod is reduced, and the amount of the decarburized surface layer is increased, which degrades the SV workability and the fatigue properties

of the steel wire rod. Accordingly, the Si content needs to be 3.0% or less. The lower limit of Si content is preferably 1.6% or more (more preferably, 1.7% or more), and the upper limit of Si content is preferably 2.8% or less (more preferably, 2.5% or less).

5 [Mn: 0.5% to 1.5%]

[0029] Manganese (Mn) element is also necessary for deoxidation of the steel, as with Si, and increases the hardenability to contribute to improve the spring strength in addition to fixing S element in the steel as a compound MnS. To exhibit these effects, the Mn content needs to be 0.5% or more. If the Mn content is excessive, however, the hardenability of the steel wire rod becomes excessively high, which allows the supercooled phase of martensite, bainite, and the like to be easily formed. Accordingly, the Mn content needs to be 1.5% or less. The lower limit of Mn content is preferably 0.6% or more (more preferably, 0.7% or more), and the upper limit of Mn content is preferably 1.4% or less (more preferably, 1.3% or less).

15 [Cr: 0.02% to 0.5%]

[0030] Chromium (Cr) element improves the spring strength by enhancing the hardenability and the resistance to temper softening, and effectively reduces the activity of carbon to thereby prevent decarburization upon rolling and heat treatment. If the Cr content is excessive, however, the Cr-based alloy carbides, nitride, and carbonitride are precipitated much, thus degrading the SV workability. Accordingly, the Cr content needs to be 0.5% or less (preferably, the upper limit of Cr content is 0.45% or less, (more preferably, 0.40% or less)). To exhibit the above effects, the Cr content is 0.02% or more. The lower limit of Cr content is preferably 0.05% or more (more preferably, 0.10% or more).

25 [Al: 0.010% or less]

[0031] Aluminum (Al) element is a deoxidizing element, and forms an Al_2O_3 inclusion and an AlN inclusion in the steel. Such inclusions significantly reduce the fatigue life of the spring. For this reason, the Al content should be reduced as much as possible. From this aspect, the Al content needs to be 0.010% or less, preferably 0.008% or less, and more preferably 0.005% or less.

30 **[0032]** Basic components of the steel wire rod for a high-strength spring according to the present invention have been described above, in which the remainder includes iron and inevitable impurities (for example, P, S, and the like). The steel wire rod for a high-strength spring in the present invention may contain at least one of (a) V in a content of 0.5% or less (excluding 0%), and Nb in a content of 0.5% or less (excluding 0%); (b) Mo in a content of 0.5% or less (excluding 0%); (c) Ni in a content of 1.0% or less (excluding 0%); (d) Cu in a content of 0.5% or less (excluding 0%); and (e) B in a content of 0.010% or less (excluding 0%), as necessary. Accordingly, the characteristics of the steel wire rod are improved depending on the components included therein. The preferable range of content of each of components (elements) in the chemical composition is specified for the following reason.

40 [At least one of V: 0.5% or less (excluding 0%), and Nb: 0.5% or less (excluding 0%)]

[0033] Both vanadium (V) and niobium (Nb) elements have the effect of making the crystal grains finer in the hot-rolling process as well as the quenching-tempering process, to thereby improve the ductility/toughness of the steel wire rod. Among them, vanadium (V) element effectively contributes to improve the spring strength due to secondary precipitation hardening induced in stress relief annealing after molding of the spring. If the V content is excessive, however, composite alloy carbides containing the V or Nb element and the Cr element are precipitated in a large amount, which degrades the SV workability. Accordingly, each of the V content and the Nb content is preferably 0.5% or less. To exhibit the effects described above, the lower limit of each of V and Nb content is preferably 0.05% or more (more preferably, 0.10% or more), and the upper limit thereof is preferably 0.45% or less (more preferably, 0.40% or less).

50 [Mo: 0.5% or less (excluding 0%)]

[0034] Molybdenum (Mo) element effectively contributes to improve the spring strength due to secondary precipitation hardening induced in stress relief annealing after molding of the spring. If the Mo content is excessive, however, composite alloy carbides containing the Mo element and Cr element are precipitated in a large amount, which degrades the SV workability. Accordingly, the Mo content is preferably 0.5% or less. To exhibit the above effects, the Mo content is preferably 0.05% or more. The lower limit of Mo content is preferably 0.10% or more, and the upper limit of Mo content is preferably 0.45% or less (more preferably 0.40% or less).

