Research of 1 770 MPa galvanized steel wire for stay cable of domestic bridges

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Abstract: This paper focuses on introducing the manufacture technology of 1 770 MPa galvanized steel wires for stay cables applied to domestic bridges. During the development practices of high strength galvanized wire for stay cables used in Sutong Bridge, Baosteel has established three key technologies based on research of manufacture technology and technical innovation. The three key technologies are: "Double Tensioning + limiter die" process, "dominant process + fine adjustment" in integrated optimization technology and "three-level control" in hot dip galvanization. With these key technologies, Baosteel has produced 1 770 MPa galvanized wires for stay cable, which has high tensile strength, low relaxation and good torsion performances.

Key words: galvanized wire; torsion; Double Tensioning; limiter die; gravel wiping

1 Introduction

The geographic location of Sutong Bridge and its main span which ranks first in the world bring about the particular requirements for stay cable in anti-vibration properties induced by rain and wind. All the mechanical tests about cables, including the conventional rupture test, fatigue test, or up-to-date bending fatigue test made on stay cable can't be done without the load bearing effect of galvanized wires. Therefore, higher technical conditions have been brought on the galvanized steel wires used in Sutong Bridge, and the core in them is high strength, low relaxation and good torsion.

Nevertheless, the top strength level for ϕ 7.0 mm galvanized steel wire used in stay cable in the world is 1 670 MPa so far. From 2001 on, although ϕ 7.0 mm galvanized steel wire with 1 770 MPa was successively reported in the world, it was not reported that this kind of steel wire had been applied to bridge construction all the time in the reported country. In pace with development of bridges in the world, a trend of high strength, big unit weight and high technical contents has been presented in galvanized steel wires for bridge cables. Under the restriction of technological level of material development, imported wire rods made by Nippon steel have been monopolizing the market of bridge cable-use galvanized wires for a long time in our country. Therefore, it is necessary to research and develop the galvanized steel wires for stay cables having Chinese independent intellectual property and characterized in high strength, low relaxation and good torsion, which has great strategic significance in establishing the national brand in construction of China's oversized bridges, keeping up with the advanced global standard and promoting the competitive power in the world.

2 Analysis of technical specifications

2.1 Analysis of technical requirements

The technical standards of galvanized steel wire for bridge-use stay cable are GB/T17101 at home and NF A35 – 035 *Prestressed Hot Dip Galvanized Round Steel Wire and Strand* (NF) in the world. In GB/T17101, the highest strength level for galvanized steel wire is stipulated to 1 670 MPa; as to international standards of the same products in the developed countries, 1 770 MPa galvanized steel wire is only provided in NF A35-035. Based on the above two standards, higher technical requirements are brought on galvanized steel wires for stay cables used in Sutong Bridge. Therefore, it is more difficult for galvanized steel wire for stay cables used in Sutong Bridge to meet the corresponding technical specifications. Table 1 shows the major technical indices of GB/T17101 and NF A35-035 and main technical specifications of galvanized steel wire for stay cable used in Sutong Bridge.

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Table 1　Major indicators of galvanized steel wires for stay cables

Standard	Tensile strength/ MPa	Yield strength/ MPa	Elongation/%	Bending/ times	Elastic modulus/ GPa	Relaxation rate/%	Zn-coating mass /(g· m^{-2})	Torsion/ turns	Copper sulphate (Dipping) test /times
GB/T17101	1 570, 1 670	1 330, 1 410	≥4.0	≥5	190 ~ 210	≤2.5	≥300	—	≥4
NFA35-035	≥1 770	≥1 570	≥3.5	≥5 (R = 22.5 mm)		≤2.5	190 ~ 350	—	≥2
Sutong Bridge	≥1 770	≥1 450	≥4.0	≥5	195 ~ 210	≤2.5	≥300	≥6	≥4

From above Table 1, it is found that the indices of elongation, reverse bending, Zn-coating weight, and dipping test for Sutong Bridge stay cables are obviously higher than the requirements of NF A35-035 and the indices of diameter tolerance, tensile strength, yield strength, elastic modulus, straightness (row height) for Sutong Bridge stay cables are also obviously higher than the requirements of GB/T17101. The Sutong Bridge stay cables have torsion index while GB/T17101 and NF A35-035 haven't this index.

