Development of High-Strength Steel Wire with Superior Weldability

Hiromu IZUMIDA*, Kenichi SHIMIZU, Shinei TAKAMURA, Yasuhiro SHIMODA,
Osamu MOMOZAWA and Teruyuki MURAI

High-carbon steel wires, such as piano, hard-drawn, or oil-tempered wire, are used for automotive and electronic parts. Despite their outstanding advantages in strength, ductility, and fatigue resistance, these wires are susceptible to fracture due to the brittle as-quenched martensite structure formed by welding. To overcome this problem, we have developed a high-strength steel wire that consists of a bainitic matrix phase to enhance weldability, by adding carbide former elements to low-carbon steel. The developed wire features 1) a finely recrystallized bainite phase in place of the brittle martensite phase even after welding treatment, 2) work hardening behavior and tensile strength equal to and 3) a softening resistance superior to those of a piano wire, 4) a low degradation in the tensile strength (approx. 4%) after welding, and 5) a fatigue limit equivalent to that of a piano wire after 2×10^6 rotational bending. Sumitomo (SEI) Steel Wire Corp. has already started supplying the wire and is currently working to broaden its application field.

Keywords: steel wire, low carbon, high weldability, high strength, bainite phase

1. Introduction

1-1 Development concept

Owing to their superiority in strength, ductility and fatigue resistance, high-carbon steel wire*1 (e.g., piano wire*2 and hard-drawn steel wire) and oil-tempered wire are widely used as automotive and household electrical appliance parts materials. When welded, however, these wires are susceptible to quenching cracks, due to the brittleness of the hardened structure (martensite phase*3). When they are heat-treated after welding, the welded sections are often affected by welding heat and are reduced in strength. Steel has a general trade-off relationship between strength enhancement and weldability improvement, as described above. The common practices for avoiding such a trade-off are to use different joining methods, such as adhesive joining and brazing, or to increase the number of parts, instead of welding.

With the aim of creating a high-strength carbon steel wire that would not deteriorate in terms of ductility even after hardening subsequent to welding, the authors have developed a high-strength steel wire by adding a carbide precipitation element to low-carbon steel. The newly developed steel wire has a bainite phase*4 as its matrix.

This paper discusses the mechanism for enhancing the weldability of the new steel wire, as well as its characteristics.

2. Chemical Composition Design

The chemical composition of the newly developed steel wire is shown in **Table 1**. Compared to conventional piano wire and hard-drawn steel wire, the new wire contains only 0.2% of carbon to reduce its susceptibility to quenching cracks. Increased manganese (Mn) content and the addition of chromium (Cr) improve the strength, ductility and other mechanical characteristics of the new wire.

Table 1. Chemical composition of newly developed steel wire

	C	Si	Mn	Cr
New wire	0.20	0.86	1.54	0.94
Class B piano wire (for comparison)	0.84	0.21	0.70	–

(mass%)

3. Optimization of Heat Treatment

A typical manufacturing process for conventional piano wire and hard-drawn steel wire is shown in **Fig. 1**. A cast billet is hot-rolled into wire rods. The wire rods are then heat-treated to homogenize their metallic structure, thereby enhancing their drawability, strength and ductility to required levels. Subsequent to the above heat treatment, the wire rods are drawn into wires of specified sizes.

The same process will be used to manufacture the developed steel wire. Heat treatment of the new steel wire is essential in ensuring the required characteristics.

To establish the heat treatment conditions most appropriate for the developed steel wire, we developed a time-temperature-transformation (TTT) diagram. In the course of diagram preparation, we carried out an experiment to observe the metal structure of the test specimens

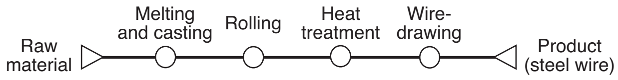


Fig. 1. Piano wire and hard-drawn steel wire manufacturing process

during their isothermal transformation. In the experiment, the austenitizing temperature was set at 900°C; the test specimens were air-cooled and immersed in a lead bath or fused salt bath. The TTT diagram developed on the basis of the experimental results is shown in **Fig. 2**.

