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Fatigue Strength of Wires

Résistance à la fatigue des fils

Ermüdungsfestigkeit von Drähten

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SUMMARY
This paper describes the fatigue strength of prestressing wires which have been manufactured by the state-of-the-art. Taking wires for the automobile engine valve spring as an example, measures to enhance the fatigue strength of plain carbon wire are discussed. Finally, fatigue test data are presented for 7 mm diameter galvanized wire manufactured with all possible precautions to reduce flaws in the process.

RÉSUMÉ
Cet article traite de la résistance à la fatigue des fils de précontrainte fabriqués par les procédés les plus avancés. A partir de l'exemple de fils destinés aux ressorts de soupapes des moteurs de voiture, la discussion porte sur les mesures envisagées pour augmenter la résistance à la fatigue de fils d'acier au carbone non allié. Pour terminer, l'auteur présente des résultats d'essais effectués sur des fils galvanisés de 7 mm, pour lesquels toutes les précautions envisageables ont été prises afin d'éviter l'apparition de défauts de fabrication.

ZUSAMMENFASSUNG
Der Beitrag behandelt die Ermüdungsfestigkeit von nach modernsten Verfahren gefertigten Spanndrähten. Am Beispiel der Drähte für die Ventilfedern von Automotoren werden Maßnahmen zur Steigerung der Ermüdungsfestigkeit reiner Kohlenstoffstahldrähte diskutiert. Abschliessend werden Versuchsergebnisse für 7mm dicke galvanisierte Drähte präsentiert, bei denen alle denkbaren Vorkehrungen gegen Herstellungsfehler getroffen wurden.

1. INTRODUCTION

The ISO Standard for steels for the prestressing of concrete (ISO 6934-1,2,3,4 and 5) prescribes that, if agreed between purchaser and manufacturer, the material shall withstand 2 x 10^6 cycles of a stress fluctuating down from maximum stress of 70% of the nominal tensile strength and that the stress range shall be 200 N/mm^2 for plain wires, 180 N/mm^2 for indented and ribbed wire, 195 N/mm^2 for all strands.(1) The valve spring wire for automobile engine is considered to be the most stringent fatigue oriented product in the wire industry. The high tensile valve spring wire, manufactured by the quenching and tempering method with minimal flaws, can withstand more than 1 x 10^7 cycles at a stress amplitude of more than ±600 N/mm^2 in a rotating bending fatigue test.

It may be possible to improve the fatigue strength of plain carbon wires such as wire for prestressing of concrete and galvanized wire for parallel wire cables if we take some measures to reduce, if not eliminate totally, the flaws in the wire during manufacturing process in a manner as it is done for the valve spring wire. This paper describes how wires are manufactured and consideres where the flaws come in or removed during the manufacturing process of wires. An example of the improvement is given for a commercially manufactured 7 mm diameter galvanized wire for the stay cables of a world class cable stayed bridge.

2. PRESTRESSING WIRE

2.1 Specifications for Prestressing Wire

The tendons in the prestressed concrete members are subjected to relatively small stress fluctuations such as 50 N/mm^2 and a high fatigue performance is not a major requirement for the tendons. Few manufacturers, therefore, paid much attention to the fatigue property of the prestressing steels in the past. The prestressing wires, strands and bars are standardized by most national norms. They are now popular tension elements used to fabricate cables for cable supported structures in many parts of the world because they are strong, easily available and relatively economical. Fatigue requirements are gradually recognized by the users of the prestressing steels. Table 1 shows examples of the specifications for typical prestressing wires.

2.2 Manufacturing Method for Prestressing Wire

ISO 6934 "Steels for Prestressing of Concrete"(1) prescribes only the sulfur and phosphorus contents (both of which not to exceed 0.04%) because the chemical composition shall be related to the type of product, its size and tensile strength. ASTM A 421-90 "Uncoated Stress-Relieved Steel Wire for Prestressed Concrete"(2) also limits only phosphorous and sulfur contents, the maximum being 0.040% and 0.050%, respectively. It states that variations in manufacturing processes and equipment among wire manufacturers necessitate the individual selection of an appropriate chemical composition at the discretion of the manufacturer.

JIS G 3536 "Uncoated Stress-Relieved Steel Wires and Strands for Prestressed Concrete"(3) requires to select wire rod from "JIS G 3502 Piano Wire Rods"(4) as the material for prestressing wires and strands, which means that sulfur and phosphorus contents are lower than those prescribed by ISO and ASTM. The selection of the carbon content, however, is left to the discretion of the manufacturer. JIS further requires patenting for the manufacture of prestressing wires and strands.

Fig. 1 shows a diagram for the manufacture of prestressing wires. To take 7 mm diameter prestressing wire as an example, 12 mm dia. 0.77% carbon wire rod conforming to SWRS 77B in Table 2 is selected. The wire manufacturer receives wire rods from a steel mill. The wire rods are transferred from the storage area to the heat treatment area using a folk-lift truck or a hoisting crane, mounted on a pay-off stand, uncoiled and subjected to "patenting" where it passes through a heating furnace and lead bath and then is coiled. The tensile strength is approximately 1,260 N/mm².