[Ni: 1.0% or less (excluding 0%)]

[0035] Nickel (Ni) element contributes to improve the ductility/toughness and resistance to corrosion after the quenching-tempering process, while suppressing the decarbonization in the hot-rolling process. If the Ni content is excessive, however, the hardenability is excessively improved, whereby a supercooled phase containing martensite, bainite, and the like are more likely to be formed. Further, in the quenching-tempering process of the manufacturing procedure of an oil tempered wire (OT wire), retained austenite is formed in an excessively large amount, which might drastically reduce the settling resistance of the spring. Accordingly, the Ni content is preferably 1.0% or less. The lower limit of Ni content is preferably 0.05% or more (more preferably, 0.10% or more), and the upper limit of Ni content is preferably 0.9% or less (more preferably, 0.8% or less).

[Cu: 0.5% or less (excluding 0%)]

[0036] Copper (Cu) element contributes to improve the corrosion resistance, while suppressing the decarbonization in the hot-rolling process. If the Cu content is excessive, however, the hot ductility of the steel wire rod is reduced to possibly cause a crack in the hot-rolling process. Accordingly, the additive amount of Cu is preferably 0.5% or less. The lower limit of Cu content is preferably 0.05% or more (more preferably, 0.1% or more), and the upper limit of Cu content is preferably 0.45% or less (more preferably, 0.40% or less).

[B: 0.010% or less (excluding 0%)]

[0037] Boron (B) element effectively improves the hardenability and also improves the ductility/toughness by cleaning the austenite grain boundary. If the B content is excessive, however, composite compounds of Fe and B are precipitated to possibly cause cracks in the hot-rolling process. The hardenability is excessively improved, whereby the supercooled phase containing martensite, bainite, and the like are more likely to be formed. Accordingly, the B content is preferably 0.010% or less. The lower limit of B content is preferably 0.0010% or more (more preferably 0.0015% or more, and most preferably, 0.0020% or more), and the upper limit of B content is preferably 0.0080% or less (more preferably, 0.0060% or less).

[0038] The high-strength steel wire rod of the invention is intended to be obtained after the hot-rolling process. Further, such a high-strength steel wire rod will be subjected to shaving, annealing, pre-wire-drawing (pickling), wire-drawing, coiling, quenching-tempering, surface treatment, and the like to thereby form the high-strength spring. The thus-obtained high-strength spring exhibits the excellent characteristics.

EXAMPLES

[0039] The present invention will be described in more detail using experimental examples below. It should be noted that, however, these examples are never construed to limit the scope of the invention; and various modifications and changes may be made without departing from the scope and spirit of the invention and should be considered to be within the scope of the invention.

[0040] Steel ingots having chemical compositions given in the following Tables 1 and 2 were made in a converter and then bloomed into steel billets having a cross section of 155 mm by 155 mm. The steel billets were heated to 1000°C and hot-rolled. Then, the rolled steel was cooled at conveyor placing temperatures given in Tables 3 and 4 (that is, placing temperature after the hot-rolling) at an average cooling rate (specifically, at average cooling rates in a range from the placing temperature to 600°C, and in another range from a temperature less than 600°C to 400°C), thereby producing coils having a diameter of 8.0 mm and an individual weight of 2 ton (test No. 1 to No. 31).

[Table 1]

Steel	Chemical compositions* (in mass%)										
	C	Si	Mn	Ni	Cr	V	Cu	Mo	Nb	B	Al
A	0.81	1.56	0.75	-	0.22	-	-	-	-	-	0.003
B	0.69	1.89	0.81	-	0.06	-	-	-	-	-	0.004
C	0.55	2.11	1.05	-	0.16	-	-	-	-	-	0.002
D	1.12	1.89	0.79	-	0.33	-	0.34	-	-	-	0.003
E	0.44	2.09	0.93	0.25	0.47	-	-	-	0.0031	0.0031	0.003

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(continued)