There are two schools in the manufacturing technologies of galvanized steel wire for stay cable used in bridge in the world. European & American countries laid stress on the "high strength and low relaxation" of galvanized steel wire, while Japan gives emphasis to its "high strength and good torsion". By combining the technical characteristics of European & American and Japanese technical schools, the technical requirements of Sutong Bridge have focused on "ultra high strength (≥1 770 MPa level), low relaxation (II relaxation rate ≤2.5 %) and good torsion (torsion time≥6)". Consequently, the construction of Sutong Bridge have created four records about "the first in the world" (the largest foundation of pile group, the highest main bridge tower, the longest stay cable and the longest main span) and become the top of the world in technical specifications for bridge stay cable. (The galvanized wire of stay cable for Stonecutter Bridge with 1 018 m main span which was being built same stage has no torsion index in technical requirement.)

2.2　Analysis of raw material production

In 2005, Baosteel Group successfully developed B82MnQL wire rod used in main cables of suspension bridge and applied it to a series of domestic great bridge works. As to the special requirements for galvanized steel wire for stay cable used in Sutong Bridge, Baosteel Group researched and developed B82MnQL wire rod and a series of ϕ 7.0 mm galvanized steel wire for stay cable with 1 770 MPa level by adopting technology of microalloying, clean steel smelting, specially controlled rolling and cooling technologies and Double Tensioning technology for stabilization of finished galvanized steel wire. The wire passed the inspection tests by 2 authorized institutes in July 2005 and passed the technical accreditation organized by Shanghai Science Committee. The chemical compositions of the special-purpose B87MnQL wire rod of Baosteel stay cable is shown in Table 2 and Table 3.

Table 2　Mass percentage of the chemical compositions of B87MnQL wire rod　%

Major elements	C	Si	Mn	P	S	Cu	Cr	V
Smelting components	0.85 ~ 0.90	0.12 ~ 0.32	0.60 ~ 0.90	≤0.025	≤0.025	≤0.10	0.10 ~ 0.25	≤0.06
Tolerance	±0.02	±0.03	±0.03	+0.00	+0.00	±0.03	±0.03	±0.01

Table 3　Mechanical properties of B87MnQL wire rod

Steel grade	Diameter /mm	Tolerance/mm	Out of roundness /mm	Tensile strength /MPa	Reduction area/%
B87MnQL	13 ~ 14	±0.30	≤0.48	1 350 ±60	≥30(≥35 after aging)

The total content of non-metallic inclusions of Baosteel's special-purpose B87MnQL wire rod ≤0.10 %, testing standard is JISG0555-1998, total drawable compression ratio ≥86 %. The depth of decarburized layer complies with the requirements of GB/T224-1987, and the total decarburized layer (full decarbonization + transition layer) is no more than 0.07 mm.

Though Baosteel's B87MnQL wire rod has passed through scientific and technical evaluations, it is still not applied to large scale production. Therefore, at the initial stage of batch production, the performance indices such as tensile strength, reduction of cross-sectional area, elongation, etc. of galvanized steel wire for stay cable produced by using B87MnQL wire rod are overstable rather than the relatively unstable torsion. By means of extensive data acquisition and detection and test, it is discovered that the torsion performance is very sensitive to fine changes of uniformity of the chemical compositions (degree of segregation), cleanliness of molten steel (control of non-metallic inclusions and harmful elements), structure (such as obviousness of grain boundary cementite and sorbite slices, thickness of slice, uniformity of texture) of B87MnQL wire rod with high carbon content.

