## Technical Report

UDC 669 . 14 . 018 . 295

# Development of Environmental Load Reducing Type High-strength Wire Rods for Parallel Wire Strand

Toshiyuki MANABE\* Arata ISO Hiroshi OHBA Naoki MATSUI Shingo YAMASAKI Naoshi HIKITA Seiki NISHIDA

# Abstract

The DLP (Direct in-Line Patenting) process was applied to high-strength wire rods for bridge cable use. In applying the DLP process to Si-added high carbon steel, the main problem was how to inhibit the formation of the upper bainite in the wire rod subsurface. It was revealed that the upper bainite is suppressed by boron segregated at the grain boundary. By applying the developed B-added high carbon steel, the manufactured wire of 1960MPa grade satisfied the requisite properties. This technology enables enhanced productivity and reduction of CO<sub>2</sub> emission, and the consumption of lead in the manufacturing process of high tensile grade wire.

#### 1. Introduction

Suspension or staying designs by means of main cables are applied to long-span bridges with span lengths exceeding 400 m. The main cable is composed of parallel wire strands (termed as PWS), with each strand consisting of bundled element wires laid in parallel. The main cable is a vitally important member that determines the specification of a bridge and the higher strength is required of the element wire to meet the growth in span length and to allow for greater freedom in design.

In Japan, several long-span bridges such as the Honshu-Shikoku Bridge were constructed after the 1970s as national projects. For almost half a century since the 1940s, wires of 1570 MPa grade were mainly used. In the Akashi-Kaikyo Bridge completed in 1998, a suspension bridge with the world's longest span length of 1991 m, the 5 mm/1770 MPa grade wire was applied for the first time (**Fig.** 1). Four main cables could be reduced to two in the designing stage and shortening of the construction period and reduction in the construction cost could be realized. The 7 mm/1770 MPa grade wire was applied to the staying type Tappu Oohashi in Hokkaido in 2004. In the newly-emerging countries, traffic network infrastructures are being expanded rapidly, and a number of long-span bridge projects that call for higher strength wires such as 1870 MPa grade and 1960 MPa grade are being planned. Wires used for long-span bridges are generally the hot-dip galvanized steel wires of high carbon steel with pearlite microstructure. To develop the pearlite microstructure, the wire rod needs to be heated up to the austenite region and held in the temperature range of 500–600°C for the isothermal transformation treatment (patenting). This article reports the technology developed for the high ten-



<sup>\*</sup> Senior Researcher, Bar & Wire Rod Research Lab., Steel Research Laboratories 20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

sile strength wire rod for bridge cable use, realized by processing through the DLP (Direct in-Line Patenting) equipment at the Kimitsu Works.

# 2. Process of Enhancing Strength of Wire Rods for PWS Wire and Subject in Production

#### 2.1 Method of enhancing strength of high carbon steel wire

For high strength steel wires such as those for bridge cables, PC (prestressed concrete) steel wire, ropes of various types, steel cords (hereinafter termed as STC), saw wire and so forth, high carbon steel is used because the pearlite microstructure of high carbon steel obtained by patenting exhibits excellent work-hardening characteristics by wire drawing processing (drawing) when compared with other metallic microstructures. Pearlite microstructure is a lamellar microstructure composed of ferrite and cementite, and in the patenting stage, the strength is governed by the cementite fraction (carbon content), lamellar spacing and ferrite strength.

With the rotation of the crystalline orientation developed by the wire drawing processing, the lamellar microstructure is aligned in the direction of drawing and an aggregate structure is formed wherein the lamellar ferrite crystalline orientation is assembled on the <110> face with respect to the direction of drawing. Furthermore, strength is enhanced by the refinement of the lamellar spacing (**Fig. 2**). Kanie and Tomota et al.<sup>1,2)</sup> verified the excellent workhardening characteristics of the pearlite microstructure with the neutron diffraction stress measuring method and concluded that a stress distribution is generated between the lamellar ferrite and the cementite wherein the cementite bears the greater stress. Furthermore, they report that in the pearlite microstructure that underwent a heavy processing of wire drawing, the ferrite phase is also strengthened.

