

PC STEEL WIRE OR ROD

The present invention relates to a PC steel wire or rod to be used as a reinforcement for a PC pile or a PC pole prepared by autoclave curing method, and more particularly, to improvements in its straightness and pressure-formability.

In recent years, the use of PC steel wires or rods having a low relaxation has been keenly desired in PC piles or PC poles produced by autoclave curing method. Known methods for reducing relaxation can be roughly divided into two groups, i.e., a method which comprises the addition of alloy elements to a steel wire or rod material to exert an effect of intensifying solid solution or deposition, and a method which comprises tensile working or bending working to intensify strain aging, as disclosed in JP-B-51-7145 and JP-B-62-49334 (The term "JP-B" as used herein means an "examined Japanese patent publication"). More recently, these methods have been used in combination, for example, the improved method disclosed in JP-A-64-65232 (The term "JP-A" as used herein means an "unexamined published Japanese patent application").

When the relaxation is drastically reduced by the conventional methods, PC steel wires or rods produced

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particularly by heat treatment are seriously disadvantageous in that they suffer from deterioration of straightness, pressure-formability, etc.

The straightness is a property defined by the height of warpage of a PC steel wire or rod having a length of 1.5 meter. In a heat treatment process including working in a hot zone, straightness can hardly be given to PC steel wires or rods. These PC steel wires or steel rods thus have a poor straightness before being wound. Further, since PC steel wires or rods are stored wound in a coil, they suffer from deterioration of straightness with the passage of time due to curling. Therefore, the deterioration of straightness becomes larger when the outdoor temperature is higher, e.g., in the summer season. Steel materials having a poor straightness cannot smoothly roll over an inclined table in a cutting machine and a terminal working machine in the production of PC piles or PC poles and thus can be caught by the machine or come off the conveyor roll. As a result, these steel materials often terminate the operation of unmanned automatic working machine, impairing the production efficiency.

The pressure-formability indicates the mechanical properties of hot- and pressure-formed portion (head portion) as an anchorage with which a PC steel wire or rod is prestressed. In this respect, prior art PC steel wires or rods have the following disadvantages: A large amount of



silicon is incorporated in the steel material as an alloy element for the purpose of improving the relaxation properties thereof. Therefore, the working properties, including electrical conductivity, are changed, making the mechanical properties of the pressure-formed portion unstable. In some detail, the pressure-formed portion sometimes undergoes brittle fracture shortly before or after the predetermined stretching load is reached upon. This accident is a serious problem that not only makes a PC pile or pole to turn out a failure but also jeopardizes the safety of workers involved in stretching. The present invention has been worked out to solve these problems.

An object of the present invention is to provide a PC steel wire or rod having an excellent straightness and pressure-formability.

The above and other objects of the present invention can be accomplished by a PC steel wire or rod having an excellent straightness and pressure-formability, the wire or rod being prepared by a process which comprises:

heating a steel wire or rod;

annealing the wire or rod while being simultaneously provided with a tensile stress of from 6 to 14% of the proportional limit at the ambient temperature and a minute bending strain of from 0.1 to 0.5% of the proportional limit

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at the ambient temperature, in the annealing temperature range or in a cooling step; and

quenching the wire or rod,

the steel wire or rod comprising 0.20 to 0.40% by weight of C, 1.00 to 1.40% by weight of Si, 0.60 to 0.90% by weight of Mn, 0.04 to 0.06% by weight of Mo, 0.10 to 0.30% by weight of Cr, and the balance of iron, with unavoidable impurities.

Fig. 1 is a schematic diagram of an apparatus for producing the product of the present invention;

Fig. 2 is a graph illustrating the straightness change with time after winding in a coil; and

Fig. 3 is a graph illustrating the pattern of load-elongation curves developed when the pressure-formed portion is fractured.

Numeral 1 denotes a pinch roll; 2 denotes a hardening heater; 3 denotes a water-cooling nozzle; 4 denotes a pinch roll; 5 denotes an annealing heater; 6 denotes a vertical direction correcting roll; 7 denotes a longitudinal direction correcting roll; 8 denotes a water-cooling nozzle; and 9 denotes a pinch roll. Symbol W denotes a steel material.