Table 1 Specifications for Typical Prestressing Wires

	ISO 6934-2	ASTM A-421	JIS G-3536
Nominal Diameter, mm Tolerance, mm	7	6.35 ±0.05	7 ±0.05
Tensile Strength, N/mm²	1,570 1,670	1,655	1,520 1,620
0.1% Yield Strength, N/mm²	1,255 1,340	NS	NS
0.2% Yield Strength, N/mm²	NS	1,403	1,325 1,420
Elongation, %/G.L. mm	3.5/200	3.5/250	4.5/100
Reverse Bending, R=20mm	5	NS	NS
2 Million Fatigue Str., N/mm²	200**	NS	NS
Curvature (Bow height) mm/m	30/1.0	76/1.524	NS

NS: "not specified".
**: at maximum stress of 70% of nominal tensile strength.

Table 2 Chemical Compositions for Prestressing Wires (by weight %)
(Excerpt from JIS G 3502)

Element	C	Si	Mn	P	S	Cu
SWRS 77B	0.75-0.80	0.12-0.32	0.60-0.90	0.025 max.	0.025 max.	0.20 max.
SWRS 80A	0.78-0.83	0.12-0.32	0.30-0.60	0.025 max.	0.025 max.	0.20 max.
SWRS 80B	0.78-0.83	0.12-0.32	0.60 0.90	0.025 max.	0.025 max.	0.20 max.
SWRS 82A	0.80-0.85	0.12-0.32	0.30 0.60	0.025 max.	0.025 max.	0.20 max.
SWRS 82B	0.80-0.85	0.12-0.32	0.60-0.90	0.025 max.	0.025 max.	0.20 max.

The patented wire rod is supported with a hairpin hook, pickled in an acid bath, neutralized in a sodium nitrite solution, rinsed in water, dipped in a zinc phosphate solution, and then baked in an oven to dry the coating.

High Carbon Wire Rod — Lead Patenting — Descaling/Coating — Drawing — Hot-Stretching Treatment — Coiling

Fig. 1 Diagram for Manufacturing Method for Prestressing Wire

The wire rod is transferred to a drawing shop and mounted on a pay-off stand in front of a drawing machine. The 12 mm dia. wire rod is drawn to 7 mm dia. wire in 5 passes through tungsten carbide dies. The drawn wire is spooled or coiled for handling and is subjected to "hot stretching treatment" where the wire is heated to approximately 400°C and is stretched to yield 1% permanent strain and then wound into a coil of 1.5 to 2.0 meter in diameter. The coil is secured with steel straps. The minimum guaranteed tensile strength is 1,620 N/mm^2.

2.3 Fatigue Test Data

Many fatigue tests have been done for prestressing wire in the past and the test results are available. However, testing conditions are not necessarily unified and the direct comparison of the various test data is very difficult. ISO 6934-2 calls for a fluctuating stress down from maximum stress of 70% of the nominal tensile strength; many of the specifications for stay cables prescribe a maximum stress of 45% of GUTS; some other tests have been carried out at a minimum stress of 50 kgf/mm^2, and so on. Fig. 2 illustrates some examples of the definitions of the stress in fatigue tests.

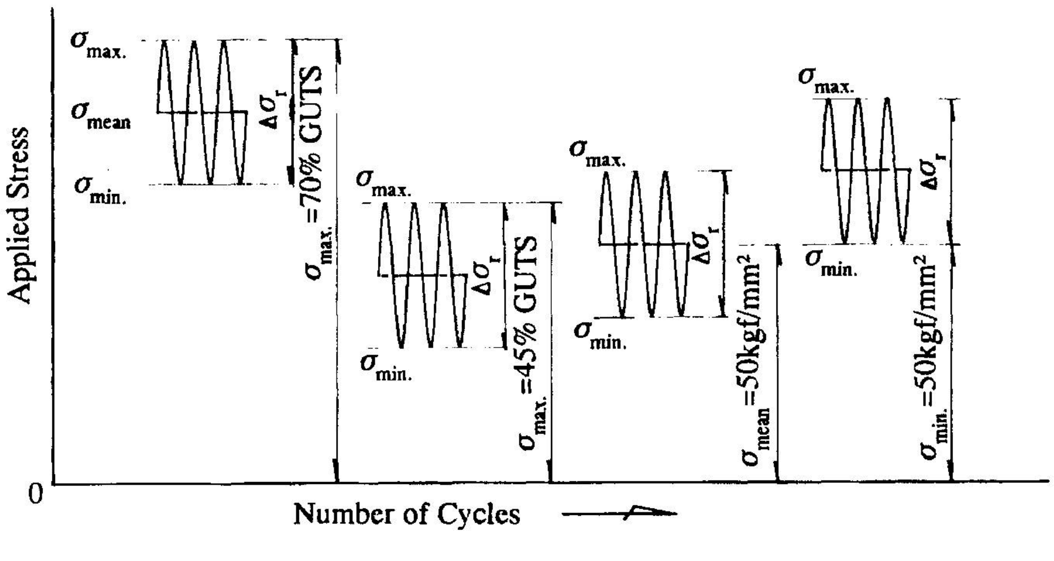


Fig. 2 Examples of the Definitions of Stresses in Fatigue Tests

Fig. 3[5] is an example of a fatigue test result for 7 mm dia. prestressing wire at a mean stress of 50 kgf/mm^2 (490 N/mm^2). The endurance limit is determined to be 40 kgf/mm^2 or 392 N/mm^2. Combining with other test results, and assuming that the distribution of the data follows the normal distribution, it is reported that a 5% fractile fatigue strength for the wire to be 36 kgf/mm^2 or 354 N/mm^2.