Steel	Chemical compositions* (in mass%)										
	C	Si	Mn	Ni	Cr	V	Cu	Mo	Nb	B	Al
F	0.78	2.51	1.38	0.22	0.31	-	-	0.22	-	-	0.002
G	0.61	2.01	1.05	-	0.29	0.22	-	-	-	-	0.006
H	0.83	1.82	0.77	-	0.11	-	0.18	-	0.41	-	0.003
I	0.77	2.51	1.40	-	0.08	-	-	-	0.23	-	0.003
J	0.71	1.85	0.68	-	0.22	0.18	-	-	-	0.0051	0.004
K	0.63	2.81	1.13	0.71	0.37	0.41	-	-	-	-	0.003
L	0.53	1.77	0.81	-	0.28	-	0.41	-	0.08	-	0.002
M	0.49	1.66	0.88	0.42	0.16	-	-	0.18	-	-	0.002
N	0.58	1.95	1.00	-	0.18	-	0.22	-	-0.0037	0.0037	0.003
O	0.62	2.31	1.28	-	0.06	0.08	-	-	-	0.0024	0.005
* The remainder being iron and inevitable impurities											

[Table 2]

Steel	Chemical compositions* (in mass%)										
	C	Si	Mn	Ni	Cr	V	Cu	Mo	Nb	B	Al
B1	0.69	1.89	0.81	-	0.06	-	-	-	-	-	0.004
B2	0.69	1.89	0.81	-	0.06	-	-	-	-	-	0.004
C1	0.55	2.11	1.05	-	0.16	-	-	-	-	-	0.002
C2	0.55	2.11	1.05	-	0.16	-	-	-	-	-	0.002
E1	0.44	2.09	0.93	0.25	0.47	-	-	-	-	0.0031	0.004
G1	0.61	2.01	1.05	-	0.29	0.22	-	-	-	-	0.003
G2	0.61	2.01	1.05	-	0.29	0.22	-	-	-	-	0.002
L1	0.53	1.77	0.81	-	0.28	-	0.41	-	0.08	-	0.002
P	0.71	3.22	1.12	-	0.35	-	-	0.31	-	-	0.001
G	0.84	1.76	1.72	-	0.18	0.08	0.22	-	0.15	-	0.002
R	0.88	2.05	1.13	1.21	0.27	0.22	-	-	-	0.0035	0.003
S	0.58	1.95	0.81	-	0.71	-	-	0.21	-	0.0028	0.005
T	0.68	1.66	0.98	0.31	0.41	0.75	0.21	-	0.19	-	0.003
U	0.47	2.51	1.41	0.12	0.08	-	-	0.75	-	-	0.008
V	0.73	1.88	1.05	-	0.34	0.18	-	-	0.65	-	0.005
W	0.59	1.86	0.61	-	0.18	0.17	-	-	0.34	0.0135	0.003
* The remainder being iron and inevitable impurities											

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[Table 3]

Test No.	Steel	Placing temperature after rolling (°C)	Average cooling rate (°C/sec)	
			From placing temperature to 600°C	From less than 600°C to 400°C
1	A	950	2.5	4.0
2	B	900	3.0	3.5
3	C	890	3.5	4.0
4	D	940	3.5	3.5
5	E	1030	6.5	5.0
6	F	910	2.0	3.5
7	G	880	4.0	4.0
8	H	930	4.0	4.0
9	I	930	3.5	7.0
10	J	910	4.0	5.0
11	K	960	5.0	3.5
12	L	900	3.5	4.0
13	M	890	3.5	4.0
14	N	910	3.0	5.0
15	O	900	4.0	3.5

[Table 4]

Test No.	Steel	Placing temperature after rolling (°C)	Average cooling rate (°C/sec)	
			From placing temperature to 600°C	From less than 600°C to 400°C
16	B1	1130	4.0	3.5
17	B2	840	3.0	5.
18	C1	920	0.5	5.0
19	C2	930	3.0	2.0
20	E1	910	11.5	4.0
21	G1	950	0.5	3.5
22	G2	910	3.0	1.5
23	L1	920	4.0	11.0
24	P	880	3.5	4.0
25	Q	910	3.0	6.5
26	R	890	2.5	3.5
27	S	950	4.0	4.5
28	T	940	3.0	3.5
29	U	920	3.5	4.5
30	V	890	2.5	3.5
31	W	880	3.0	4.5

[0041] Then, each of the thus-obtained coils was examined on its pearlite area fraction, pearlite nodule size, total decarburized depth of the surface layer, a content of Cr-based alloy carbide, and SV workabilities. In examination of the SV workability, each coil examined had the entire weight of 2 tons. Regarding properties other than the SV workability, each one ring was cut from an end of each 2 ton coil for examination of each kind of workability, and then the ring was separated into 8 parts in its circumferential direction (corresponding to 8 parts in the longitudinal direction of the wire rod) as shown in Fig. 1 to produce samples. The measured values of the respective samples were averaged to determine a representative value of each coil.

