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Wire Rod for 2,000 MPa Galvanized Wire and 2,300 MPa PC Strand

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Abstract

There is a steady demand of high strength steel wires for bridge cable and PC strand. To achieve strengthening of high carbon steel wire, it is important to prevent the occurrence of delamination and suppress the loss of strength in galvanizing or blueing process. Strengthening of patented wire is more effective than increasing the total amount of reduction to depress delamination. Si and Cr, elements that enhance the patented wire strength and retard the spheroidization rate of lamellar cementite, are useful in suppressing the loss of strength during galvanizing. Based on these findings, the galvanized steel wire with a tensile strength of 2,000 MPa and the PC strand featuring a tensile strength of 2,300 MPa have been developed. The new wires have properties equal to or better than those of the conventional wires.

1. Introduction

High carbon steel wire strengthened by the drawing of high carbon pearlitic steel is known as the strongest of the mass-production steels. Its strength has especially increased in recent years. For example, the strength of tire cord as a representative fine wire product has reached 4,000 MPa for the weight reduction of tires[1]. Galvanized bridge wire had hovered in the strength range of 1,500 to 1,600 MPa (150 to 160 kgf/mm^2) for more than a half century. The construction of the world's longest Akashi Kaikyo Bridge called for the development of bridge wire with a strength of the 1,800-MPa (180-kgf/mm^2) class[2-4], contributing to lower construction costs. Japan is also studying construction of still longer bridges: for example, Tokyo Bay Mouth Bridge and Kitan Kaikyo Bridge. In response to these projects, bridge wire development work has progressed to such a level as to achieve a strength of 2,000 MPa (200 kgf/mm^2)[5].

Prestressed-concrete (PC) steel wire is also increasing in strength. Steel wire of 1,860 MPa was long used in PC applications. Commercialization of higher-strength concrete or simplification of concrete construction has demanded PC wire of higher strength. To meet the demand, PC wire with a strength of 2,300 MPa is developed[6,7].

Here are described the strengthening considerations for galvanized bridge wire and PC wire, and the development results of 2,000 MPa galvanized bridge wire and 2,300 MPa PC strand wire rods.

2. Methods for Increasing Strength of High Carbon Steel Wire

The strength of steel wire may be increased by:
1) Increasing the strength of patented wire rods
2) Increasing the total amount of reduction in drawing; or
3) Increasing the work hardening rate during drawing

For bridge wire and PC wire that are hot-dip galvanized or blued after drawing, it is also important to:
4) Preventing the strength from being reduced during hot-dip

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galvanization or bluing

Each of these methods can increase the strength of steel wire. Since the ductility of wire varies with strengthening methods, it is important to select the combination of methods that produces the smallest possible ductility degradation.

The ductility of wire is usually evaluated by torsion test. As the wire increases in strength and decreases in ductility, it develops a longitudinal crack along the drawing direction, what is called the delamination, in the early stage of torsional deformation. Preventing the occurrence of delamination is an important factor for increasing the strength of steel wire.

The relationship between the patented wire rod strength and the drawn wire strength at which delamination occurs is shown in **Fig. 1**[3]. As compared with wire of the same strength but strengthened by increasing the total amount of reduction in drawing, wire strengthened by increasing the strength of the patented rod is found to develop no delamination until the high strength region. This indicates that increasing the strength of patented rod and the work hardening rate during drawing is more effective than increasing the total amount of reduction in drawing as the method for accomplishing both the enhancement of wire strength and the prevention of delamination.

The strength of the patented wire rod may be increased by:
1) Decreasing the pearlite lamellar spacing
2) Ferrite solid solution and precipitation strengthening; or
3) Increasing the volume fraction of cementite

It is known that increasing the carbon content[1,8] and adding chromium are effective in reducing the pearlite lamellar spacing and that solid solution strengthening by silicon and precipitation strengthening by vanadium are effective in increasing the strength of ferrite. To increase the volume fraction of high strength cementite, the carbon content must be increased.