The two photographs of Fig. 4 (A) and (B) show a typical example of a fatigue failure of the prestressing wire. It is obvious that the fatigue failure started at a surface flaw that was present before it was subjected to the fatigue test.

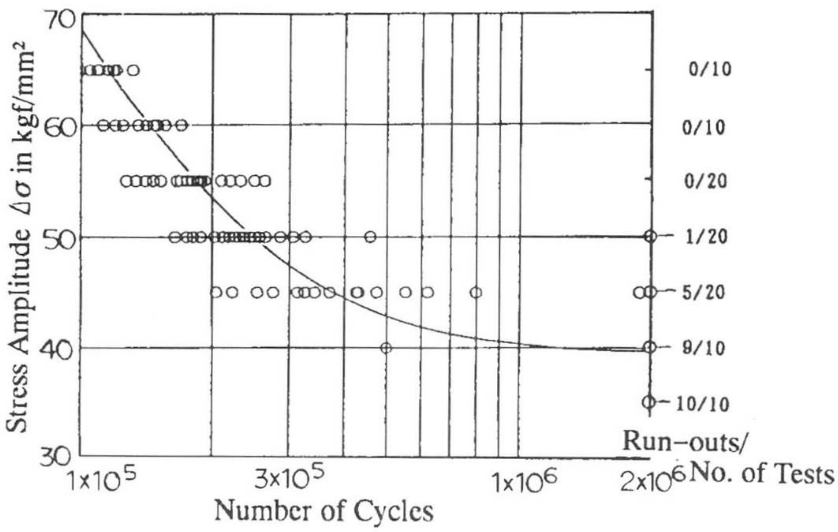
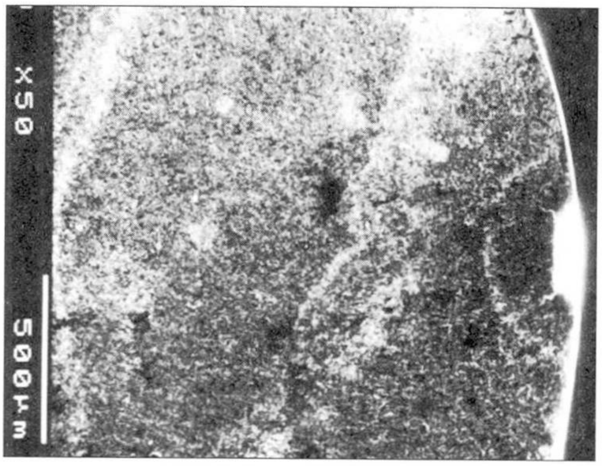
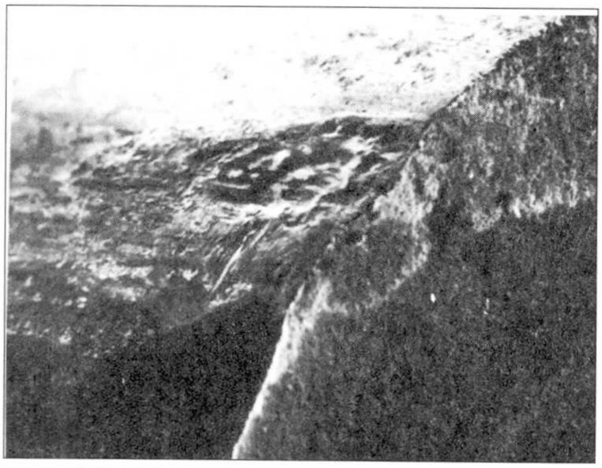


Fig. 3 An Example of Fatigue Test Results for a 7 mm Prestressing Wire



(A) Fatigue Fracture Surface
(50 Magnifications)



(B) Side View of Fracture End
(50 Magnifications)

Fig. 4 An Example of Fatigue Failure of Prestressing Wire

3. VALVE SPRING WIRE

3.1 Requirements

The intake and exhaust valves of an automobile engine are compressed from 250 to 4,000 times every minute (an average of 1,500 rpm) depending on the type of the car and type of operation. The valve springs must not fail during the life time of the car, say about 10 years. They are considered to experience something like 1 to 2 x 10^8 stress cycles at a temperature of about 100°C in service.