Figure 2 clearly shows that the developed steel wire's transformation curve is shifted toward the longer time side, thereby delaying transformation initiation and termination. This is because the new steel wire contains chromium (Cr), a carbide-forming element, in a greater percentage than the high-carbon steel used for manufacturing piano wire and hard-drawn steel wire. The new steel wire required a particularly long time of at least 6 to 7 minutes before pearlite transformation[*5] began at a temperature between 550°C and 700°C. In contrast, it was confirmed that bainite transformation completed within a relatively short period of time (approximately 20 seconds at 420°C).

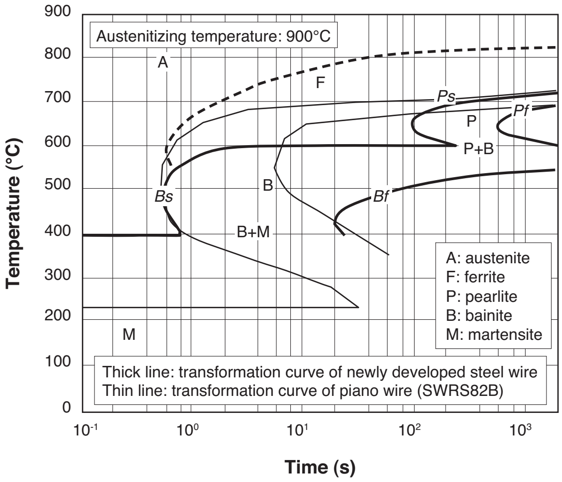
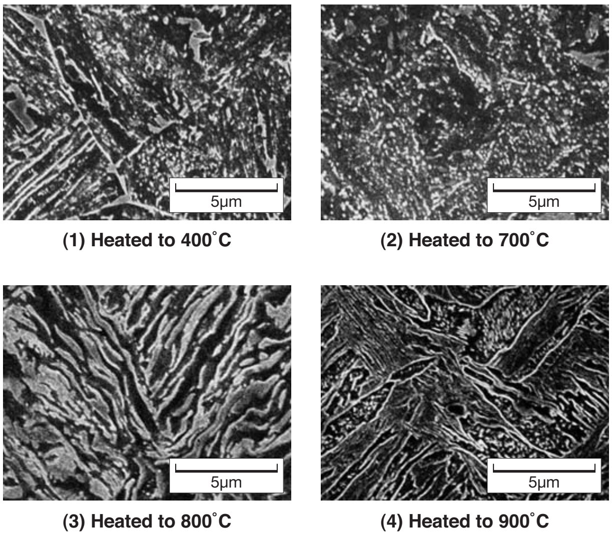


Fig. 2. TTT diagram of newly developed steel wire

We knew from our past research studies that the strength and fatigue resistance of bainite steel wire are comparable to those of pearlite steel wire(1). On the basis of this knowledge, we decided to introduce bainitization heat-treatment to facilitate mass-production of the new steel wire. This report describes the evaluation results of a new steel wire experimentally produced by bainitization heat treatment at 420°C for 20 seconds via the process shown in **Fig. 1**.

4. Change in Metal Structure by Welding

Photo 1 shows the metal structures of developed steel wires that were heated and cooled to simulate the effect of welding heat. Heat-treated for bainitization, the wires were cut into approximately 0.5 mm thick slices. These sample slices were heated at a predetermined temperature for 1 minute and cooled naturally. They were then polished and corroded in picric aid ethanol to visualize the metal structure. Particularly in this observation, each sample slice was heated to 400°C through 1,100°C at 100°C intervals. **Photo 1** shows typical examples of metal structure change. It was confirmed from **Photo 1** that cementite[*6] spheroidization accelerated as the temperature increased from 400°C to 700°C, while the ferrite phase was recrystallized when the temperature exceeded 800°C. No hardened structure (martensite phase) was observed in either cementite or ferrite phase. Many coarse, spherical cementite particles were observed at 800°C; at 900°C or higher, however, the cementite particles were thoroughly dissolved and crystallized again. The recrystallized particles were then precipitated along grain boundaries and in transgranular regions (bainite structure). Since the recrystallized structures contained finely dispersed carbides, it was expected that the developed steel wire would maintain high hardness even if heated and cooled in a relatively short period of time by welding.