The pearlite lamellar spacing has a predominant effect on the work hardening rate. The work hardening rate increases as the initial pearlite lamellar spacing after patenting decreases. In the region where the total amount of reduction in drawing is small as for bridge wire and PC wire, the work hardening rate is not expected to appreciably increase with decreasing pearlite lamellar spacing[9].

The loss of strength in the hot-dip galvanization or bluing process is mainly caused by the fragmentation and spheroidization of severely deformed cementite, resulting in the collapse of the lamellar structure of ferrite and cementite[10]. **Fig. 2** shows the effects of pre-galvanization wire strength, and silicon and chromium on the loss of strength during hot-dip galvanization at 450°C[4]. The greater the total amount of reduction in drawing and the higher the strength, the greater the strength loss that results. The effect of alloying elements is conspicuously recognized. The loss of strength can be reduced about 100 MPa by increasing the silicon content from 0.25% to 1.0%. The addition of chromium can further prevent the loss of strength.

As shown in **Fig. 3**, silicon is low in solubility in cementite and is enriched at the ferrite/cementite interface, while chromium is concentrated in cementite[11]. Since the spheroidization of cementite requires the diffusion of silicon at the interface, increasing the silicon content is considered to decrease the spheroidization rate of cementite and to diminish the loss of strength[10]. Chromium is lower in diffusion rate than silicon, with the result that the spheroidization rate of cementite is controlled by the diffusion of silicon and chromium and is reduced. That is, the addition of silicon or chromium maintains the lamellar structure even after hot-dip galvanization, making the loss of strength less difficult to occur.

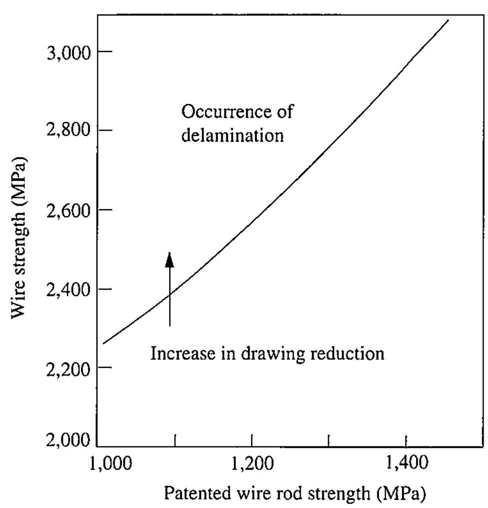

Fig. 1 Effect of patented wire rod strength on occurrence of delamination

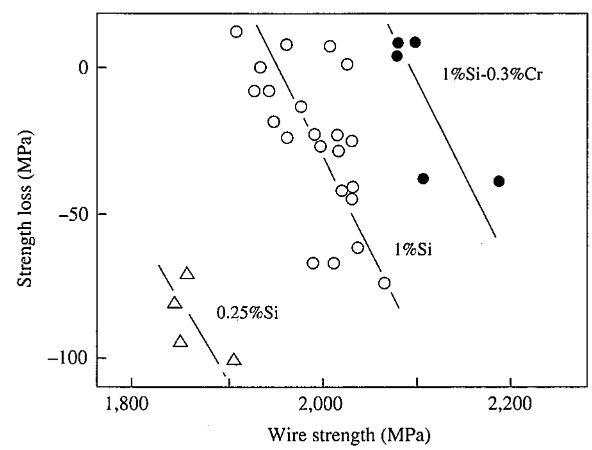

Fig. 2 Effects of silicon and chromium on strength loss during hot-dip galvanization