In view of technical analysis, Baosteel takes a series of effective measures: further optimize the matching of chemical compositions scientifically and reasonably, further reduce the contents of N, P and O in steel to decrease non-metallic inclusions and improve ultra cleanliness of molten steel.

3 Production practice of galvanized steel wire

3.1 Production process flow

Production process flow of galvanized steel wire for stay cable used in bridge:

Rechecking wire rod → surface pretreatment → wire drawing → hot dip galvanizing → stabilization → inspection and warehousing

3.2 Design of major technological parameters

3.2.1 Surface pretreatment of wire rod

The surface pretreatment of wire rod not only offers a lubricating carrier for the subsequent wire drawing, but the cleanliness of the treated surface of wire rod also affects the quality of galvanized coating as to the galvanized product. The major procedures of surface pretreatment includes flushing after descaling using 10 % ~20 % chlorhydric acid, phosphate treatment through immersing the wire rod in the tank filling with zinc dihydric phosphate, 5 ~7 min boronizing and drying.

3.2.2 Wire drawing

According to the previous experiences, loss of strength of hot galvanizing is 3 % ~5 %, the diameter of steel wire calculated at ≥ 300 g/m^2, Zn-coating mass of finished product is 6.92 mm, and the intensity of drawn steel wire is controlled at ≥1 870 MPa. The specification of wire rod is calculated by the following empirical formula[1]:

$$D = \left(\frac{\sigma_b}{\sigma_{b0} \cdot \kappa}\right)^2 \times d = \left(\frac{1870}{1\,300 \times 1.03}\right)^2 \times 6.92 = 13.5 \text{ mm} \qquad (1)$$

Where, d is diameter of semi-finished drawn wire, mm; κ is drawing coefficient 0.95 ~1.05, $\kappa = 1.03$; σ_{b0} is tensile strength of wire rod (1 300), MPa; σ_b is tensile strength of the drawn steel wire (1 870), MPa; and D is diameter of wire rod, mm.

So, the total compression ratio on wire drawing

$$\varepsilon_\Sigma = 1 - \left(\frac{d}{D}\right)^2 = 1 - \left(\frac{6.92}{13.5}\right)^2 = 73.72\ \% \qquad (2)$$

Drawing passes is 8 passes. The assignment of compression ratio of each pass is shown in Table 4.

Table 4 Wire drawing process (8 passes)

Drawing pass	0	1	2	3	4	5	6	7	8
Dimension /mm	13.50	12.14	11.00	10.03	9.21	8.50	7.90	7.37	6.92
Compression ratio /%	73.72	19.13	17.90	16.86	15.68	14.82	13.62	12.97	11.84

When drawing by using 8 passes, the compression ratios of the average passes are 15.39 %. From view of the principle of distortion of metallic cold processing for the integral improvement of all round properties of steel wire; this has been testified by the data of production practice.

3.2.3 Hot dip galvanizing

Process data are as follows: the temperature of lead tank is 420 ℃, temperature of zinc tank is 450 ℃, temperature of galvanizing aid bath is 60 ℃ and coating speed is 14 m/min.

3.2.4 Stabilization

The purpose of stabilization treatment is primarily to eliminate the residual stress of galvanized steel wire, increase its creep resisting capability, simultaneously improve and enhance its other performance indicators such as linearity, times of torsion, etc. The key parameters of stabilization treatment are tension, matching and setting of temperature. After multi tests, tension is set to 1 200 kg, temperature is 400 ℃ and production speed is 70 ~150 m/min.

The correct setting for process parameters is an important link for product quality to meet technical requirements. However, because the technical requirements for galvanized steel wire for stay cable used in Sutong Bridge concentrate on "high strength, low relaxation and good torsion performances", the two technical indices of tensile strength and torsion performance must be evaluated comprehensively. Therefore, it is difficult to manufacture galvanized steel wire through batch production. If conventional processes are adopted, the rate of products meeting standards will be relatively low. Baosteel has explored the new process and technological methods by technical innovation on basis of existing equipment and process parameters, and finally developed the three key technologies for manufacturing stay cable-use galvanized steel wire that Baosteel owns independent intellectual property.

