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New Wire Rods Produced by In-Line Heat Treatment

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Abstract

Main examples of newly developed wire rods produced by the In-line heat treatment such as the In-line QT wire rods of middle carbon and low alloy steels manufactured in Muroran woks and the Bainitic wire rods of high carbon steels in Kimitsu works are introduced. The former manufactured by the combination of controlled cooling by spraying of cold or hot water and In-line tempering has homogenous properties free from cracks during cooling. The latter manufactured by the direct isothermal heat treatment in the salt bath after wire rod rolling has upper bainite microstructure. As the cementite in upper bainite is short and scattered, dislocation moves smoothly during deformation leading to high ductility and drawability.

1. Introduction

In the wire rod field, various in-line controlled cooling techniques have been developed to improve drawability, increase strength and toughness, control scale, and simplify or eliminate secondary working processes[1-3]. The initial controlled cooling techniques developed by Nippon Steel are described in detail by Yada et al[2]. As recent new typical examples of in-line heat treating techniques established thereafter, this report describes the manufacturing processes and characteristics of direct quenched and tempered wire rods (hereinafter referred to as in-line QT wire rods) produced at the Muroran Works and of bainite wire rods produced at the Kimitsu Works.

2. In-Line QT Rods

2.1 Description of in-line QT rods

In 1975, the wire rod mill of the Muroran Works started the manufacture of 1,500-N/mm^2 high-strength steels as pre-stressed concrete (PC) steel bars for concrete piles and poles by direct quenching through the application of controlled cooling with a jet of water after wire rod rolling. As compared with wire rods quenched after re-heating, the direct quenched wire rod is small in strength variations and credited with extremely high reliability. The commercial production of in-line QT wire rods from medium-carbon steels and low-alloy steels was accomplished by the progress of direct quenched wire rod manufacturing technology and the addition of in-line tempering.

2.2 Manufacturing equipment of in-line QT rods

2.2.1 Manufacturing process

The manufacturing process is shown in **Fig. 1**. The billet heated to the rolling temperature in the reheat furnace is rolled on the mill with alternately arranged pairs of vertical and horizontal rolls. After being adjusted with its finishing temperature and coiling temperature, the wire rod is charged into the quenching bath from an appropriate quenching temperature. The wire rod is removed from the quenching bath and then tempered in the low-temperature tempering furnace before banding in order to prevent delayed fracture. The wire rod coils are then stored in the warehouse and then tempered with the batch furnace to adjust to the desired strength.

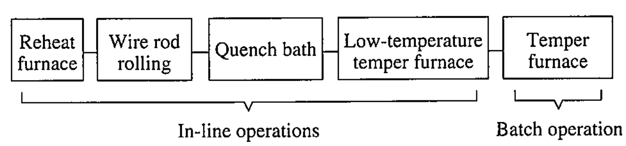

Fig. 1 Manufacturing process

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2.2.2 Quenching equipment

The quenching equipment is schematically shown in **Fig. 2**. The wire rod is laid in rings on the roller conveyor, recuperated on the roller conveyor, and continuously charged into the direct quenching bath. The charged wire rod is cooled in the quenching bath while it is carried by the chain conveyor and is pulled out of the quenching bath. Warm or cold water is selected as the quenching medium depending on specific steel grades. Warm-water quenching is applied to alloy steels of high crack susceptibility, and produces a mild quenched condition by making use of a boiling water film formed on the wire rod surface. Cold-water quenching is applied to medium-carbon steels of low hardenability. Stable quenching is achieved by the swirl flow pattern created by injecting cold water into the quenching bath.

The new quenching equipment was designed to obtain a uniform cooling rate over the entire length of the wire rod, after a quenching model bath was installed and good flow condition was analyzed. When the cooling water is horizontally injected into the bath as shown in **Fig. 3**, the flow condition in the quenching bath is a piston flow. Mixed agitation is not maintained to a sufficient degree, and the wire rod cooling rate varies. When the injected cold water directly hits the wire rod, the wire rod is rocked and is not properly carried, or the wire rod is unevenly cooled locally and is cracked. When the cooling water is vertically jetted to have no direct impingement on the wire rod and to form a swirl flow pattern of uniform velocity near the wire rod as shown in **Fig. 4**, the wire rod is cooled at a uniform rate, and the quenching medium is properly mixed without bath temperature unevenness.