To enhance the pearlite strength and the wire strength after drawing, the addition of carbon that increases the fraction of cementite and Cr that refines the lamellar spacing as alloying elements is effective. In particular, as Cr enhances strength greatly in the high strain wire drawing processing, for STC that is processed to the true strain of three or higher, a hyper eutectoid steel of the composition system added with Cr is used.

For wires with a large diameter such as those for bridge cable use and PC wire use, since the effect of enhancing strength by means of wire drawing as in the case of STC cannot be calculated, the effort of enhancing strength focuses on the means of enhancing strength by patenting and, as an example of enhancing the strength of the ferrite phase, Si and V are added to enhance strength in the forms of Si solid solution and VC precipitation hardening. Furthermore, when hot-dip galvanizing is applied after drawing, Si and Cr are added to suppress the deterioration of strength due to the fragmentation of the lamellar cementite (spheroidizing). **Table 1** shows the chemical compositions applied to the wire rod for STC and bridge cables.

#### 2.2 Production process of PWS and its subject

Figure 3 shows the production process of PWS. Patenting-applied wire rods with a diameter of 10 mm or above are used as material and they are drawn after descaling and lubricant coating treatment. The wire so produced is processed to the final product wire by applying hot-dip galvanizing that renders the coating weight of zinc of  $300 \text{ g/m}^2$  or more after the pretreatment of degreasing, pickling and flux coating for rust prevention. In recent years, for hot-dip galvanizing, Zn-Al alloy is also used.

Afterwards, wires are bundled into a strand using the AS (air spinning) method, a method widely employed in Europe wherein each wire is stranded at the bridge construction site and the wire



Fig. 2 Microstructure of wire rod and drawn wire

 Table 1
 Chemical compositions example

					(mass%)	
Steel	C	Si	Mn	Cr	Application	
S82A	0.82	0.20	0.40	-	STC	
S92ACr	0.92	0.20	0.30	0.25		
SWRS82B	0.82	0.20	0.75	-		
S82BM	0.82	0.90	0.75	-	PWS	
S87AM	0.87	1.05	0.35	0.25		



Fig. 3 Manufacturing process of main cable



Fig. 4 Outline of DLP process

strands so built or the prefabricated parallel wire strands (PPWS) are converged to complete a cable after squeezing, banding and wrapping<sup>3</sup>). PPWS is a strand prefabricated in a shop by converging wires and bundling. The PPWS method is employed in Japan and is effective for shortening the construction period.

The patenting process is vital in the production process of the wire for bridge cable use. The conventional process of patenting of wire rods has been the lead patenting treatment (LP) in wire manufacturers wherein wire rods are reheated and dipped in a lead bath. However, the heat treatment process has the following problems: (1) Use of lead, a material hazardous to the environment, (2) Higher energy cost and increased emission of  $CO_2$  induced by reheating the wire rods and heating lead in the production process, and (3) Limited patenting capacity of wire manufacturers.

Due to (3) in particular, in a suspension bridge project that requires main cable steel material exceeding 10000 tons, the heat treatment capacity becomes a bottleneck in the production and, in some cases, the production of the wire has to be shared by several wire manufacturers. In this case, the uneven quality developed in the heat treatment process of different wire manufacturers becomes a concern. Furthermore, the production of wire overseas may possibly be affected by the restriction imposed on the environmentally hazardous lead.

# 2.3 Application of DLP equipment to patenting treatment and its issues

The schematic drawing of DLP equipment at the Kimitsu Works is shown in Fig. 4. The DLP equipment is an in-line heat treatment equipment capable of applying patenting by dipping wire rods in a molten salt bath directly right after hot-rolling<sup>4</sup>). However, it has not been applied to bridge use Si-added wire of 1860MPa grade or above. The inapplicability of DLP is attributed to the growth of hardenability in Si-added high carbon steel and further, to the instable wire rod quality that is caused by the microstructure of the metal developed by DLP treatment which differs from those of the steel with the ordinary Si content, caused by the rise of the nose temperature in the time-temperature-transformation (TTT). Since the heat treatment is rendered in the spiral-form-like posture, the variation of the mechanical characteristics in the longitudinal direction was large and the achievement of the torsional performance essentially required for bridge cable use wire was difficult. The torsional performance is evaluated by the number of torsions applied before reaching fracture and the mode of the fracture surface. The longitudinal crack (hereinafter referred to as delamination) is particularly problematic in that it takes place in the early stage. To apply DLP treatment to Si-added steel wire rods for bridge cable use, the subsurface bainite microstructure of the wire rod had to be reduced.