3.3 "Double Tensioning + limiter die" process technology

The process scheme of single tensioning die drawing is mostly applied to the stabilization treatment of galvanized steel wire for stay cable used in domestic bridges. The arrangement of single tensioning bar drawing technology is shown in Fig. 1.

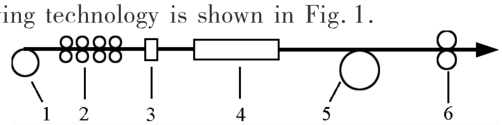

Fig. 1 Schematic diagram of single tensioning die drawing of galvanized wire

In Fig. 1, heavy line and the tip represent galvanized steel wire and its direction of travel respectively. Between reducing die and pinch roller, the galvanized steel wire is heated by induction furnace at the same time that the tension is applied on it, and then the stabilization treatment is completed. The key of process scheme of single tensioning die drawing is the design of compression ratio of reducing die to galvanized steel wire.

The processing arrangement of stabilizing production line of galvanized steel wire for stay cable used in Baosteel is shown in Fig. 2.

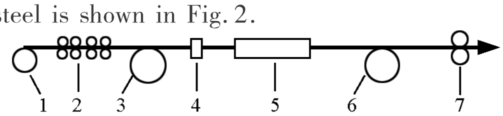

Fig. 2 Schematic diagram of stabilization process of galvanized steel wire of Baosteel

In Fig. 2, heavy line and the tip represent galvanized steel wire and its direction of travel respectively. The galvanized steel wire between front tension pulley and back tension pulley is heated by induction furnace at the same time that the tension is applied on it and then stabilization treatment is completed, which forms the double tensioning process scheme. The tension can be adjusted by PLC (programmable logic controller) control system at any time. When the front tension pulley is removed, it becomes the layout of single tensioning die drawing process, having more flexibility.

At the preproduction stage of galvanized steel wire, the test results from research of the two different schemes of process technologies are as follows:

1) If adopting Double Tensioning technology, we can get a lot of torsion times of galvanized steel wire; the fracture surface of test specimen is smooth and vertical to the center line of test specimen. If using single tensioning die drawing technology, we can only get less the torsion times of galvanized steel wire; the fracture surface of test specimen presents indented tear and there are radiating cracks on the square end and out of plumb with the center line of test specimen. In general, the fracture surface of test specimen with good torsion is smooth and vertical to the center line of test specimen.

2) During all body mechanical property test about "uniform loop difference", the tension performance of galvanized steel wire by adopting single tensioning die drawing technology is unstable. If adopting Double Tensioning technology, the galvanized steel wire is comparatively stable. The test of mechanical property that is conducted by supervising team of Wuhan Datong Supervision Company for stay cable of C3J bid section of Sutong Bridge through random sampling on the finished coil of galvanized steel wire trial-produced by Baosteel using Double Tensioning technology identifies that Double Tensioning technology has good effect on the improvement of the torsion performance of galvanized steel wire. The test data are shown in Table 5.

Table 5 Detection of all body mechanical property of galvanized steel wire

Specimen coding	Tensile strength / MPa	Yield strength / MPa	Elongation / %	Torsion / r	Wrapping
1	1 830	1 610	5.6	22	
2	1 810	1 600	5.6	22	
3	1 810	1 600	4.8	23	
4	1 820	1 610	5.6	21	
5	1 810	1 590	6.0	24	
6	1 810	1 590	5.2	23	Qualified
7	1 810	1 600	5.6	22	
8	1 810	1 600	5.6	22	
9	1 820	1 600	5.6	23	
10	1 820	1 610	5.2	23	