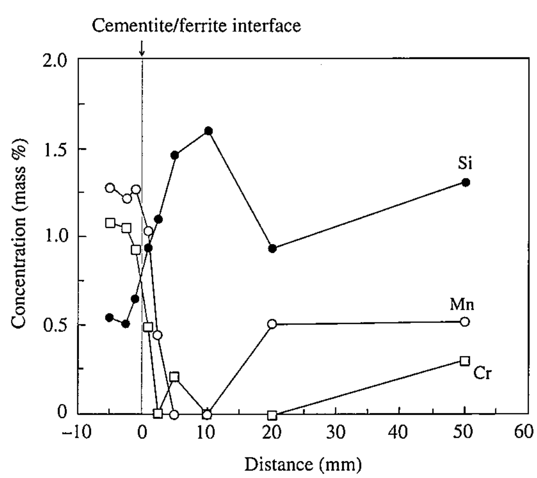

Fig. 3 Silicon, manganese, and chromium concentration distributions at ferrite/cementite interface

The above discussion indicates that the strength of galvanized bridge wire and PC wire can be effectively increased as described below.

1) In order to enhance the strength of patented wire rods, silicon and chromium are added for solid solution strengthening of lamellar ferrite and refinement of pearlite lamellar spacing, and carbon content is increased to raise the volume fraction of cementite.
2) Silicon and chromium are added to prevent the loss of strength during bluing and hot-dip galvanization.

3. Galvanized bride steel wire with strength of 2,000 MPa

3.1 Manufacturing conditions

Based on the above-mentioned strengthening ideas, a steel of the chemical composition given in **Table 1** was designed as galvanized bridge wire with a size of 5 mm and strength of 2,000 MPa. The chemical composition of a 1,800 MPa wire is also given for comparison. The point was the increased carbon and silicon contents and chromium addition, as compared with the 1,800 MPa wire used in the fabrication of main cables for the Akashi Kaikyo Bridge, in order to increase the patented rod strength, to inhibit the loss of strength in the galvanization process, and to prevent delamination.

The 2,000 MPa steel was melted in a furnace and hot rolled to a 12-mm rod at the Muroran Works of Nippon Steel. It was then patented, drawn to a size of 4.9 mm, and hot-dip galvanized at Tokyo Rope Mfg. Co., Ltd. The strength of the 2,000 MPa steel rod after patenting is 1,450 MPa and is 125 MPa higher than that of the 1,800 MPa steel rod.

3.2 Properties of 2,000-MPa galvanized steel wire

The mechanical properties of the 5 mm prototype galvanized steel wire are listed in **Table 2**. The tensile strength is 2,059 MPa, and the elongation is better than the specified level. The wire did not delaminate in torsion testing and exhibited good torsion performance. The prototype steel wire was investigated for fatigue, low-temperature, and delayed fracture properties.

Since the stresses applied to the main cables of bridges are mostly tensile, partially pulsating-tension fatigue test was conducted using a Vibrophore fatigue tester. For comparison, the 1,600 MPa wire and 1,800 MPa wire were also tested. The minimum stress increased in increasing order of strength, or was 490 MPa for the 1,600 MPa wire, 552 MPa for the 1,800 MPa wire, and 604 MPa for the 2,000 MPa wire.

Fig. 4 shows the relationship between the wire strength and fatigue limit (10^7 cycles) of the galvanized steel wire specimens. The fatigue limit increases with increasing strength. Despite its high minimum stress, the 2,000 MPa wire has a fatigue limit superior to that of the 1,800 MPa wire. The rotational bending fatigue limits of the specimens determined by a Nakamura rotational bending fatigue tester are also given in Fig. 4 for reference. The rotational bending fatigue limit of galvanized steel wire also increases with increasing tensile strength.

Low-temperature strength was evaluated by the tensile test of smooth specimens with a parallel portion diameter of 4 mm and of notched specimens cut in the circumferential direction with a notch with a radius curvature of 0.1 mm, depth of 0.5 mm and angle of 60°. The test results of the smooth specimens and notched specimens are shown in **Figs. 5** and **6**, respectively. Like the conventional wire steels, the smooth specimens of the 2,000 MPa wire steel increase in strength with decreasing test temperature. The notched specimens of the 2,000 MPa wire steel are free from severe degradation at low temperatures and have excellent low-temperature strength.