### 3. Development of Technology Suppressing Subsurface Bainite

#### 3.1 Study on process of formation of subsurface bainite

The addition of Si to steel raises the nose temperature in the transformation to pearlite microstructure. In the conventional heat

treatment through DLP, the transformation temperature is low in relation to the nose temperature and particularly, in the utmost upper subsurface layer of the wire rod that directly contacts the coolant, bainite is formed (**Fig. 5**). Furthermore, as indicated by **Fig. 6** wherein examples of upper bainite of steels with 0.2% Si and 1.0% Si are shown, the Si-added steel is characterized by the fewer amounts of cementite in the bainite microstructure and the precipitation of coarse cementite. It is considered that the added Si delays the formation of cementite after the formation of bainite.

The aforementioned delamination is considered to take place in the subsurface of the wire and, as the cause thereof, increased material heterogeneity due to the resolution of cementite<sup>5)</sup> and the formation of voids at the boundary between cementite and ferrite<sup>6)</sup> are proposed. Particularly, it is considered that the formation of upper bainite microstructure in the Si-added steel wherein coarse cementite precipitates must be avoided from the viewpoint of suppressing the delamination. Then, the transformation process during the isothermal transformation of Si-added high carbon steel (0.7%C-1.0% Si-1.0%Mn) was studied with a fully automatic transformation measuring and recording device (Formastor test machine).

The study on the process of isothermal transformation was conducted at 525°C in the temperature range where pearlite and upper bainite exist in a mixed manner and is the temperature at which the upper bainite is most frequently formed at the prior  $\gamma$  grain boundary. **Figure 7** shows the microstructure formed through the isothermal transformation at 525°C. The lightly contrasted areas denote the upper bainite microstructure and the deeply contrasted areas denote the pearlite microstructure.

<u>20µт</u>

Furthermore, in Fig. 8, an example of the transformation at the





Fig. 6 Bainite morphology change according with Si content



Fig. 7 Microstructure transformed at 525°C



Fig. 8 IPF (Inverse pole figure) map of initial microstructure transformed at 525°C

prior  $\gamma$  grain boundary right after the start of transformation is shown. In certain regions, the formation of ferrite from the  $\gamma$  grains at the  $\gamma$  grain boundary and further, the formation of upper bainite along the ferrite boundary were observed. The result of the analysis by electron backscatter diffraction (EBSD) indicates that the ferrite and the upper bainite possess the same orientation relation, and the ferrite is considered to be the precedent phase of upper bainite.

# 3.2 Suppression of formation of subsurface bainite by addition of $B^{\ensuremath{\tau}\xspace}$

The addition of B was studied to suppress the upper bainite in Si-added high carbon steel. To date, the addition of B to high carbon steel is not considered to be effective in improving hardenability<sup>8</sup>). Accordingly, cases of employing B to effectively control the micro-structure of high carbon steel are scarce<sup>9</sup>). For this reason, B was added to suppress the formation of ferrite, the precedent phase of upper bainite.

B was added to the aforementioned base steel of (0.7%C-1.0% Si-1.0%Mn), the steel was heated to 950°C and the isothermal heat treatment was applied at various temperatures. As **Fig. 9** shows, it was confirmed that the bainite areal fraction decreases greatly in the B-added steel. An example of the microstructure developed through the isothermal transformation at 525°C is shown in **Fig. 10**.

# **3.3** State of added B effective in suppressing the formation of subsurface bainite

To utilize the abovementioned bainite-suppressing effect of B stably in actual production, it is necessary to clarify the state in which B works effectively. As the existing states of B, B in the following forms is considered: general solid solution on matrix, precipitations as BN and/or  $M_{23}(C, B)_6$  and segregation at the grain boundary. In low carbon steel, B segregated at the grain boundary suppresses the formation of ferrite and improves hardenability. Meanwhile, the possibility of Fe<sub>23</sub>(C,B)<sub>6</sub> segregated at the grain boundary is suggested to suppress the formation of the nucleus by



Fig. 9 Area fraction of upper bainite in a variety of isothermal transformation temperature



Fig. 10 Microstructure transformed at 525°C

lowering the grain boundary energy by maintaining the K-S (Kurdjumov-Sachs) relation with the opposite austenite phase<sup>8)</sup>.