By comparing the two different schemes of process technology, if adopting single tensioning die drawing, the drawing of galvanized steel wire by using the die in the process of stabilization not only upgrades the dimensional accuracy of galvanized steel wire, but processes the harsh surface of galvanized steel wire so as to make its galvanized coating relatively smooth. For the Double Tensioning technology, due to remove the drawing die, effective processing can not made on the surface of galvanized steel wire in the course of stabilization, which makes its surface rather harsh. As to process of single tensioning die drawing, because of the influence of compression ratio of reducing die (10 % ~25 % generally), plastic deformation occurs to the galvanized steel wire, dislocation density of metal structure increases, accordingly, the torsion performance reduces. In reverse, for the Double Tensioning technology, the galvanized steel wire does not suffer from influence of plastic deformation in the process of stabilization, therefore, its torsion performance is good.

Through analysis, the scheme of "Double Tensioning + limiter die" process technology is put forward. For the new scheme, a "limiter die" is added on the base of Double Tensioning technology. The inner diameter of "limiter die" is designed as per the upper limit of allowable tolerance of finished product in order that plastic deformation does not occur to the galvanized steel wire passing through the die and the harsh surface of galvanized steel wire is processed and smoothed simultaneously.

3.4 "Dominant process + fine adjustment" integrated optimization technology

The test data from semi-finished products shows that the performance of steel wire drawn out wire rod will change greatly by hot dip galvanizing. For the hot galvanized wire, its tensile strength nearly reduces by 3 % ~5 % and torsion times decreases by 10 % ~ 20 % approximately under the effects of strain aging. However, the performance of stabilized hot galvanized steel wire does not change greatly in general. It can be seen from this that the key factors influencing the equilibrium of tensile strength and torsion performance are determined by wire drawing and hot dip galvanizing, and the critical process parameters include drawing speed, molten lead temperature and dipping length in lead bath . Practice shows that the drawing speed is increased properly, and the tensile strength of finished galvanized steel wire will rise, but torsion times do not change basically. If properly raising temperature of molten lead and extending time of dipping into lead bath, the torsion times of finished galvanized steel wire will increase and tensile strength will fall. Therefore, the adjustment of processing parameters that ensure the performance of final finished products should make a start on the key factors influencing product performances.

By means of the above-mentioned analysis, the "Dominant process + fine adjustment" integrated optimization technology of galvanized steel wire for stay cable used in Sutong Bridge is established. The Dominant process means conventional process of wire drawing and hot dip galvanizing; the fine adjustment refers to the proper adjustment of processing parameters influencing the performances of the final products.

In order to improve the hit rate of "Dominant process + fine adjustment" integrated optimization technology and ensure the step-by-step adjustment of processing parameter, each furnace must be selected and ordered. The test procedure for selecting and ordering ("7-5 detection" for short): randomly choose 7 wire rods from each furnace and make preproduction by adopting Dominant process ; in the process of preproduction, detect the semi-finished products of each process step by sampling, and "uniform loop difference" detection should be made for finished product. In relation to the technical data from "7-5 detection", fine adjustment and optimization of processing parameter should be conducted on basis of Dominant process so that the integral percent of pass will be improved.

3.5 "Three-level control" hot galvanizing operation technology

The surface quality of galvanized steel wire is dependent on the hot galvanizing of steel wire to a large extent. The wiping system of "gravel wiping + H_2S" is used for production line of hot dip galvanizing by Baosteel. The application of this wiping method to the domestic hot galvanizing is relative less, so no existing experience may be referred to for the control of surface quality of hot dip galvanizing.

Control of weight of zinc coating is to control adherence and flowing of liquid zinc on the surface of zinc iron alloy coating. When wiping by using wood carbon dust, the thickness of galvanized coating of steel wire surface mainly determined by speed of hot galvanizing[2]; as to gravel wiping, the thickness of galvanized coating is dependent on the "three-level" of the wiping gravel that is stack height, density and graininess of gravel. Through contrast test, the average graininess of the gravel used in hot galvanizing of ϕ7.0 mm galvanized steel wire should be ϕ(8 ~10) mm in control generally. In general, the stack height of gravel is preset, and the key adjustment in the process of production is to control the density of gravel.