In the present invention, the improvement of relaxation is accomplished by the technique developed by the present inventors, as disclosed in JP-A-64-65232, which

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features that the continuous application of a small tensile stress and a minute bending strain the material in the annealing temperature range or in a cooling step provides a synergistic effect of the tensile stress and the bending strain that drastically improves the anti-high temperature relaxation characteristics. Further, since the bending of the material can be minimized, the reduction of uniform elongation and straightness can be prevented. Thus, the resulting uniform elongation and straightness are more than 3.5% and less than 2.5 mm, respectively, attaining a high quality. In other words, a countermeasure has been attained for straightness in hot working.

The present invention attains further improvements in straightness and pressure-formability by improving the composition of the material of the steel wire or rod on the basis of the foregoing technique.

The improvement in straightness is accomplished on the basis of a knowledge that when a slight amount of alloy elements capable of improving the hardenability of the material is incorporated in the material paying attention to straightness developed upon hardening, a uniform hardenability can be obtained, attaining an excellent straightness. The incorporation of these alloy elements keeps the level of straightness high and minimizes the dispersion of straightness shortly before working in the hot

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range, i.e., annealing range, making it possible to improve the straightness before winding.

Further, a countermeasure has been considered against the deterioration of straightness due to curling after winding on the basis of a knowledge that the curling is attributed to a fully-decarbonized layer produced annularly on the product. That is, the content of Si is reduced to suppress the production of a fully-decarbonized layer and hence inhibit the deterioration of straightness.

With respect to the improvement of pressure-formability, the pressure-formed portion which is susceptible to brittle fracture under low load. As a result, it has been found that both the breaking load and breaking extension are remarkably small on the load-extension curve of the pressure-formed portion. Thus, elements useful for the improvement of high temperature strength and fracture toughness of the pressure-formed portion are incorporated in the material to improve the mechanical properties thereof.

The composition of the steel material for the steel wire or rod will be described hereinafter.

The content of C (carbon) is from 0.20 to 0.40% by weight. If the content of carbon falls below 0.20% by weight, a strength necessary for hardening cannot be obtained. If the content of carbon exceeds 0.40% by weight, it deteriorates the weldability and toughness of the product.

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The content of Si (silicon) is from 1.00 to 1.40% by weight. The increase in the content of Si thermodynamically gives a rise to the carbon activity and thus helps cause decarbonization. Therefore, the content of Si is made less than that of conventional low relaxation products (1.5 to 2.0% by weight). If this content falls below 1.00% by weight, the high temperature relaxation value of the product gets above the upper limit (8%) after autoclaving. If this content exceeds 1.40% by weight, a fully-decarbonized layer is annularly formed on the products, causing a deterioration in the straightness thereof after winding.

The content of Mn (manganese) is from 0.60 to 0.90% by weight. Mn not only is an element necessary as a deoxidizer but also enhances the strength of the material upon quenching.

The content of Cr (chromium) is from 0.10 to 0.30% by weight. Cr enhances the hardenability upon quenching to maximize and uniformize the straightness after quenching. Cr is added also to enhance the high temperature strength upon hot pressure-forming. If the content of Cr exceeds 0.30% by weight, the resulting product exhibits a reduced weldability that leads to a rise in the cost of raw material. Therefore, the content of Cr is reduced to the minimum necessary value.

The content of Mo (molybdenum) is from 0.04 to 0.06% by weight. Mo is added to drastically improve the fracture



toughness of the pressure-formed portion. If the content of Mo falls below 0.04% by weight, the resulting improvement is reduced. On the contrary, if the content of Mo exceeds 0.06% by weight, it doesn't add to the improvement too much.

The present invention will be further described by referring to the following examples, but is not construed as being limited thereto.

In the examples described later, samples to be tested corresponding to odd-shaped PC steel rod having a diameter of 9.2 mm as defined in JIS G 3109 were prepared from steel materials containing additive elements by using an apparatus shown in Fig. 1. In Fig. 1, a steel material W is continuously passed through various steps by means of pinch rolls 1, 4, and 9 which serve as feeding means as well as tensile stress providing apparatus. These pinch rolls are each composed of one or more pairs of rollers. These pinch rolls have different diameters and thus give different circumferential speeds and the roller pressure in these pinch rolls are properly selected so that a predetermined tensile stress can be applied across two adjacent pinch rolls.