[0042] As shown in Fig. 2 (which is a cross-sectional view exemplarily showing the microstructure observation positions), the pearlite area fractions of the respective 8 parts of the rolled wire rod were measured using a light microscope at a surface layer (two fields of view) of each part and in positions of D/4 thereof (where D represents the diameter of the wire rod: two fields of view) and D/2 thereof (the center between the above-mentioned D/4 positions: one fields of view) (that is, five fields of view in total). In more detail, the hot-rolled wire rod was embedded in an appropriate material or the like and its cross section was polished and subjected to chemical corrosion using picric acid. Then, images of the wire rod microstructure in a region of 200 μm x 200 μm were taken by the light microscope under a magnification of 400 times. Each image was binarized using an image analysis software ("image pro plus" manufactured by Media Cybernetics, inc.), whereby pearlite area fractions in the images were determined and then calculated to obtain an average pearlite area fraction. In this way, the pearlite area fractions in the respective five fields of view for each of the eight parts were determined and averaged to thereby calculate the average pearlite area fraction per coil. In the presence of a decarburized surface layer, the whole decarburized parts defined under JIS G0558-4 were omitted from the parts of interest for measurement. Herein, P indicates a phase having a pearlite area fraction of 90% or more, and "P + B + M" or "B + M" represents the formation of bainite or martensite together with the pearlite phase having a pearlite area fraction of less than 90%.

[0043] As shown in Fig. 2, the pearlite nodule sizes of the respective 8 parts of the rolled wire rod were measured using a light microscope at a surface layer (two fields of view) of each part and in positions of D/4 thereof (where D represents the diameter of the wire rod: two fields of view) and D/2 thereof (the center between the above-mentioned D/4 positions: one fields of view) (that is, five fields of view in total). As used herein, the term "pearlite nodule" refers to a region in which ferrite grains of the pearlite phase have the same orientation. The measurement method for the pearlite nodules are as follows. First, the hot-rolled wire rod of each coil was embedded in an appropriate material, and its cross section was polished and then subjected to corrosion using a mixture of a concentrated nitric acid solution (62%): alcohol = 1 : 100 (in volume ratio) (at this time, pearlite nodule grains seemed to emerge from the section due to a difference in amount of corrosion from that on the crystal surface of the ferrite grain), whereby the grain size number of the pearlite nodules was measured. Specifically, the grain size numbers of the pearlite nodules in five fields of view of each of 8 parts were measured, and averaged to thereby calculate an average value Pave of the pearlite nodule size every coil. The grain size number of the pearlite nodules was measured in conformance with "Measurement of Austenite grain number" defined by JISG0551.

[0044] As shown in Fig. 3 (which is a cross-sectional view exemplarily showing decarburization observation positions), the total decarburized depth of the layers were measured at 8 points of the surface layer of each of the 8 parts of the hot-rolled wire rod by use of the light microscopy. Specifically, the hot-rolled wire rod was embedded in the appropriate material, and its cross section was polished, and then subjected to chemical corrosion using picric acid and observed. The maximum depth among 8 points was measured at each part, and further the deepest total decarburized depth of the layer among the 8 parts was defined as the total decarburized depth of the layer of the coil. The total decarburized depth of the layer was determined in conformance with "Measurement of depth of decarburized layer of steel" defined by JISG0558.

[0045] The amount of Cr-based alloy carbides was determined by electrolytic extraction. First, scales of the rolled wire rod of each sample were removed with a sandpaper and washed with acetone. Then, the sample was immersed in an electrolytic solution (for example, an ethanol solution containing acetylacetone in a content of 10 mass%) (whereby the electrolytic quantity from the wire rod surface layer was set to approximately 0.4 to 0.5 g, and then the sample was taken). Then, metal Fe of a mother phase was decomposed by electric current, and alloy deposits (carbides, and nitrides and carbonitrides in a small amount) of the steel existing in the electrolytic solution were taken as residues. Thus, the content of Cr-based alloy carbides (by mass%) was determined by dividing the mass of residues by the electrolytic quantity. The alloy deposits measured include mainly Cr-based alloy carbides, but may also contain a composite alloy carbide of Cr and V, Nb, Mo, or the like upon adding a selected element. As a filter for taking the residue, a filter with a mesh diameter of 0.1 μm (for example, a membrane filter manufactured by Advantec Toyo Kaisha, Ltd) was used.