One factor that inhibits the strengthening of steel wire is delayed fracture. High carbon steel wire is known to have excellent delayed

Table 1 Chemical composition of 2,000 MPa galvanized steel wire (mass %)

Strength	C	Si	Mn	Cr
1,800 MPa	0.82	1.00	0.80	–
2,000 MPa	0.88	1.20	0.50	0.30

Table 2 Mechanical properties of 2,000 MPa galvanized steel wire

0.2% offset yield strength	1,771 MPa
Tensile strength	2,059 MPa
Elongation	6.3%
Number of turns to failure	24

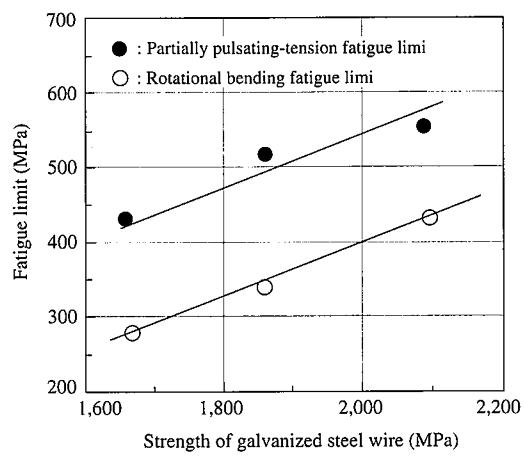

Fig. 4 Relationship between strength, partially pulsating- tension fatigue limit, and rotational bending fatigue limit of galvanized steel wire

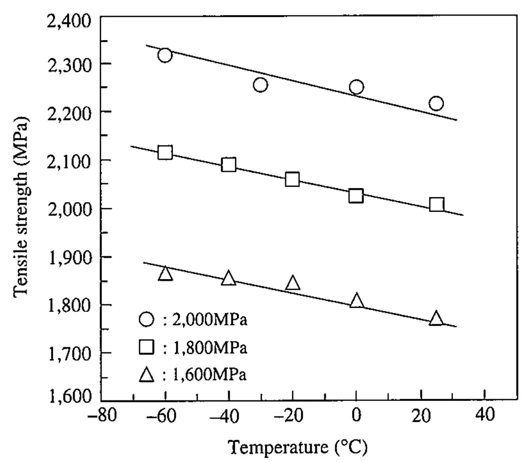

Fig. 5 Low-temperature strength of smooth specimens

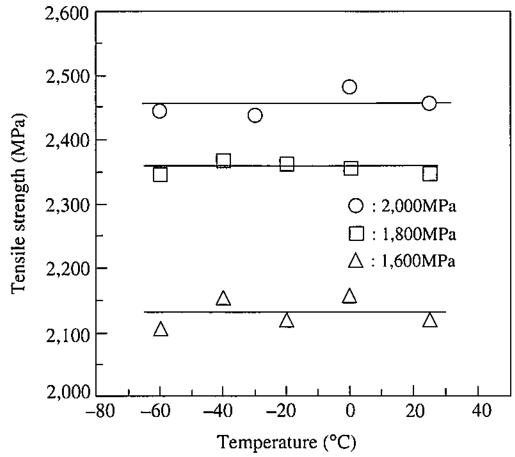

Fig. 6 Low-temperature strength of notched specimens

fracture toughness as compared with tempered martensite steel that is manufactured by quenching and tempering. Since wire of increased strength is used under increased applied stress, however, the possibility of delayed fracture cannot be denied.

Delayed fracture properties were evaluated by exposure tests in a hot and humid environment and outdoors (in the coastal area of Futtsu, a city about 50 km south of Tokyo). As-galvanized wire specimens were tested in the smooth and notched conditions. The applied stress was 1,256 MPa for the smooth specimens and 1,472 MPa for the notched specimens. The hot and humid environment exposure test specimens were exposed in an environment at a temperature of 60°C and relative humidity of over 90% for 6 months. Both smooth and notched specimens did not fracture in the hot and humid environment exposure test. The fracture loads of the specimens before and after the exposure are given in **Table 3**. Neither of the smooth or notched galvanized wire specimens declined in the fracture load after the exposure test. More than three years after the start of the outdoor exposure test, both smooth specimens and notched specimens have no delayed fractures yet. The outdoor exposure test will be continued.