(1) Heated to 400˚C **(2) Heated to 700˚C**

(3) Heated to 800˚C **(4) Heated to 900˚C**

Photo 1. Thermal effect on metal structure of newly developed steel wire

Figure 3 shows the hardness change in a developed steel wire heated and cooled on the assumption of welding. For comparison, the change in hardness of a piano wire (JIS SWRS82B; C: 0.81%) is also shown. Like structural change, the spheroidization of cementite in the new steel wire was accelerated most intensively at 700°C. When heated to 900°C or higher, the new steel wire crystallized and precipitated cementite again, thereby enhancing its strength. In contrast, the piano wire sharply increased its Vickers hardness to Hv 800 or higher when heated to 900°C or higher. The increase in hardness was attributed to the formation of a hardened structure that deteriorated the ductility of the piano wire.

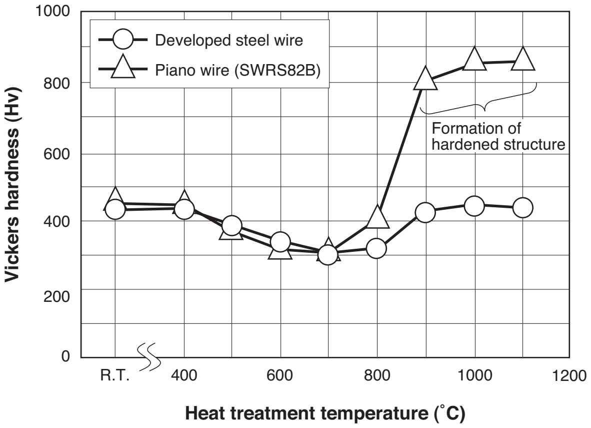


Fig. 3. Change in hardness of newly developed steel wire exposed to assumed welding heat

5. Features of Developed Steel Wire

5-1 Results of trial production of new steel wire (work-hardening rate and tempering characteristics)

Figure 4 shows the work-hardening rate from drawing of the new steel wire. For comparison, this figure also contains data on the Class B piano wire, a conventional high-strength steel wire made by drawing an SWRS82B wire rod (JIS SWP-B standards for steel wires) using the same drawing machine as for drawing the new steel wire. This figure clearly shows that the work-hardening rate and ultimate strength of the new steel wire were almost equal to those of the Class B piano wire.

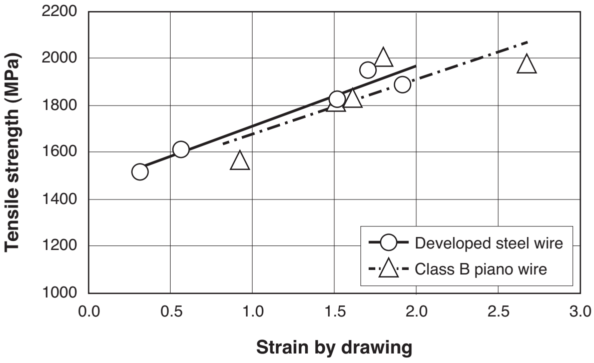


Fig. 4. Work-hardening rate of developed steel wire

Figure 5 shows the tensile strength (tempering characteristics) of developed steel wire (2.8 mm in diameter) whose residual strain from drawing was relieved by annealing. For comparison, this figure also shows the data on a Class B piano wire. This figure shows that both materials recovers toughness as the annealing temperature increases, reducing tensile strength. The Class B piano wire reduced tensile strength when annealed at a temperature of 350°C or higher. In contrast, the developed steel wire demonstrated the maximum tensile strength at nearly 350°C, verifying that it had high softening resistance against annealing. The reason is that the pearlite structure of the piano wire was spheroidized when heat-treated at 350°C or higher[(2)], while the developed steel wire precipitated carbides consisting mainly of chromium (Cr).

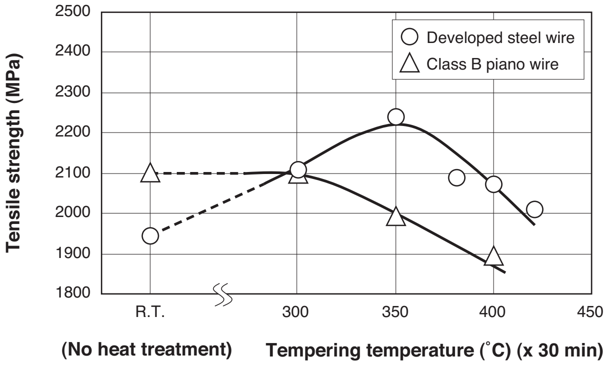


Fig. 5. Tempering characteristics of developed steel wire (2.8 mm diameter)