2.2.3 In-line tempering furnace

The in-line tempering furnace is constructed as shown in **Fig. 5**. The wire rod raised from the quenching bath and formed into a coil can be charged on a hook conveyor of the power and free type without banding and can be rapidly tempered. The tempering temperature is controlled so that each wire rod coil suspended on the hook conveyor does not deform under its own weight. Low-temperature tempering is designed to liberate diffusible hydrogen and to reduce the hardness of the wire rod to prevent its delayed fracture.

2.3 Quality of in-line QT wire rods

2.3.1 Manufacturing range

As shown in **Fig. 6**, warm-water quenching provides a mild cooling rate and allows stable quenching with a minimum of cooling rate variation by making use of the boiling water film. Warm-water quenching can quench and temper smaller diameter wire rods of low-alloy steel with a minimum DI value of 3 inches. When warm-water quenching is applied to a larger diameter wire rod, the cooling rate is not high enough, so that transitional structures like bainite is mixed with martensite after quenching and reduce the strength of the wire rod. Cold-water quenching produces such a rapid cooling rate that it can quench medium-carbon steels of low hardenability.

Increasing the carbon content increases the volume expansion resulting from martensite transformation and enhances the sensitivity to quench cracking. Smaller diameter wire rods of the same steel

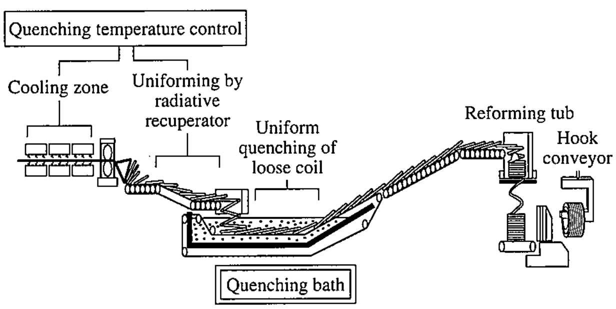


Fig. 2 Schematic of quenching equipment

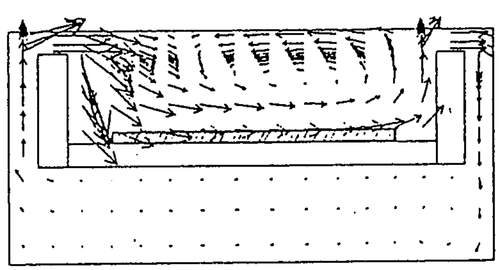


Fig. 3 Flow pattern in quenching bath during cold-water quenching (horizontal water jet stream)

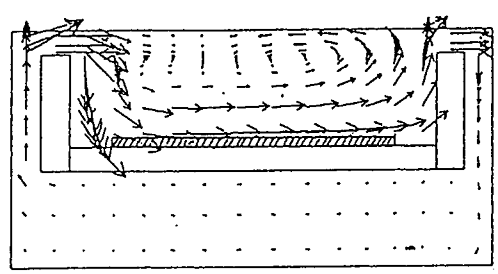


Fig. 4 Flow pattern in quenching bath during cold-water quenching (vertical water jet stream)