3.2 Manufacturing Process

Most high tensile strength valve spring wire is manufactured from the Si–Cr steel or Cr–V steel which is highly refined to reduce inclusions (Al_2O_3, SiO_2, etc.). Two examples of the chemical compositions for Si–Cr steel are given in Table 3. The blooms are subjected to extensive magnetic and ultrasonic flaw detection and any flaws are removed by hot scarfing. The blooms are rolled to billets and flaws are removed by chipping. The billets are rolled into wire rods. Extra cares are exercised to avoid mechanical damage during the blooming, hot rolling and subsequent handling. The wire rods are sometimes protected with a shock absorbing cloth and separating pad for transpiration to the wire mill. The inventories of wire rods are stored flat and are not piled up. Rough handling is strictly avoided.

The surface of the wire rod is peeled off to remove any surface imperfections such as the decarburization which might have been caused during the hot rolling and the mechanical damages which might result from the handling and transportation. For example, 8 mm rod is subjected to continuous eddy current flaw inspection and mechanically shaved to 7.4 mm in diameter using a cutting tool. The peeled rod is drawn to 4.00 mm on a continuous drawing machine. In order to achieve high tensile strength by a fine martensitic structure, the wire is heated to about 900C° and quenched in oil, followed by tempering at about 450C°. Special care is taken to avoid decarburization during the heating process. The oil tempered wire is continuously inspected with an eddy current flaw detector before it is finally wound into a coil. The maximum allowable flaw sizes are agreed between the manufacturer and the purchaser for continuous long flaws and spot flaws.

The HT Steel in Table 3 is an example of the chemical composition for a high tensile valve spring wire that is intended to help car manufacturers to reduce engine weight.

Table 3. Chemical compositions for Si-Cr Steel (by weight %)

Elements	C	Si	Mn	P	S	Cr	Cu	V
Regular Steel (JIS G 3566)	0.50- 0.60	1.20- 1.60	0.50- 0.80	0.025 max.	0.025 max.	0.50- 0.80	0.20 max.	- -
HT Steel	0.60- 0.65	1.30- 1.60	0.50- 0.80	0.025 max.	0.025 max.	0.50- 0.80	0.20 max.	0.08- 0.18

3.3 Mechanical Properties

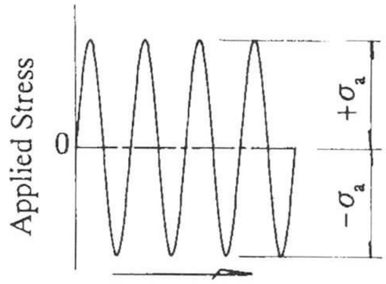
Table 4 shows the mechanical properties of the valve spring wires manufactured by the above mentioned oil tempering process. The yield strength ratio to the tensile strength is about 88% to 90%. The elongation is 4 to 6% in 100 mm gauge length.

Table 4. Mechanical Properties of Typical Valve Spring Wires
Wire Diameter: 4.0 mm

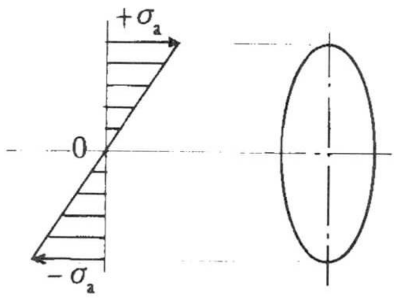
	Tensile Strength N/mm^2	Reduction of Area %
Regular Steel JIS G 3566)	1,810 - 1,960	not less than 40
HT Steel	2,010 - 2,110	not less than 30

3.4 Fatigue Strength

The fatigue tests for valve spring wires are usually carried out by a rotating bending method. Fig. 5 (A) illustrates the stress cycles at the outer fiber and Fig. 5 (B) shows the stress condition in the cross-section of the wire, respectively, in a rotating bending fatigue test. The valve springs are subjected to a shot peening treatment to enhance the fatigue performance. Table 5 shows 10^7 cycle fatigue test results for the wire as oil tempered and the wire subsequently treated by a shot peening. The tests were carried out by a Nakamura's rotating bending fatigue tester.



(A) Stress Cycles in a Rotating Bending Fatigue Test



(B) Stress Condition in a Wire

Fig. 5 Fatigue Test for Valve Spring Wire

Table 5 10^7 Cycle Fatigue Strength of High Tensile Valve Spring Wires (By Nakamura's Rotating Bending Fatigue Tester)

	As Oil Tempered N/mm²	After Shot Peening N/mm²
Regular Steel (JIS G 3566)	620	770
HT Steel	660	840

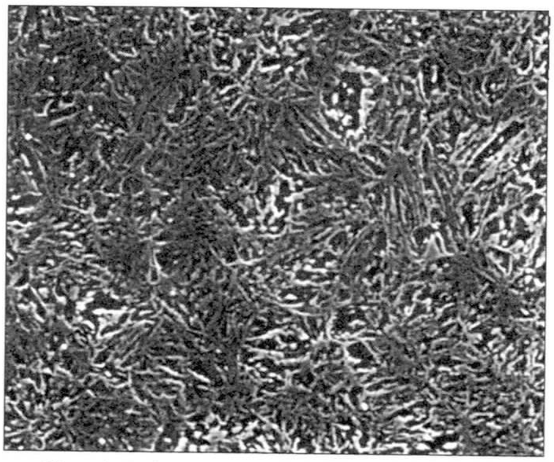


Fig. 6 Micro-Structure of an OT Wire (5,000 Magnifications)