5-2 Weldability

Developed steel wires (0.45 mm in diameter) were welded together (Electric resistance welding → natural cooling) and the tensile strength of the welded wires was measured. Burr on the welded joint was not removed by grinding, so as to keep grinding scratches from affecting the test results. The external appearances of a representative test specimen before and after the measurement are shown in **Photo 2**. The measurement results, which are the mean values of three specimens (n = 3), are shown in **Table 2**. In measurement, the welded test specimens fractured at a heat-affected zone 0.2 mm to 0.5 mm distant from the welded seam. However, the decrease in tensile strength due to welding heat was only 50 MPa (approximately 4% from 1,491 MPa to 1,441 MPa). The fractured portions showed cup-and-cone patterns, verifying that the welded joints were still highly ductile.

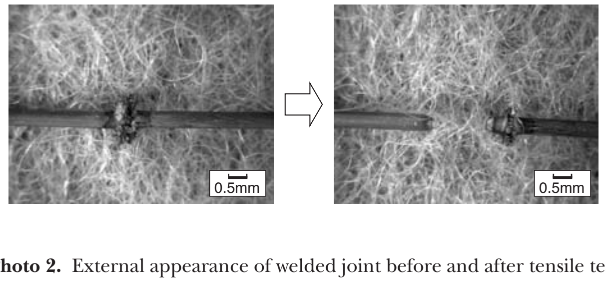


Photo 2. External appearance of welded joint before and after tensile test

Table 2. Tensile test results for welded joint

Specimen	Tensile strength (MPa)	Fracture point
Before welding	1491	—
After welding	1441	Heat-affected zone close (approx. 0.5 mm) to welded seam

The metal structure and hardness of the cross section of a fracture point are shown in **Photo 3**. As also shown in **Photo 1**, a finely recrystallized bainite phase was observed in the welded zone, and a bainite structure containing partly spheroidized cementite was observed in the heat-affected zone. Hardness measurement results verified that the test specimens fractured at a portion where hardness decreased owing to the effect of welding heat.

However, the welded section itself retained relatively high hardness, with hardness decreasing in only a limited area. As a result, it was confirmed that the rate of tensile strength decrease was small.

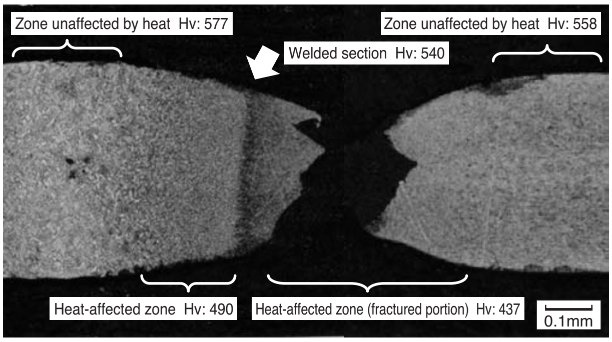


Photo 3. Metal structure and hardness of welded part fractured in tensile test

5-3 Fatigue Characteristics

We carried out a fatigue test for a developed steel wire of 0.45 mm diameter to estimate its fatigue strength.

The tensile characteristics of the test specimen are shown in **Table 3**. In this test, a Hunter rotary bending fatigue testing machine was used, with the maximum number of stress cycles set at 2 x 10^6.

The fatigue test results are shown in **Fig. 6**. They showed that the developed steel wire had a high fatigue limit of approximately 625 MPa, which is almost equal to the fatigue limit of the Class B piano wire used for comparison.

Table 3. Tensile characteristics of developed steel wire

	Wire diameter (mm)	Tensile strength (MPa)
New steel wire	0.45	1491
Class B piano wire (for comparison)	0.50	2593

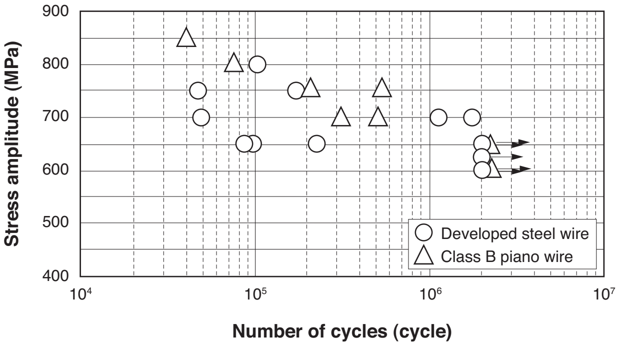


Fig. 6. Fatigue limit of developed steel wire (2 x 10^6 cycles, rotary bending fatigue test)