As evident from the results discussed above, the 5 mm prototype steel wire with a strength of 2,000 MPa has mechanical properties, fatigue strength, low-temperature strength, and delayed fracture toughness equivalent or superior to those of the conventional 1,800 MPa steel wire, and is considered to withstand practical use as bridge wire.

Galvanized wire with a diameter of 7 mm and strength of 1,800 MPa was trial produced from the 2,000 MPa steel rod whose chemical composition is given in Table 1. The 13 mm patented rod was drawn to 6.91 mm and hot-dip galvanized. The mechanical properties of the galvanized wire are shown in **Table 4**. The galvanized wire has a tensile strength of 1,832 MPa and exhibits excellent torsional performance without the occurrence of delamination. It is also confirmed that the 7 mm-1,800 MPa wire has fatigue strength, low-temperature strength, and delayed fracture toughness equivalent or superior to those of the conventional 7 mm-1,600 MPa wire.

Table 3 Fracture load of specimens before and after hot and humid environment exposure test

	Smooth specimens	Notched specimens
Before exposure	40.5kN	29.5kN
After exposure	40.3kN	29.9kN

Table 4 Mechanical properties of 7-mm, 1,800 MPa galvanized steel wire

Tensile strength	1,832 MPa
Elongation	7.1%
Number of turns to failure	23

4. Rod for 2,300 MPa Ultra High Strength PC Strands

The pre-stressing method[12] applies compressive stress to concrete using pre-stressed concrete (PC) strands and improves the tensile load resistance of concrete. PC is smaller in the cross-sectional area than reinforced concrete of the same strength.

Steel wire for PC strands has been over many years predominantly 270K (1,860 MPa) specified in ASTM A 416 and JIS G 3536. This wire is manufactured from the steel SWRS 82B (0.82C-0.2Si-0.75Mn). The commercialization of high-strength concrete demanded PC wire of higher strength, and the prototype production of 300K (2,060 MPa)[13] and even 330K (2,300 MPa) to meet the demand is reported[6,14,15]. Wire for 300K PC strands and 300K PC strands themselves were trial produced using the newly developed steel 98ASiCr.

The chemical composition of the 98ASiCr steel was designed as follows. The carbon content facilitates strengthening when it is high, but was set at 0.98% to avoid the formation of proeutectoid cementite. Silicon was added by 1.2% as solid solution strengthening element and as element imparting resistance to softening during bluing. Chromium is added to promote the formation of lamellar pearlite and to reduce the pearlite lamellar spacing. Since chromium is segregated to a high degree in high carbon steels and it is likely to facilitate the formation of micro martensite in the center segregation portion of patented rods, the chromium content was set at about 0.2%. Manganese is likely to segregate and it retards transformation like chromium, so that the manganese content was set low at about 0.3%.

4.1 Manufacturing conditions

Table 5 shows the ladle analyses of samples. The 98ASiCr is a new steel, and the SWRS 82B is a conventional steel. These two steels were manufactured in an actual production process at the Kimitsu Works of Nippon Steel. Each steel was melted in a 250-ton converter, continuously cast into a 300 by 500 mm bloom, and rolled into a 122-mm square billet. At the wire rod mill of the Kimitsu Works, the billet was heated to 1,100°C and rolled to a 10 mm or 11 mm rod under ordinary rolling conditions. Immediately after their rolling, the rod was directly patented in molten salt bath patenting equipment (DLP equipment). The DLP rods were used as test materials.