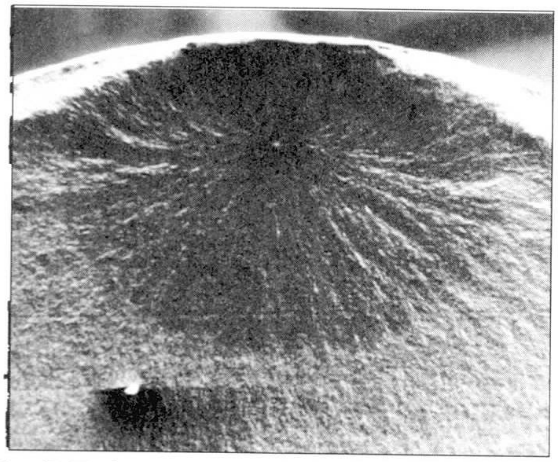


Fig. 7 Fatigue Fracture Surface of an OT Wire (50 Magnifications)

The stress condition of the wire under a rotating bending fatigue test is a tension–compression with a mean stress of zero. If the minimum stress is shifted to zero or higher, in other words, if the wire is subjected to a tension–tension fatigue test at a mean stress of, say, 1,000 N/mm², the endurance stress range will be something like 1,000 N/mm² or higher. Figs. 6 and 7 show an example of micro–structure and a fatigue fracture surface of an oil tempered wire. In most cases, the fatigue cracks of the high quality valve spring wire initiate at an internal flaw such as inclusions because there is less surface flaw.

4. GALVANIZED WIRE

4.1 Specifications for Galvanized Wires

Galvanized wire is preferred for parallel and semi–parallel wire cables even though the hot dip galvanizing process reduces the tensile strength and fatigue strength. Table 6 shows Japanese specifications for galvanized wires for bridge use.

Table 6 Japanese Specifications for Galvanized Wires for Bridge Use

Specification	JSSC JSS-12-1978	HBS G3501-1979	HBS* Special
Dimension			
Nominal Diameter, mm	5.00	5	7.00
Tolerance, mm	0.06	0.06	0.08
Out-of Roundness, mm	0.06	0.06	0.08
Physical Properties	min.- max.	min.- max.	min.- max.
Tensile Strength, N/mm²	1,569-1,765	1,569-1,765	1,569-1,765
0.7% Proof Stress, N/mm²	1,157	1,157	1,157
Elongation in 250 mm, %	4.0	4.0	4.0
Torsion, Turns/100 x d	14	14	12
Wrapping, 8 Turns/3 x d	No fracture	No fracture	No fracture
Zinc Coating			
Coating Weight, g/m²	300	300	300
Increase of Dia., mm		0.12	0.14
Curvature			
Free Coil Dia., m	4.0	4.0	
Up-lift, cm	15	14	
Bow Height, mm/m			35/2.0
Up-lift, mm/m			5/2.0

HBS*Special: a specification for specific bridge projects.

The authors' company has supplied semi–parallel wire (or long lay) cables for more than 20 cable stayed bridge projects using galvanized wire. As can be seen in Table 6, no fatigue requirements are prescribed in the Japanese specifications. However, it is obvious that stay cables are fatigue sensitive and a good wire with high fatigue strength should be used for them.

The following discussions are based on a typical production record. The Higashi Kobe Bridge, a double deck cable stayed bridge with a center span of 485 meter long required 1,300 tons of 7 mm galvanized wire for its 104 stay cables. The largest and longest cables were 357 x 7 mm diameter wires and 220 meters long. The specification for the galvanized wire was identical with the HBS Special Specification which called for the wire rod to be 13 mm diameter SWRS 82B as set forth in JIS G 3502 Piano Wire Rods.

4.2 Manufacturing Method

All possible precautions were taken by the wire rod mill to prevent metallurgical imperfections and the surface damages which might be caused during the rolling and handling. The result of ladle analysis for the chemical composition and metallurgical inspection were as shown in Tables 7 and 8, respectively

Table 7 Chemical Composition of 13 mm Dia. Wire Rod

Elements	C	Si	Mn	P	S	Cu
Spec.:JIS G 3502 SWRS82	0.80-0.85	0.12-0.32	0.60-0.90	0.025 max.	0.025 max.	0.20 max.
Ladle Analysis	0.83	0.24	0.72	0.012	0.008	0.01

The wire manufacturer's precautions started as soon as the wire rods arrived at his stock yard. Any of the sharp edges of the handling equipments were covered with soft materials. The fork-lift truck and crane operators were instructed to prevent hitting the rods against the concrete floor and other coils. The rods were stored on a soft floor in a covered storage area. The received wire rods were carefully inspected for surface flaws. Non-metallic sling was used to hoist the rods and wire. All guides and rollers were made of, or covered with, plastics.