Then, to clarify the existing state of B that effectively suppresses upper bainite, the effect of the precipitation treatment of B was studied. As for BN precipitation, a precipitation nose of 850°C in low carbon steel is reported by Tanino et al.<sup>10</sup>. Therefore, three types of steel of B-free 0.87%C-0.9%Si, the steel added with B and the steel added with B and Ti were heated up to 1100°C, retained at 850°C for a short time and isothermally transformed at 525°C. Then, the upper bainite fraction was investigated and the effect of the compositions on BN precipitation was studied.

The precipitation nose of 650–800°C is reported by Yamamoto et al.<sup>11)</sup> for the precipitation of  $Fe_{23}(C,B)_6$ . Then, the B-free steel of the above and B and Ti added steel were heated up to 950°C, retained at 675°C and isothermally transformed at the same 525°C, and the upper bainite fraction was investigated. Then, the effect of the compositions on  $Fe_{23}(C,B)_6$  precipitation was studied.

Firstly, after the abovementioned precipitation treatment, the steels were quenched to room temperature, and the precipitations of BN and  $Fe_{23}(C, B)_6$  were confirmed with the extraction replica method. However, in the steel retained at 675°C, transformation to pearlite had not commenced. An example is shown in **Fig. 11**. BN is precipitated independently or in the form of polycrystals around the nucleus of MnS and AlN, and  $Fe_{23}(C, B)_6$  is precipitated at the prior austenite boundary in the form of monocrystals, which were both observable with an optical microscope. In **Fig. 12**, the effect of BN precipitation treatment time on the upper bainite fraction is shown, and in **Fig. 13**, the effect of the  $Fe_{23}(C, B)_6$  precipitation treatment on the upper bainite fraction fraction is shown. With the B precipitating treatment, upper bainite tends to increase. However, when N is pinned with the addition of Ti, the upper bainite microstructure is sup-



Fig. 12 Effect of BN precipitation treatment time on upper bainite fraction



Fig. 13 Effect of  $\operatorname{Fe}_{23}(C,B)_6$  precipitation treatment on upper bainite fraction

pressed regardless of whether it is retained in the BN precipitation temperature region. Therefore, the upper bainite suppression effect was considered to be due to the segregation of B at the grain boundary.

# 4. Characteristics of Trial Wire of Developed Steel and State of Application

Based upon the above finding, the Si-steel bearing B and Ti as alloying elements was developed. The base compositions of the developed steel are shown in **Table 2**. They were rolled to wire rods and DLP-treated, and were drawn to 5 mm and 7 mm of 1960 MPa grade for trial purposes in Jiangsu Tokyo Rope Co., Ltd. (JTR), a joint corporation of Tokyo Rope Mfg. Co., Ltd. in China.

The results of the trial manufacturing of the wires are shown in **Table 3**. In addition to strength, the wires need to conform to the specification of the number of torsions (14 or more for a 5 mm wire and 12 or more for a 7 mm wire) stipulated in the Material Standard for Cables of Structural Use (JSS II). Although the characteristics of wires greatly depend on the secondary processing technology, the trial wires exhibited high numbers of torsion and satisfied the desired characteristic values at the 1960MPa grade strength level without developing delamination. Furthermore, as the wire rods were heat-treated in a spiral ring form, 50 wire samples in continuity were taken and the torsion test was conducted. The torsional characteristic valued. As shown in **Fig. 14**, stable torsional characteristics are obtained.

The developed steel was applied to the Jingshān Chanjiang Gonglù Great Bridge in China completed in 2010 (a cable-stayed bridge ranked 8th in the world in terms of center span length) and to Izmit Bay Bridge in the Republic of Turkey (a cable-suspended bridge ranked 4th in the world in terms of center span length). (Both rankings in parentheses are as of December 2016.)