The rods were pickled in hydrochloric acid, coated with zinc phosphate, and drawn to 4.22 or 4.35 mm on a continuous drawing machine at Suzuki Metal Industry Co., Ltd. From these wires were

Table 5 Chemical compositions of test steels (mass %)

	C	Si	Mn	P	S	Cr
98ASiCr	0.98	1.20	0.30	0.010	0.005	0.19
SWRS 82B	0.81	0.22	0.74	0.011	0.005	-

fabricated 7-wire PC strands with a nominal diameter of 12.7 mm. To establish the conditions of bluing applied to the 4.22 mm wire for straightening, the 4.22 mm wire was blued in at a temperature of 250 to 500°C for 600 seconds each and investigated for resultant changes in mechanical properties. A scanning electron microscope was used to observe the microstructure of the wire rod. The etchant was saturated picral. Proeutectoid cementite was observed by etching the specimen by the sodium picrate method specified in JIS G 0551 and examining it under an optical microscope of 500 magnifications.

4.2 Properties of 2,300 MPa high strength PC strands

The mechanical properties of the DLP rods are given in **Table 6**. The tensile strength of the 98ASiCr is about 300 MPa higher than that of the SWRS 82B. Its elongation and reduction of area are slightly lower, but posed no problems in subsequent wire drawing operations.

The microstructures of DLP wire rods are shown in **Fig. 7**. The 98ASiCr has normal pearlite structure as same as SWRS 82B and upper bainite was not observed. Since the cooling rate of DLP is high enough at about 25°C/s at the center of the 11 mm wire rod, proeutectoid cementite was not detected[16].

The changes in the mechanical properties of as-drawn wire with drawing strain are shown in **Fig. 8**. The work hardening rate of the 98ASiCr is approximately the same as that of the SWRS 82B.

Table 6 Mechanical properties of DLP rods

	Wire size (mm)	Tensile strength (MPa)	Reduction of area (%)	Elongation (%)
98ASiCr	10.0	1,570	38.1	9.6
98ASiCr	11.0	1,526	39.4	9.7
SWRS 82B	10.5	1,248	47.5	11.0