[0046] The SV workability was evaluated in the following manner. A sample coil was subjected to a SV process without a heat treatment, and then the SV workability was evaluated by the presence or absence of a break in the SV process, the load on the breaker that is installed on an inlet side of a chipper die to cut shavings, the presence or absence of a crack in the chipper die, and the like.

[Evaluation criteria of SV workability]

[0047]

(1) Presence or absence of break: In applying the SV process to an entire coil having a weight of 2 tons, a coil that did not get a break was evaluated as the good SV workability, indicated by O, and a coil that got one or more breaks was evaluated as the bad SV workability, indicated by x.

(2) Load on breaker: Variations in current (from 0 to 10 A) through the breaker for each coil was measured at intervals of 1 sec for sampling by use of a data logger. In the SV process, data on the coil except for TOP and BOT thereof each having a weight of 10 kg was used. A coil in which any part of 60-point moving average of measured data did not exceed 9 A was evaluated as the good SV workability, indicated by O, and a coil in which a part of 60-point moving average of measured data exceeded 9A was evaluated as the bad SV workability, indicated by x (see Figs. 4 and 5 to be described later).

(3) Crack of chipper die: The whole coil having a weight of 2 tons was subjected to the SV process, followed by removing the chipper die. The presence or absence of cracks in a wire contact part of the chipper die was checked by a stereoscopic microscope. A coil that did not cause any crack (crack of the chipper) in the wire contact part of the chipper die was evaluated as the good SV workability, indicated by O, and a coil that caused a crack in the wire contact part of the chipper die was evaluated as the bad SV workability, indicated by x.

[0048] The evaluation results are shown in Tables 5 and 6 below together with the rolled wire rod microstructures (pearlite area fraction, average size Pave of pearlite nodules), and the content of Cr-based alloy carbides.

[Table 5]

Test No.	Steel	Rolled wire rod microstructure		Total decarburized depth (mm)	Cr-based alloy carbide content (in mass%)	SV workability		
		Main microstructure**	Pave			Presence or absence of break	Load on breaker	Crack of chipper
1	A	P	8.5	0.07	3.8	○	○	○
2	B	P	8.0	0.11	1.1	○	○	○
3	C	P	9.5	0.08	2.6	○	○	○
4	D	P	9.5	0.06	5.2	○	○	○
5	E	P	9.0	0.05	3.8	○	○	○
6	F	P	9.5	0.09	4.2	○	○	○
7	G	P	11.0	0.15	2.5	○	○	○
8	H	P	8.5	0.04	1.8	○	○	○
9	I	P	8.5	0.10	1.3	○	○	○
10	J	P	8.5	0.07	3.5	○	○	○
11	K	P	9.5	0.06	4.6	○	○	○
12	L	p	9.5	0.11	2.7	○	○	○
13	M	P	9.0	0.11	2.1	○	○	○
14	N	P	9.5	0.09	1.6	○	○	○
15	O	P	9.0	0.11	0.9	○	○	○
**: P: Pearlite								

[Table 6]

Test No.	Steel	Rolled wire rod microstructure		Total decarburized depth (mm)	Cr-based alloy carbide content (in mass%)	SV workability		
		Main microstructure**	Pave			Presence or absence of break	Load on breaker	Crack of chipper
16	B1	P	5.5	0.05	1.1	×	-	-
17	B2	P	8.5	0.24	1.3	○	×	○
18	C1	P	5.5	0.10	2.8	×	-	-
19	C2	P	9.5	0.08	9.1	○	×	×
20	E1	B+M	-	0.01	0.2	×	-	-
21	G1	P	5.5	0.12	5.7	×	-	-
22	G2	P	9.0	0.14	8.5	○	×	×
23	L1	P+B+M	10.5	0.12	1.1	×	-	-
24	P	P	9.5	0.28	3.7	○	×	○
25	Q	P+B+M	9.0	0.05	2.3	×	-	-
26	R	P+B+M	9.5	0.07	4.8	×	-	-
27	S	P	10.0	0.14	10.8	○	×	×
28	T	P	10.5	0.06	9.5	○	×	×
29	U	P	9.0	0.08	9.7	○	×	×
30	V	P	10.0	0.11	10.5	○	×	×
31	W	P+B+M	9.0	0.16	2.8	×	-	-

** : P: Pearlite, B: Bainite, M: Martensite

[0049] Samples of Test No. 1 to No. 15 (see Table 5) satisfied the requirements defined by the invention. Samples of Test No. 16 to No. 23 (see Table 6) satisfied the required chemical compositions (steels B1, B2, C1, C2, E1, G1, G2, and L1), but did not satisfy the manufacturing conditions required to obtain the steel of the invention. Samples of Test No. 24 to No. 31 (see Table 6) had the chemical compositions (steels P to W) departing from the scope of the invention.