#### 5. Conclusion

The material of the high tensile strength PWS for bridge cables was produced by DLP processing. To suppress the formation of the subsurface bainite in the Si-added high carbon steel, a method of adding B was developed. As a result of the development of the trial wire of 1960 MPa grade from the developed steel, it was confirmed that the characteristics such as strength and ductility were satisfactory and delamination did not take place in the torsion test. The torsional characteristics in the longitudinal direction of the wire were also stable. With this development, in the production of the high strength wire rods for the 1960 MPa grade wire, productivity has been improved and the reductions in CO<sub>2</sub> emission and the amount

Table 2 Chemical compositions of developed steel

Steel	Chemical compositions (mass%)					Apply strength (MPa)	
	С	Si	Mn	Cr	B, Ti	$5\mathrm{mm}\phi$	$7\mathrm{mm}\phi$
S87BM	0.87	0.90	0.75	-	Added	1 960	1 770
S92AM	0.92	1.05	0.35	0.30	Added	1 960	1 860
S97AM	0.97	1.20	0.35	0.25	Added	-	1 960

Table 3 Trial results

	Tensile test					Torsion test	
Steel	Diameter	Tensile stress	Yield stress	Young's modulus	Elongation	Number of torsion	Delamination
	(mm)	(MPa)	(MPa)	(GPa)	(%)	(turs)	(%)
S87BM	5.42	2 0 2 0	1 796	204	6.2	25	0
S87BM	7.03	1 864	1 760	206	6.2	26	0
S92AM	7.02	1920	1 588	200	5.9	24	0
S97AM	7.01	2065	1 872	210	5.8	25	0



of lead in the wire production process have been realized.

#### Acknowledgements

We hereby wish to express our deep appreciation to the Tokyo Rope Mfg., Messrs. Kimihiro Wada, Kazuhiro Ishimoto, Yohei Nakamoto and to all concerned at the Company for their great support extended in producing the high strength PWS wire in the actual manufacturing line and the evaluation of the wire.

#### References

 Kanie, A., Tomota, Y., Suzuki, T., Torii, S., Moriai, A., Minakawa, N., Morii, Y., Kamiyama, T.: J. Soc. Mater. Sci., Jpn. 53, 772 (2004)

- 2) Tomota, Y., Suzuki, T., Kanie, A., Shiota, Y., Uno, M., Moriai, A., Minakawa, N., Morii, Y.: Acta Mater. 53, 463 (2005)
- 3) Takahashi, S.: Kawada Technical Report. 2, 222 (1981)
- Ooba, H., Nishida, S., Tarui, T., Yoshimura, K., Sugimoto M., Matsuoka, K., Hikita, N., Toda, M.: Shinnittetsu Giho. (386), 47 (2007)
- 5) Tarui, T., Maruyama, N.: CAMP-ISIJ. 13, 1247 (2000)
- 6) Shimizu, K., Kawabe, N.: ISIJ Int. 41, 183 (2001)
- 7) Manabe T., Yamasaki, S.: CAMP-ISIJ. 22, 254 (2009)
- 8) Leslie, W.C.: The Physical Metallurgy of Steels. Maruzen, 1985
- 9) Nagao, M., Yaguchi, H., Ibaraki, N., Ochiai, K.: Tetsu-to-Hagané. 89, 329 (2003)
- 10) Tanino, M., Komatsu, H., Yin, S.K.: CAMP-ISIJ. 67, S1208 (1981)
- 11) Yamamoto, K., Matsuda, S., Mukai, T., Komatsu, H., Oono, T.: CAMP-ISIJ. 68, S1513 (1982)



Toshiyuki MANABE Senior Researcher Bar & Wire Rod Research Lab. Steel Research Laboratories 20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511



Shingo YAMASAKI General Manager, Head of Div., Ph.D Bar & Wire Rod Research Lab. Steel Research Laboratories



Arata ISO Senior Manager Wire Rod Quality Control Dept. Quality Management Div. Kimitsu Works



Naoshi HIKITA Senior Manager, Head of Department Quality Management Dept. Production Div. Kamaishi Works



Hiroshi OHBA Wire Rod Technical Dept. Wire Rod Div. Kimitsu Works



Seiki NISHIDA Senior Manager Intellectual Property Dept.-II Intellectual Property Div.



Naoki MATSUI Senior Researcher Kimitsu R & D Lab.