Table 8 An Example of Inspection Results for Wire Rod

	Specification	Test Result	Judge
Dimensions	Diameter 13±0.40mm	T:13.04mm B:13.02mm	Good
	Out-of-roundness 0.4mm max.	T:0.14mm B:0.13mm	Good
Non-metallic Inclusions	Cleanliness 0.1% max.	T:0.03% B:0.02%	Good
Decarburization	Depth 0.07mm max.	T:0.04mm B:0.03mm	Good
Flaw	Depth 0.10mm max.	T:0.00mm B:0.00mm	Good

T and B: top and bottom of a length of wire rod, respectively

The manufacturing method was identical with that for prestressing wire described earlier with the only exception that hot-stretching treatment was replaced with galvanizing process: The 13 mm dia. wire rod with a chemical content as shown in Table 7 was lead patented, descaled in hydrochloric acid and was coated with zinc phosphate before it was cold drawn. The wire rod, which had a tensile strength of approximately 1,255 N/m^2, was drawn in 6 passes to 6.87±0.03mm in diameter and resulted in a tensile strength of 1,620 to 1,815 N/mm^2. The drawn wire was passed through a hot zinc bath to make 7.00±0.08mm diameter zinc coated wire.

4.3 Mechanical Properties

An example of test results for a batch of the 7 mm dia. galvanized wire is given in Table 9.

Table 9 Example of Test Results for 7 mm Dia. Galvanized Wire

	Specification	Test Result Max.	Min.	Mean	n
Dimensions					
Diameter	7.00±0.08mm	7.03	6.99	7.01	68
Out-of-Roundness	0.08mm max.	0.05	0.02	0.04	68
Physical Properties	min.- max.				
Tensile Strength	1,569-1,765N/mm²	1,657	1,608	1,638	68
0.7% Proof Stress	1,157N/mm²	1,294	1,285	1,286	8
Elongation	4.0%/250mm G.L.	6.4	5.8	6.2	8
Torsion	12 turns/100 x d	27	26	27	4
Wrap	8 turns/3 x d	No fracture			4
Zinc Coating					
Weight	300 g/m² min.	388	371	380	4
Adhesion	2 turns/5 x d	No flaking off by nail			4
Dia. Increase	0.14mm max.	0.11	0.11	0.11	4
Straightness					
Arc Height	35mm/1.5m max.	25	17	21	4
Up-lift	5mm/1.5m max.	0	0	0	4

n: number of tests.

4.4 Fatigue Test

To establish S–N diagram for the galvanized wire, fatigue tests were carried out using 200 mm long specimens on a 10 ton capacity electro-servo type fatigue tester. Fatigue test results are given in Figs. 8 and 9 for the mean stresses of 50kgf/mm² (490 N/mm²) and 100kgf/mm² (980 N/mm²), respectively.

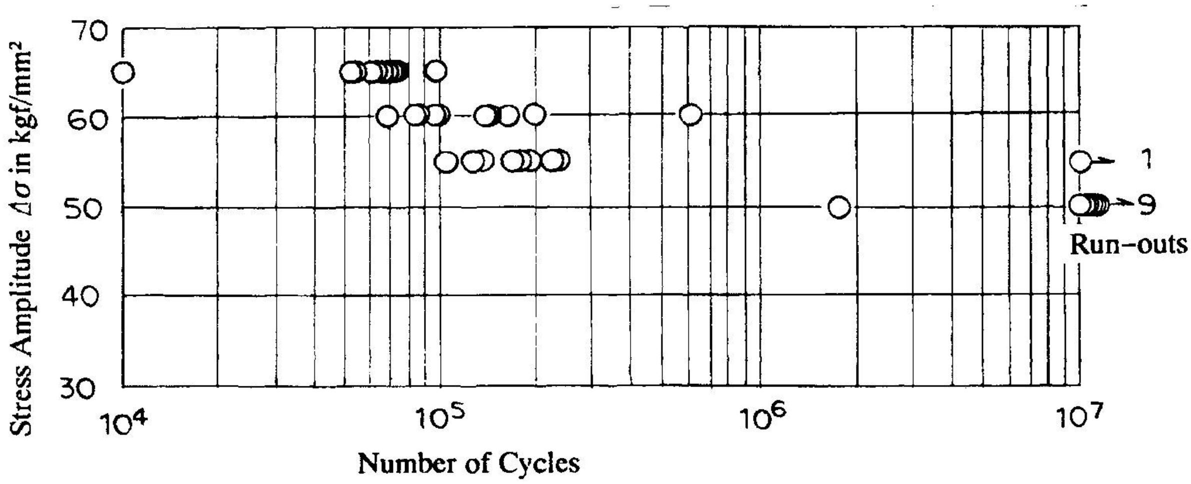


Fig. 8 Fatigue Test Result for 7 mm Dia. Galvanized Wire at a Mean Stress of 50kgf/mm² (490N/mm²)