[0050] These results can lead to the following conclusion. First, the samples of Tests No. 1 to 15 satisfied the requirements defined by the invention. There steel wire rods got very good results regarding all items on the SV workability (including the presence or absence of the break, the load on the breaker, and the crack of the chipper).

[0051] In contrast, the sample of Test No. 16 was placed at the high placing temperature after the rolling. As a result, this sample had coarse pearlite nodules of the rolled rod microstructure and got a break in the SV process. The sample of Test No. 17 was placed at the low placing temperature after the rolling. As a result, this sample had the deep decarburized surface layer in the rolled wire rod, leading to an increase in load on the breaker.

[0052] The samples of Test No. 18 and 21 were cooled at low average cooling rate down to a temperature of 600°C after being placed on the conveyor. As a result, these samples had the coarse pearlite nodules of the rolled rod microstructure, and got a break in the SV process. The samples of Test No. 19 and 22 were cooled at a low average cooling rate in a range decreasing from a temperature lower than 600°C to 400°C. As a result, the content of Cr-based alloy carbides contained in these samples was increased, leading to an increase in load on the breaker with a crack occurring in a chipper.

[0053] The sample of Test No. 20 was cooled at a high average cooling rate down to 600°C after being placed on the conveyor. As a result, the resultant steel wire rod of the sample did not become a single pearlite phase, and a martensite or bainite phase was formed in the steel wire rod, whereby the sample got a break in the SV process. The sample of Test No. 23 was cooled at a high average cooling rate in a range decreasing from a temperature lower than 600°C to 400°C. As a result, the resultant steel wire rod of the sample did not become a single pearlite phase, and a martensite or bainite phase was formed in the steel wire rod, whereby the sample got a break in the SV process.

[0054] The sample of Test No. 24 used the steel (steel P shown in Table 2) in which a Si content was excessive, so that the total decarburized depth of the surface layer of the rolled steel wire rod was very deep, resulting in an increase in load on the breaker.

[0055] The samples of Test No. 25, 26, and 31 were examples using steels (steels Q, R, and W shown in Table 2) in which a content of each component (Mn, Ni, B) was excessive. As a result, the resultant steel wire rod of each of these samples had the excessively increased hardenability, and did not become a single pearlite phase, and a martensite or bainite phase was formed in the steel wire rod, whereby these samples got a break in the SV process.

[0056] The samples of Test No. 27 to No. 30 were examples using steels (steels S, T, U, and V shown in Table 2) in which a content of each component (Cr, V, Mo, Nb) was excessive. As a result, the resultant steel wire rod of each of these samples had increased content of Cr-based alloy carbides, leading to an increase in load on the breaker with a crack occurring in a chipper.

[0057] Fig. 4 illustrates variations in current through the breaker in the sample of Test No. 2 (example of the invention), and showed that the current values were stable. In contrast, Fig. 5 illustrates variations in current through the breaker in the sample of Test No. 27 (comparative example), and shows that the load on the breaker partly increased (specifically, the load on breaker as illustrated in a part enclosed by a broken line in the figure was high and the current value in the part was large).

Claims

1. A steel wire rod for high-strength springs, the steel wire rod having been hot-rolled and exhibiting excellent shavability, the steel wire rod comprising, as a chemical composition: C in a content of 0.4% or more and less than 1.2%; Si in a content of 1.5% to 3.0%; Mn in a content of 0.5% to 1.5%; Cr in a content of 0.02% to 0.5%; and Al in a content of 0.010% or less, in mass percent, with the remainder being iron and inevitable impurities, wherein the steel wire rod has a microstructure with an area fraction of pearlite of 90% or more, an average grain size number P_{ave} of pearlite nodules satisfies the following formula (1), a total decarburized depth of the surface layer is 0.20 mm or less, and a content of Cr-based alloy carbides is 7.5% or less relative to an entire mass of the steel wire rod:

$$6.0 \leq P_{ave} \leq 12.0 \quad \dots \quad (1).$$

2. The steel wire rod for high-strength springs according to claim 1, further comprising at least one of V in a content of 0.5% or less (excluding 0%), and Nb in a content of 0.5% or less (excluding 0%).
3. The steel wire rod for high-strength springs according to claim 1, further comprising Mo: 0.5% or less (excluding 0%).
4. The steel wire rod for high-strength springs according to claim 1, further comprising Ni: 1.0% or less (excluding 0%).
5. The steel wire rod for high-strength springs according to claim 1, further comprising Cu: 0.5% or less (excluding 0%).
6. The steel wire rod for high-strength springs according to claim 1, further comprising B: 0.010% or less (excluding 0%).
7. A high-strength spring obtained using the steel wire rod for high-strength springs according to any one of claims 1 to 6.

FIG. 1

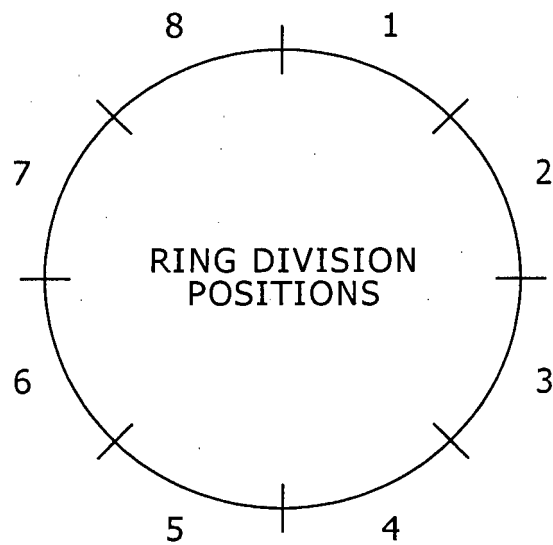


FIG. 2

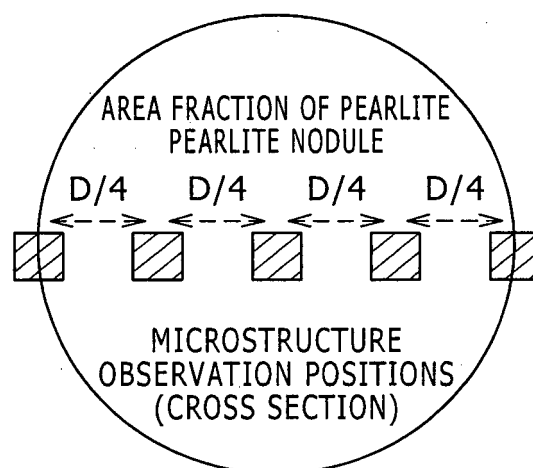


FIG. 3

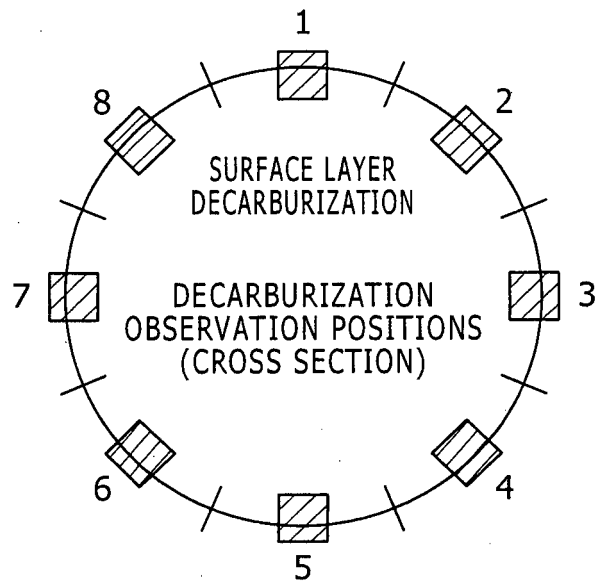


FIG. 4

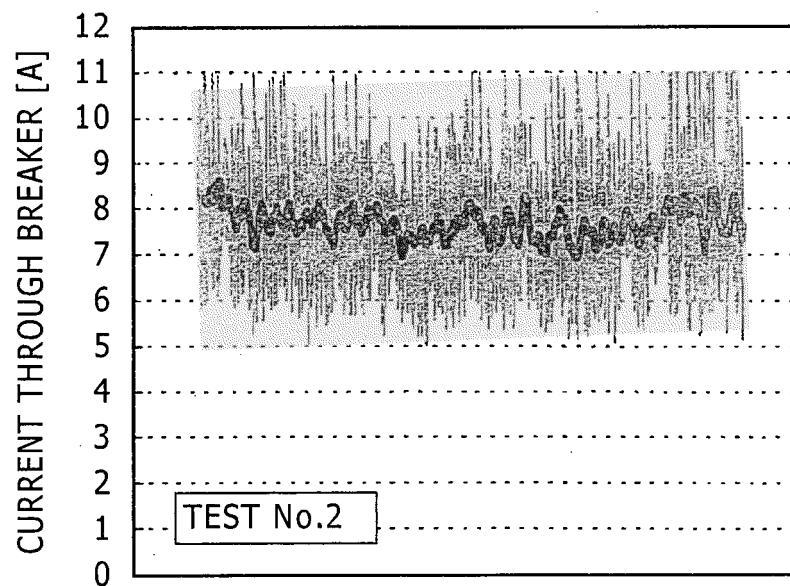
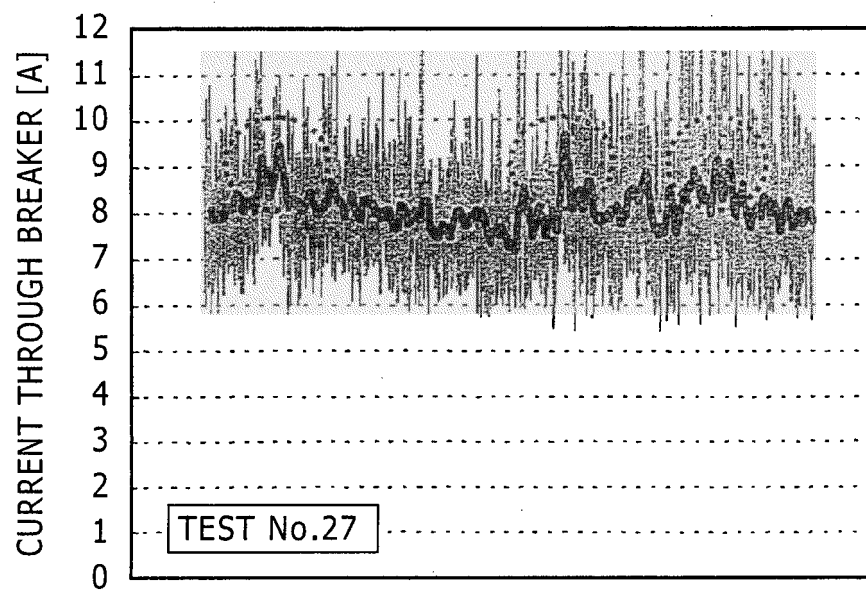


FIG. 5



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2013/058564

A. CLASSIFICATION OF SUBJECT MATTER

C22C38/34(2006.01)i, C22C38/54(2006.01)i, F16F1/02(2006.01)i, C21D8/06(2006.01)n

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C38/00-38/60, F16F1/02, C21D8/06

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 1996-2013
Kokai Jitsuyo Shinan Koho 1971-2013 Toroku Jitsuyo Shinan Koho 1994-2013

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2012/029812 A1 (Kobe Steel, Ltd.), 08 March 2012 (08.03.2012), claims; table 1 & JP 2012-72492 A	1-7
A	JP 2009-46763 A (Kobe Steel, Ltd.), 05 March 2009 (05.03.2009), claims; tables 1, 2 & US 2009/0020189 A1 & EP 2017358 A2	1-7
A	JP 7-173577 A (Kobe Steel, Ltd.), 11 July 1995 (11.07.1995), claims & US 5508002 A & EP 657557 A1	1-7

☒ 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

13 May, 2013 (13.05.13)

Date of mailing of the international search report

21 May, 2013 (21.05.13)

Name and mailing address of the ISA/
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INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2013/058564

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 11-199977 A (Kobe Steel, Ltd.), 27 July 1999 (27.07.1999), claims; table 2 (Family: none)	1-7

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

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2000256785 A [0008]
- JP 2010222604 A [0008]
- JP 2000239797 A [0008]