At first, the steel material which has been passed by the pinch roll 1 is sent to a hardening heater 2 where it is heated to a hardening temperature, and then the steel material is then cooled by a water-cooling nozzle 3. The quenched steel material is then passed to the subsequent steps while being given a predetermined tensile stress across

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the pinch rolls 4 and 9. Under such conditions, the steel material W is heated by an annealing heater 5, given a minute bending strain by vertical direction correcting rolls 6 and longitudinal direction correcting roll 7 which crosses the rolls 6, rapidly cooled by a water-cooling nozzle 8, and then taken off by the take-off pinch roll 9.

EXAMPLE 1

Using the foregoing apparatus, steel materials (Samples a and b) containing the following chemical components (unit: percent by weight) were subjected to quenching alone under the same heat treatment conditions to prepare samples. Another batch of these steel materials were subjected to quenching, annealing, hot working and cooling in sequence to prepare samples. The quenching temperature was 950°C. The annealing was effected at an optimum temperature such that a tensile strength of 1,470 N/mm² was attained. During the annealing, the steel material was hot-worked at a tensile stress of 76 N/mm² and a bending strain of 0.4%. This tensile stress value is 10 to 11% of the proportional limit (686 to 785 N/mm²) at the annealing temperature. The following examples used the same conditions.

<u>Sample</u>	<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Mo</u>	<u>Cr</u>
a	0.30	1.12	0.80	<0.01	0.02
b	0.31	1.06	0.79	0.04	0.25

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These samples were then examined for straightness.
The results are set forth in Table 1 below.

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TABLE 1

Sample	Straightness after hardening (mm)					Straightness after heat treatment (winding) (mm)				
	<u>n</u>	<u>max.</u>	<u>min.</u>	<u>av.</u>	<u>std.</u>	<u>n</u>	<u>max.</u>	<u>min.</u>	<u>av.</u>	<u>std.</u>
a	24	9.9	2.7	6.4	1.9	24	1.7	1.0	1.3	0.2
b	24	5.3	1.2	2.9	1.3	24	0.9	0.4	0.7	0.2

Note: n number of specimens to be tested
max. maximum value
min. minimum value
av. average value
std. standard deviation

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The table shows that the sample which has been subjected to not only quenching but also subsequent heat treatment exhibits a better straightness than the other sample which has been subjected to quenching alone. Further, Sample b which has greater Mo and Cr contents, exhibits a better straightness than Sample a.

EXAMPLE 2

It has been known that conventional low relaxation products exhibit a reduced straightness due to curling after being wound in a coil. In order to investigate the cause of the defect, samples were prepared from steel materials (Samples c and d) containing the following chemical components (unit: percent by weight). Sample c was a conventional low relaxation product, and Sample d was a conventional ordinary relaxation product.

<u>Sample</u>	<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Mo</u>	<u>Cr</u>
c	0.31	1.66	0.79	<0.01	0.03
d	0.31	0.25	0.80	<0.01	0.02

The samples were prepared by deforming and heat-treating a steel bar of 9.15 mm in diameter made from a wire rod of 10 mm in diameter. The hardening temperature was 900 to 1,000°C. The annealing was effected at an optimum temperature such that a tensile strength of 1,470 N/mm² was attained. Sample c was hot-worked in the same manner as

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effected in Example 1 during annealing. These materials to be tested were wound in a coil. The change of straightness (average of 10 specimens) with time was then examined. The results are set forth in Table 2 below.

TABLE 2

<u>Sample</u>	<u>Straightness before winding (mm)</u>	<u>Straightness after winding (7 days) (mm)</u>
c	0.6	2.0
d	0.5	0.6

Thus, it was confirmed that Sample c as a low relaxation product exhibits a gross straightness change with the passage of time after being wound. In order to fully investigate the cause of the defect, the microstructure of the section of these materials to be tested were observed. As a result, Sample d as an ordinary relaxation product showed no fully-decarbonized layer. On the contrary, Sample c as a low relaxation product showed an annularly formed fully-decarbonized layer having a thickness of 20 to 40 μm .

In general, when a steel material is subjected to heat treatment involving, e.g., rapid heating and quenching by means of the apparatus shown in Fig. 1, no fully-decarbonized layer is produced. Sample c already produced



the similar fully-decarbonized layer when it was in the state of wire material before heat treatment.

A wire material having the same chemical components as Sample c was shaved to fully remove fully-decarbonized layer, and then subjected to heat treatment in the same manner as above. The wire material was then wound in a coil. The wire material was then examined for straightness change with time.