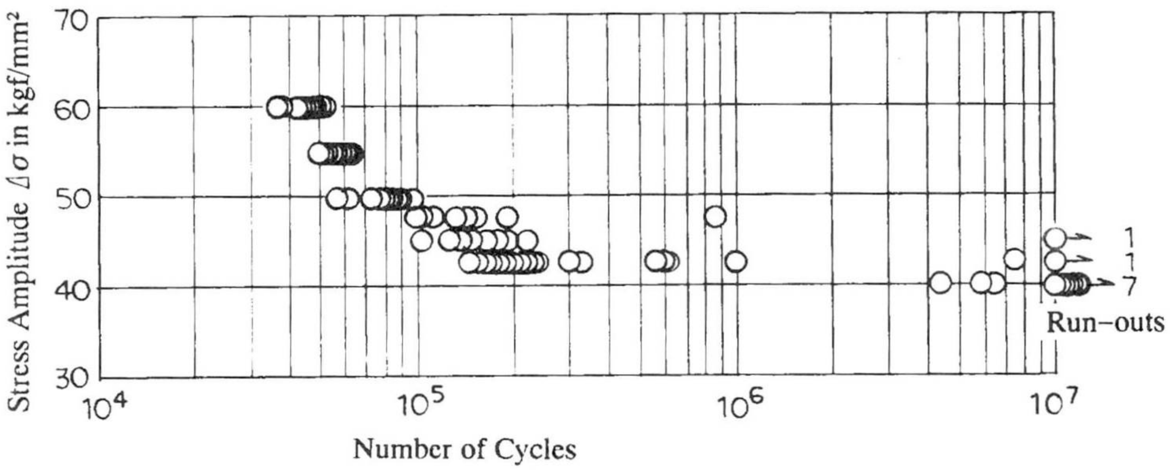


Fig. 9 Fatigue Test Result for 7 mm Dia. Galvanized Wire at a Mean Stress of 100 kgf/mm^2 (980 N/mm^2)

The fatigue tests are still under way to establish a statistical analysis. However, the number of the test data available to date is not enough to permit a statistical calculation of the fatigue values and so we have to guess the endurance limit from the S–N diagrams. It is considered that the endurance limits are 50 kgf/mm^2 (490 N/mm^2) and 40 kgf/mm^2 (392 N/mm^2) for the mean stress of 50 kgf/mm^2 (490 N/mm^2) and 100 kgf/mm^2 (980 N/mm^2), respectively.

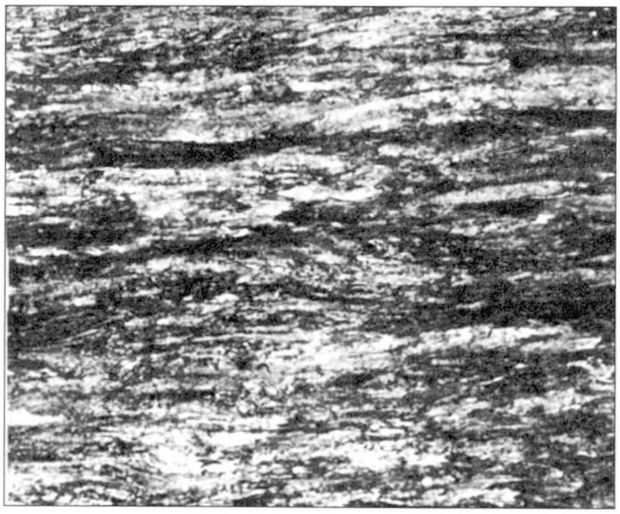


Fig. 10 Micro–Structure of a Galvanized Wire (400 Magnifications)

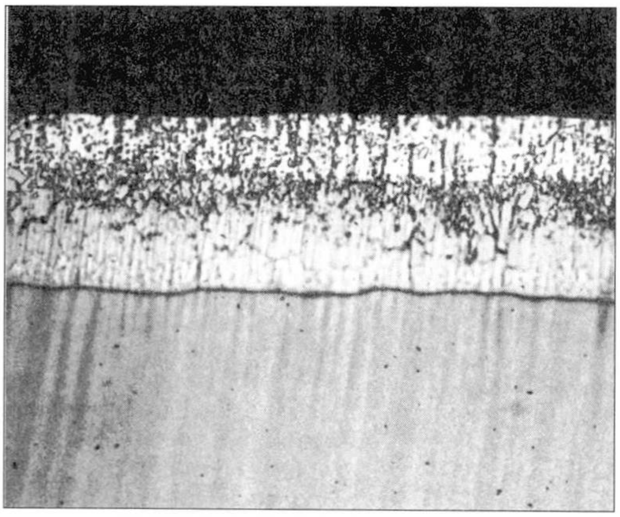
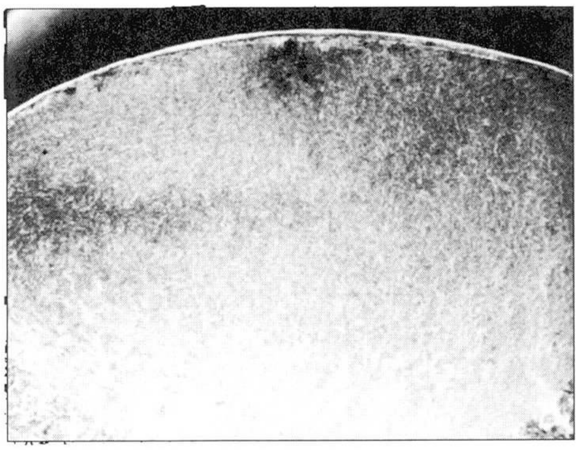