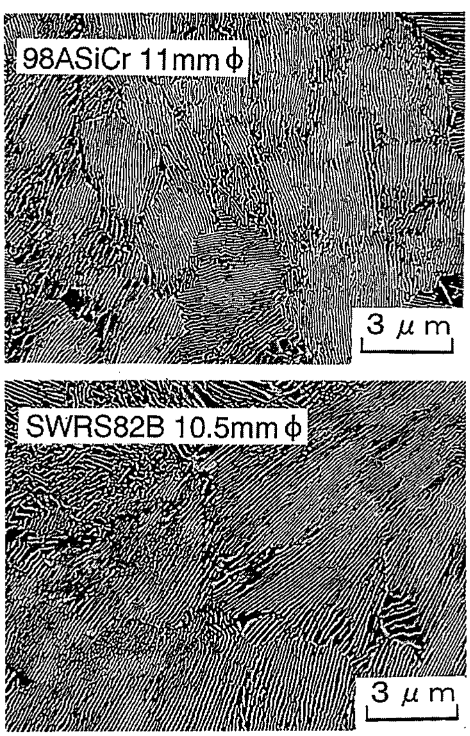

Fig. 7 SEM microstructures of DLP rods

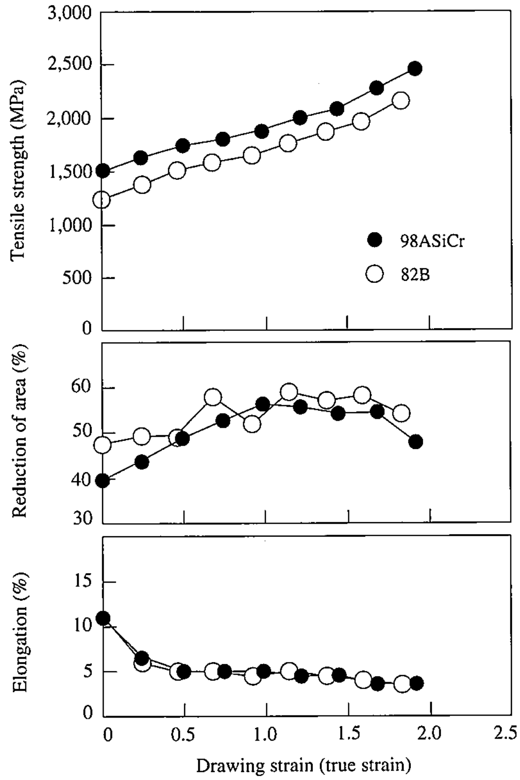

Fig. 8 Mechanical properties of as-drawn wire

This is because the total amount of reduction in drawing is low at 85.3% or less (true strain $\varepsilon \leq 1.92$). The effect of refinement of the pearlite lamellar spacing in hypereutectoid steel on the work hardening clearly appears when the true strain is high at $\varepsilon \geq 2$. The 98ASiCr is slightly lower than the SWRS 82B in the reduction of area in the rod condition but is approximately equal to the SWRS 82B in the reduction of area after drawing.

The mechanical properties of the wire after bluing are shown in **Fig. 9**. The 98ASiCr is recognized to have resistance to softening at a bluing temperature of 400°C or less thanks to the silicon addition. The elongation recovery temperature of the 98ASiCr is about 400°C and is 30 to 50°C higher than that of the SWRS 82B. The optimum bluing temperature of the 98ASiCr is thus 380 to 400°C.

The tensile test results of 7-wire PC strands (12.7 mm diameter) after warm stretching are shown in **Table 7**. The strength is higher than the target requirement of 330K (2,300 MPa). The 98ASiCr is strengthened, but the increase in the yield ratio is small. This is probably because the 98ASiCr is equivalent to the SWRS 82B in the total reduction in drawing. The elongation of the 98ASiCr is practically the same as that of the SWRS 82B, and its ductility is as good as the conventional 270K wire steel.

In addition, relaxation, tension fatigue, and anchoring tests were conducted. It is confirmed that these properties of the 98ASiCr are approximately the same as those of the conventional 270K wire[17].

4.3 Summary

For the purpose of developing 330K (2,300 MPa) PC strands, the high-silicon hypereutectoid steel 98ASiCr (0.98%C-1.20%Si-0.33%Mn-0.19%Cr) was melted in an actual converter and was

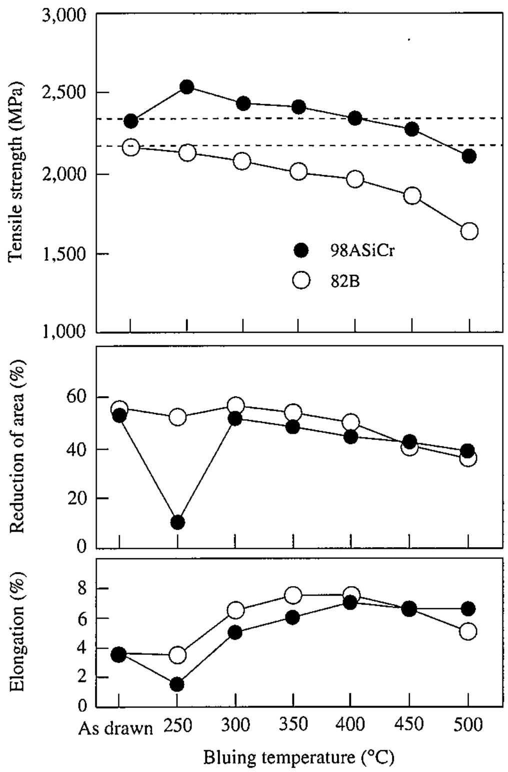

Fig. 9 Mechanical properties of wire after bluing

Table 7 Mechanical properties of PC strands

Steel	Rod size (mm)	Tensile strength (MPa)	Yield stress (MPa)	Yield ratio (%)	Young's modulus (GPa)	Elongation (%)
98ASiCr	10.0	2,343	2,144	91.5	2.02	8.2
98ASiCr	11.0	2,383	2,233	93.8	1.98	7.0
SWRS 82B	10.5	1,913	1,775	92.7	2.01	8.0

conventionally rolled to rods and drawn to wire. Prototype 12.7-mm diameter, 7-wire PC strands were fabricated from the wire thus made.