As a result, it was confirmed that the wire material exhibits a straightness of 0.6 mm before being wound but exhibits a straightness of 0.7 mm 7 days after being wound, showing little or no straightness change with time.

It can therefore be presumed that the deterioration of straightness due to curling means plastic deformation due to a remarkable drop of the strength of the surface layer which is fully decarbonized.

EXAMPLE 3

It was thus made clear that the fully-decarbonized layer has a great effect on the straightness after winding. Various methods for preventing the production of fully-decarbonized layer were studied. In the production of PC steel wire and steel rod, the prevention of the production of fully-decarbonized layer between steelmaking and rolling requires a huge plant and equipment investment and thus is undesirable in industrial production. Further, the removal of fully-decarbonized layer by shaving is disadvantageous in



that it causes a drop in the production yield and hence a rise in the production cost. Therefore, the inventors proposed that the production of an annularly-formed fully-decarbonized layer be inhibited by adjusting the chemical components in the steel material.

In general, it has been said in the art that the production of fully-decarbonized layer relates to the activity of carbon and the rise in the carbon and silicon contents dynamically raises the activity of carbon, accelerating decarbonization. Carbon is a basic element for heat treatment, and the change in the carbon content has a great effect on the hardening strength, etc. Silicon is an element which is very useful for the improvement of relaxation properties. Focusing the relationship among the silicon content, the production of fully-decarbonized layer and the relaxation properties, the following experiments were made.

Steel materials (Samples a, e, f, and g) containing the following chemical components (unit: percent by weight) having a diameter of 10 mm were each deformed and drawn into a material having a diameter of 9.2 mm, and then subjected to heat treatment using the apparatus shown in Fig. 1. The quenched temperature was 930 to 1,000°C. The annealing temperature was adjusted depending on the chemical components in the material so that the tensile strength was uniformized to almost the same level. These steel

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materials were hot-worked under the same conditions at a tensile stress of 76 N/mm² and a bending strain of 0.4%.

Sample a was the same as used in Example 1.

<u>Sample</u>	<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Mo</u>	<u>Cr</u>
e	0.30	0.95	0.80	<0.01	0.03
a	0.30	1.12	0.80	<0.01	0.02
f	0.31	1.38	0.77	<0.01	0.02
g	0.31	1.58	0.75	<0.01	0.06

The samples thus obtained were then measured for mechanical properties, presence of decarbonized layer and relaxation value. The various testing conditions were as follows:

1. Mechanical properties

These materials to be tested were each subjected to tensile test defined in JIS G 3109 to determine its tensile strength, yield point and elongation.

2. Presence of fully-decarbonized layer

A sample was each collected at an arbitrary position on these samples. The section of the sample was observed under an optical microscope.

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3. Relaxation

Initial load: 39.8 kN

Loading method: The initial load is reached in 1 minute, immediately followed by the rise in temperature as well as measurement.

Temperature history: The sample is heated to a temperature of 180°C in 4 hours, kept at the same temperature for 3 hours, and then allowed to cool in the furnace.

Relaxation: The relaxation value determined 23 hours after the beginning of the rise in the temperature is defined as high temperature relaxation value.

The results obtained are set forth in Table 3 below.

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TABLE 3

<u>Sample</u>	<u>Tensile strength</u> (N/mm ²)	<u>Yield point</u> (N/mm ²)	<u>Elongation</u> (%)	<u>Fully-decarbonized layer</u>		<u>High-temperature relaxation value</u> (%)
				<u>Form</u>	<u>Thickness</u> (μm)	
e	1,475	1,409	9.5	scattered	5 - 15	8.1
a	1,460	1,408	10.0	about 1/3 of periphery	10 - 15	7.6
f	1,484	1,445	9.5	about 2/3 of periphery	15 - 20	7.2
g	1,492	1,468	9.5	all around periphery	20 - 40	6.5

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Table 3 shows that the less the silicon content is, the more sparsely lies the annularly formed fully-decarbonized layer, and the less is the thickness thereof. It was also found that the less the silicon content is, the more is the high temperature relaxation value. When the silicon content is 0.95%, the high temperature relaxation value exceeds 8%, which is the predetermined upper limit of the high temperature relaxation value of PC steel rod obtained by the autoclave method.