Fig. 11 Micro–Structure of Zinc Coating (400 Magnifications)

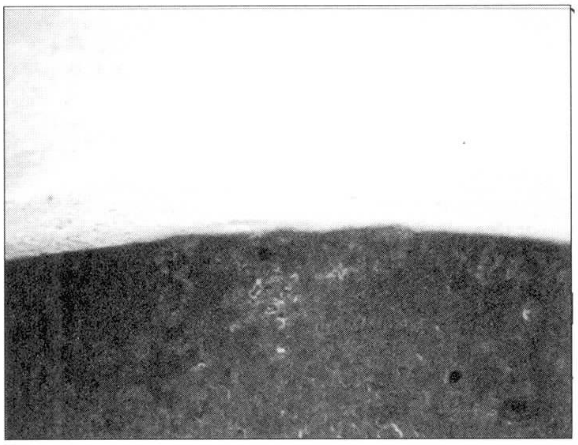
4.5 Microscopic Observations

Fig. 10 is a micro–structure of the galvanized wire. This is a typical fiber structure and is identical with that of the prestressing wires. Note that the micro–structure is entirely different from the one shown in Fig. 6 for oil tempered wire. Fig. 11 is a micro–structure of the zinc coating.

Fig. 12 (A) is an SEM photograph of a broken end of a 7 mm galvanized wire after fatigue test. The fatigue failure obviously started at a surface flaw of the steel. The surface of the wire was exposed by resolving the zinc coating in an acid and was observed: a small indentation was found at the initiation of the fatigue crack as shown in Fig. 12 (B).



(A) As Broken
(35 Magnifications)



(B) After Zinc Coating Removed
(100 Magnifications)

Fig. 12 SEM Photographs of a Fatigue Failure of a 7 mm Galvanized Wire

For a comparison, the zinc coating was removed from the galvanized wire specimens in an acid and the specimens were subjected to fatigue test. The bare wire withstood 1×10^7 at a stress range of 55 kgf/mm^2 (539 N/mm^2) at a mean stress of 100 kgf/mm^2 (980 N/mm^2). Therefore, the galvanizing reduced the fatigue strength by about 15 kgf/mm^2 (147 N/mm^2).

5. DISCUSSIONS ON THE POSSIBLE SOURCE OF FLAWS

Almost all of fatigue failures of wires, whether a wire for valve spring or a wire for stay cables, are associated with some kind of flaws. It is not possible to determine where such flaws exist before the wire fails in a fatigue test or in service.

There are flaws that originate at the steel mill such as segregation, non-metallic inclusions, decarburization, and the like. There are also external imperfections such as nicks and corrosion. At modern steel mills, molten and refined steel is continuously cast into blooms. Each length of the blooms is hot scarfed to remove surface imperfections. The blooms are rolled into billets. Any external flaws are chipped off. The billets are subsequently rolled into wire rods. The wire rod is laid into coil and secured with steel straps for handling. The wire rods may be stored a concrete floor for a few days to several months at the rolling mill's warehouse or open yard. Corrosion may take place during storage at the rod mill and wire mill. During the transportation and storage, the wire rods are in direct contact with other wire rods and may suffer abrasion indents and scratches during the transportation.

In most cases, flaws in the wire rod are carried through the wire making process. In addition, there are sources of the flaws at the wire mill that may be attributed to the mechanical damages and corrosion of the wire rod or the wire in process. There is a possibility that mechanical damages may be caused whenever the wire touches with any metallic tools, guides and rollers in handling, processing, packing and storage. Steel straps, hoisting hooks and rope slings are also suspected.

We know that oil tempered wire cannot be used for prestressing tendons and stay cables because of its high susceptibility to stress corrosion, and that the steel grades and manufacturing methods are different for valve spring wire and prestressing wire. However, the difference of the carefulness during the manufacture of the valve spring wire may indicate a way of improving the fatigue strength of the plain carbon wires for structural cables. In fact, high fatigue performance was achieved for 7 mm diameter galvanized wire which was manufactured on a commercial production basis with some precautionary measures in the wire production.

6. CONCLUSIONS

(1) The fatigue strength of prestressing wire available on the market place vary widely and an example of 5% fractile fatigue strength of a prestressing wire was reported to be 354 N/mm^2 at a mean stress of 490 N/mm^2.

(2) A valve spring wire for automobile engine, which is manufactured by the quenching and tempering method with the utmost care, can withstand more than 1 x 10^7 cycles at a stress amplitude of $\pm$840 N/mm^2 in a rotating bending fatigue test.

(3) There is a possibility to improve the fatigue strength of plain carbon wire if some precautions are exercised in the wire manufacturing process.

(4) The fatigue strength of the 7 mm diameter galvanized wire, which was manufactured with care and used for an actual bridge, was determined to be 490 N/mm^2 and 392 N/mm^2 at the mean stresses of 490 N/mm^2 and 980 N/mm^2, respectively.

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