6. Conclusion

The new steel wire development activities are summarized as follows:

- With the aim of developing a high-weldability, high-strength steel wire, we have succeeded in test manufacturing a bainite steel wire by adding chromium (Cr) to difficult-to-harden low-carbon steel, thereby strengthening carbide precipitation.
- Development of the developed steel wire's time-temperature-transformation (TTT) diagram has enabled bainitization heat treatment of the new steel wire at 420°C for 20 seconds.
- After heating and cooling the new wire as though it were welded, the structure of the wire was observed and its hardness was measured. Results showed that the wire did not produce a hardened structure, verifying that the zone exposed to high welding heat produces a finely recrystallized bainite phase.
- The work-hardening rate by drawing and the tensile strength of the newly developed steel wire were comparable with those of piano wire.
- The tempering characteristic of the developed steel wire was tested. The results showed that, though piano wire began softening when heated to 350°C, the new steel wire's tensile strength reached the maximum value at 350°C. The new steel wire also had high softening resistance.
- The tensile strength of the developed wire after welding was tested. In the test, the specimen began to fracture at the heat-affected zone; the rate of strength deterioration was approximately 4%.
- The rotary bending fatigue strength of the developed steel wire was measured. The measurement results showed that the fatigue limit of the new wire was 625 MPa for a number of stress cycles of 2 x 10^6; this fatigue limit was nearly equal to that of piano wire.

The developed wire is superior in weldability, strength and ductility. Sumitomo (SEI) Steel Wire Corp. has already begun supplying this new steel wire as an automotive parts material. With a development of a welding method that can keep welding heat from affecting wire tensile strength, the new wire's field of application will be broadened further.

Technical Terms

*1 Steel wire: Steel is an alloy made by adding carbon to iron in order to its intrinsic properties (such as strength and ductility). Steel generally refers to carbon steel with carbon content of 0.3% ~ 2.0%. Steel wire is made by rolling or drawing a wire rod.

*2 Piano wire: Piano wire is high-strength, superior fatigue-resistant carbon steel wire consisting mainly of a pearlite phase as its matrix.

*3 Martensite phase: Martensite phase is a very hard, brittle structure that is formed in carbon steel when heated to a high temperature and then cooled rapidly (for hardening). When welded, carbon steel often begins cracking in this phase.

*4 Bainite phase: Bainite phase is a quasi-stable structure of steel. This phase is formed in the temperature zone between pearlite formation temperature and martensite formation temperature, when steel is heated to a high temperature and then cooled. The bainite phase comprises ferrite in which fine iron carbides are precipitated in the form of cementite.

*5 Pearlite phase: Pearlite phase is a lamellar structure of steel formed by a eutectoid reaction. This phase consists of alternating layers of extremely thin sheet-like ferrite (metal structure of iron at normal temperature) and cementite. When a wire rod is drawn into wire, the lamellar structures lie in the drawing direction, forming a texture with reinforced fiber dispersion.

*6 Cementite: Cementite is an extremely hard (Approx. 1,340 Vickers hardness), brittle structure of iron carbide (Fe_3C). Being a compound of metal and nonmetal, cementite is a ceramic.

References

(1) H. Izumida, N. Kawabe, "WIRE JOURNAL INTERNATIONAL", p.80-83 (June 2001)
(2) N. Kawabe, H. Izumida et al., "SEI TECHNICAL REVIEW No.157", P.110-115 (2000)

Contributors (The lead author is indicated by an asterisk (*).)

H. IZUMIDA*
- Assistant General Manager, Advanced Materials R&D Laboratories
He has been engaged in the development of steel and alloy wires for automotive parts.

K. SHIMIZU
- Doctor of Engineering
Assistant General Manager, Advanced Materials R&D Laboratories

S. TAKAMURA
- Department Manager, Sumitomo (SEI) Steel Wire Corp.

Y. SHIMODA
- Assistant Manager, Sumitomo (SEI) Steel Wire Corp.

O. MOMOZAWA
- Assistant Manager, Sumitomo (SEI) Steel Wire Corp.

T. MURAI
- Senior Specialist,
Director and Chief Engineer, Sumitomo (SEI) Steel Wire Corp.