These materials to be tested were each subjected to heat treatment, and then wound in a coil (inner diameter: 2,000 mm). These materials were then measured for straightness change with the passage of time. The results are graphically shown in Fig. 2. As shown in the graph, the less the fully-decarbonized layer is, the less is the deterioration of straightness. Sample f (silicon content: 1.38%) satisfies the expected limit of straightness upon ordinary use (2.0 mm).

EXAMPLE 4

Conventional low relaxation products rarely undergo brittle fracture at pressure-formed portions under a low load during stretching. Therefore, the load-elongation curve of pressure-formed portion was extensively studied. As a result, it was found that the load-elongation curve can be classified into three patterns (A to C) as shown in Fig. 3. Pattern A exhibits a very small breaking load as well as a

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very small elongation. Pattern B exhibits a higher breaking load as well as a higher elongation. Pattern C exhibits an even higher breaking load as well as an even higher elongation, showing excellent mechanical properties.

Steel materials containing the following chemical components (unit: percent by weight) having a diameter of 10 mm were each deformed and drawn into a sample having a diameter of 9.2 mm using the apparatus shown in Fig. 1. These samples were each subjected to tensile test at pressure-formed portion. For the heat treatment of samples, the quenching temperature was 930 to 1,000°C. The annealing was effected at an optimum temperature such that a tensile strength of 1,470 N/mm² was attained. During annealing, the samples were each hot-worked under the same conditions as in Example 1.

<u>Sample</u>	<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Mo</u>	<u>Cr</u>
a	0.30	1.12	0.80	<0.01	0.02
b	0.31	1.06	0.79	0.04	0.25
h	0.30	1.33	0.80	0.06	0.17
i	0.29	1.10	0.77	0.06	0.03

For the tensile test, a horseshoe testing plate was prepared on the basis of the shape of an end plate for use with PC pile. The foregoing materials to be tested were each pressure-formed under the same pressure-forming conditions as

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the testing plate. The load-elongation curves were recorded on an autographic recording chart mount on the testing machine. These curves were each classified into the three patterns shown in Fig. 3. The results are set forth in Table 4.

TABLE 4

<u>Sample</u>	<u>Run No.</u>	<u>Tensile load</u> (kN)	<u>Pattern of</u> <u>load-elongation curve</u>
a	1	45.1	A
	2	59.8	A
	3	81.4	B
b	1	90.7	B
	2	91.7	C
	3	91.7	C
h	1	91.2	C
	2	91.7	C
	3	91.2	C
i	1	90.2	C
	2	90.2	C
	3	90.7	C

Table 4 shows that the fracture toughness of the pressure-formed portion is improved by adding a small amount of Mo. Further, if Cr is added in combination with a small amount of Mo, not only the toughness but also the tensile strength of the pressure-formed portion are improved. It is considered that the high temperature strength is improved by the addition of Cr.

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As mentioned above, PC steel wire or rod of the present invention suffers from minimized deterioration of straightness, particularly after being wound in a coil, and thus can be prevented from being caught in automatic working machines. Further, the PC steel wire or rod of the present invention exhibits drastic improvements in quality, particularly strength and toughness, of pressure-formed portion in the pressure-forming process popular among the manufacturers of PC piles and poles. Thus, the PC steel wire or rod of the present invention can be prevented from suffering brittle fracture at pressure-formed portion upon stretching, providing an enhancement of working reliability.

Therefore, when the products of the present invention are applied to the production of high strength PC piles whose predetermined upper limit of high temperature relaxation value is 8%, which have rapidly become popular, the production efficiency of cutting machine and automatic working machine can be enhanced.

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CLAIMS

1. A PC steel wire or rod having an excellent straightness and pressure-formability, said wire or rod being prepared by a process which comprises:

heating a steel wire or rod;

annealing said wire or rod while being simultaneously provided with a tensile stress of from 6 to 14% of the proportional limit at the ambient temperature and a minute bending strain of from 0.1 to 0.5% of the proportional limit at the ambient temperature, in the annealing temperature range or in a cooling step; and

quenching said wire or rod,

said wire or rod comprising 0.20 to 0.40% by weight of C, 1.00 to 1.40% by weight of Si, 0.60 to 0.90% by weight of Mn, 0.04 to 0.06% by weight of Mo, 0.10 to 0.30% by weight of Cr, and the balance of iron, with unavoidable impurities.

2. A PC steel wire or rod substantially as hereinbefore described with reference to any one of Examples 1 to 4 and the corresponding drawings.

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