The master of "three-level control" hot galvanizing operation technology for gravel wiping and strict supervision of control point of hot galvanizing quality lay strong foundation for the good surface quality of galvanized steel wire for stay cable used in Sutong Bridge.

4 Practical quality level

The three key technologies developed by Baosteel research institute of manufacturing technology of galvanized steel wire have solved the technical problems of producing galvanized steel wire, which provides technical support for the quality of galvanized steel wire for stay cable used in Sutong Bridge and construction schedule. By the time of April 10, 2007, Baosteel completed manufacturing task of domestic production of galvanized steel wire for stay cable used in Sutong Bridge, and total delivery quantity reaches 6 934 t. The primary indicators of product practicality quality see to Table 6.

Table 6 Major technical requirement and practical quality of galvanized steel wire for stay cable used in Sutong Bridge

Testing item	Standard of detection	Technical requirement s for Sutong Bridge	Detecting frequency	Maximum value of practical quality	Minimum value of practical quality	Average value of practical quality
Nominal diameter and Tolerance /mm	GB/T17101	7.00 ± 0.06	6 612	7.05	6.95	7.03
Tensile strength σ_b/MPa	GB228	≥1 770	6 612	1 950.00	1 770.00	1 821.82
Yield strength σ_s/MPa	GB228	≥1 450	6 612	1 850.00	1 560.00	1 714.26
Elongation /% (L = 250 mm)	GB228	≥4.0	6 612	8.00	4.00	5.29
Reserve bending /times (R = 20 mm)	GB228	≥5	6 612	10.00	5.00	7.23
Torsion performance/round (L = 700 mm)	GB/T17101	≥6	6 612	26.00	6.00	18.44
Wrapping /round	GB/T17101	3d × 8	6 612	Qualified	Qualified	Qualified
Elastic modulus /GPa	GB8653	190 ~ 210	6 612	208	190	196
Bow height /(mm· m^{-1})	GB/T17101	≤15	6 612	15.00	1.50	7.25
Natural tip rise /mm	GB/T17101	≤150	6 612	88.00	2.00	23.30
Weight of zinc coating /(g· m^{-2})	GB2973	≥300	6 612	594	300	388.88
Copper sulphate (Dipping) test /(times· min^{-1})	GB2972	≥4	6 612	9	4	5.17
Adhesion /round	GB/T17101	5d × 8	6 612	Qualified	Qualified	Qualified

5 Conclusions

The successful application of wire rod used in bridge stay cable with scale production to Sutong Bridge by Baosteel adopting technology of microalloying, super clean steel smelting, special controlled rolling and cooling technologies fills the gap of 1 770 MPa wire rod for stay cable and galvanized steel wire in China, realizes a big breakthrough for bridge stay cable produced domestically, and indicates that Baosteel keeps ahead in manufacturing technology of wire rod for bridge cable in China.

The stabilization process technology of "Double Tensioning + limiter die" innovated independently by Baosteel, "Dominant process + fine adjustment" integrated optimization technology of wire drawing and galvanization and "three-level control" hot dip galvanizing operation technology are the three key technologies in manufacturing galvanized steel wire with high strength, low relaxation and good torsion performances for stay cable used in Sutong Bridge. This new technology makes the manufacturing engineering of galvanized steel wire integrated with production of wire rods, which ensures the quality stability of galvanized steel wire for stay cable used in Sutong Bridge with scale production.

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3) Comparing with the corresponding code abroad, the difference of the result obtained by Sutong Bridge researching is small, and it already has some security surplus degree.

4) The drag coefficient calculation formula for cable in longitudinal direction wind load calculating proposed by Sutong Bridge can also be applied to the transverse direction wind load calculating, the formula is unity and applicability well.

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