1) PC strands of the 330K (2,300 MPa) class can be manufactured by approximately the same process as conventional 270K (1,860 MPa) PC strands.
2) The elongation, relaxation value, and fatigue strength of the 2,300 MPa PC strands are practically the same as those of the conventional 270K PC strands.

5. Conclusions

The additions of silicon and chromium, elements effective in increasing the strength of patented rods and inhibiting the loss of strength during hot-dip galvanization and bluing, were studied as means for strengthening galvanized bridge steel wire and pre-stressed concrete (PC) strands. As a result of these efforts, the authors succeeded in developing 2,000 MPa galvanized steel wire for bridge cables and 2,300 MPa steel wire for PC strands. It was confirmed that these new wires have no loss of ductility and have fatigue and delayed fracture properties equivalent or superior to those of the conventional galvanized bridge steel wire and PC strand wire.

References

1) Ochiai, I., Nishida, S., Tashiro, H.: Wire J. Int. 26, 50 (1993)
2) Yamaoka, Y., Hamada, K., Tsubono, H., Kawasaki, H., Oki, Y., Kawaguchi, Y.: Trans. I.S.I.J. 26, 1059 (1986)
3) Takahashi, T., Konno, S., Sato, H., Ochiai, M., Noguchi, Y., Serigawa, S., Tawaraya, Y.: Seitetsu-Kenkyu. (332), 53 (1989)
4) Takahashi, T., Tarui, T., Konno, S.: Journal of Constructional Steel. 1, 119 (1994)
5) Takahashi, T., Ohashi, S., Tarui, T., Uemori, T., Maruyama, N.: CAMP-ISIJ. 7, 777 (1994)
6) Nishida, S., Yoshie, A., Ochiai, M., Asano, I., Tominaga, J., Komori, H.: CAMP-ISIJ. 8, 1371 (1996)
7) Ibaraki, N., Kaiso, M., Makii, K., Ho, S., Kodama, M.: "R&D" Kobe Steel Engineering Reports. 46 (3), 13 (1996)
8) Kanetsuki, Y., Ibaraki, N., Ashida, S.: ISIJ Int. 31, 304 (1991)
9) Tarui, T., Takahashi, T., Tashiro, H., Nishida, S.: Metallurgy, Processing and Applications of Metal Wires. TMS, 1996, p.87
10) Tarui, T., Ohashi, S., Takahashi, T., Uemori, R.: Iron & Steelmaker. (Sep.), 25 (1994)
11) Maruyama, N., Uemori, T., Morikawa, H.: Shinnittetsu Giho. 359, 6 (1996)
12) Aida, T. et al.: Wire Rope *Binran*. Hakua Syobo
13) Kawabata, Y, Tsubono, H., Yamaoka, S., Hamada, K., Kawaguchi, Y., Takahashi, H.: Tetsu-to-Hagané. 71, s1524 (1985)
14) Kodama, M., Murayori, T., Yamaoka, S., Ibaraki, N.: Development of Pressed Concrete. 1995, p.561
15) Ochiai, M., Komori, H., Tominaga, J., Yoshie, A., Nishida, S., Asano, I.: 40th Subcommittee Meeting of Wiredrawing Technology, JSTP, 1995
16) Ochiai, M., Nishida, S., Ohba, H., Serikawa, S., Takahashi, H.: Materia. 33, 2061 (1994)
17) Ochiai, I., Komori, H., Hagiwara, M., Ichihara, T.: Pressed Concrete. 39, 79 (1997)