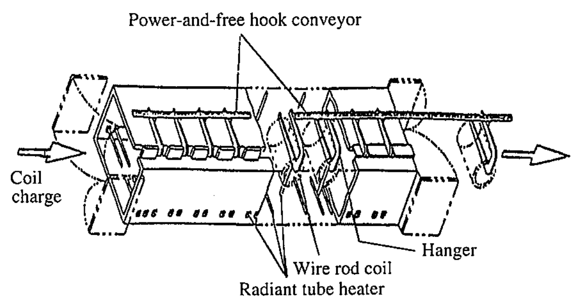


Fig. 5 Schematic of in-line tempering furnace

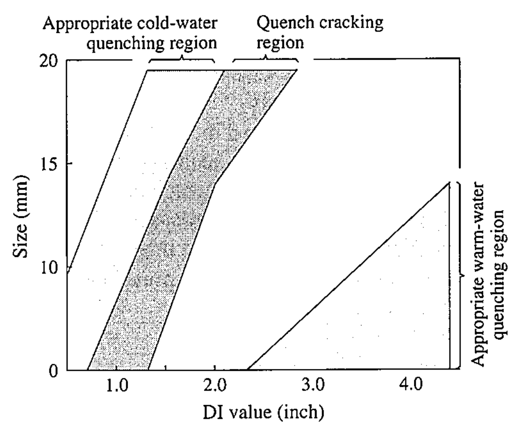
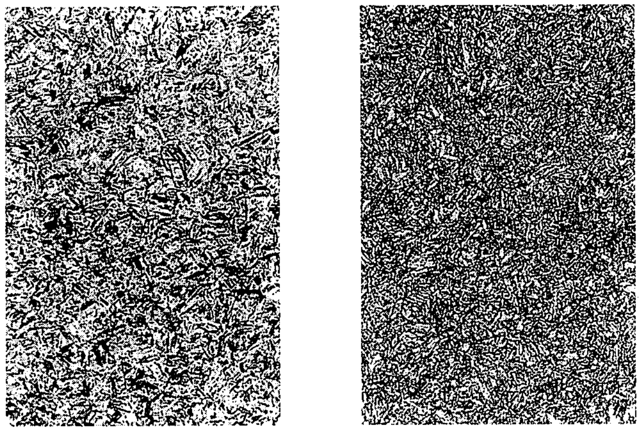


Fig. 6 Appropriate quenching range of in-line QT wire rods



(a) As quenched (b) Tempered at 500°C

Photo 1 Microstructures (× 400)

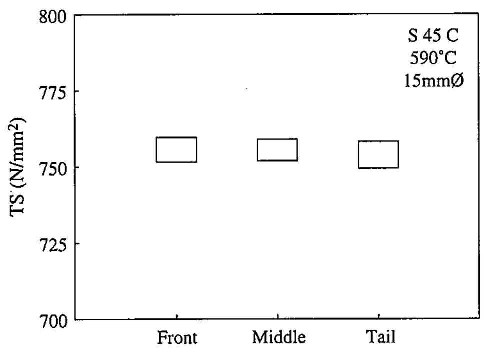


Fig. 7 In-coil variation of tensile strength

cool at a higher rate, increase in volume expansion with increasing volume fraction of martensite, and increase in the occurrence of quench cracks. Increasing the wire rod diameter, on the other hand, lowers the cooling rate and reduces the strength of wire rod. Therefore, steel grades of an appropriate DI value such that martensite is produced with some retained austenite can be stably quenched without cracking.

2.3.2 Microstructure and mechanical properties

The microstructure is uniform tempered martensite as shown in **Photo 1**. **Fig. 7** shows that the tensile strength (TS) after tempering of a warm-water quenched wire rod of SCM 440 and a cold-water quenched wire rod of S 45 C is extremely small in in-coil variation and is stable. **Fig. 8** shows the effect of the tempering temperature on the tensile properties of the warm-water quenched SCM 440 rod and the cold-water quenched S 45 C rod.

2.4 Summary of in-line QT rods

Direct quenching after rolling and in-line tempering before banding made it possible to manufacture quench-tempered wire rods of uniform quality at low cost without quench cracks and soft spots. The in-line QT wire rods are suited for long-sized parts with a lower forging reduction and high strength, and they are used to produce special bolts and rotor shafts for automobiles and industrial machines.

3. Bainite Wire Rods

3.1 Description of bainite wire rods

The steel wire drawn with a high reduction has problems of ductility deterioration, such as occurrence of delamination as a result of increased strength. Kawana et al.[4] reported that if a upper bainite

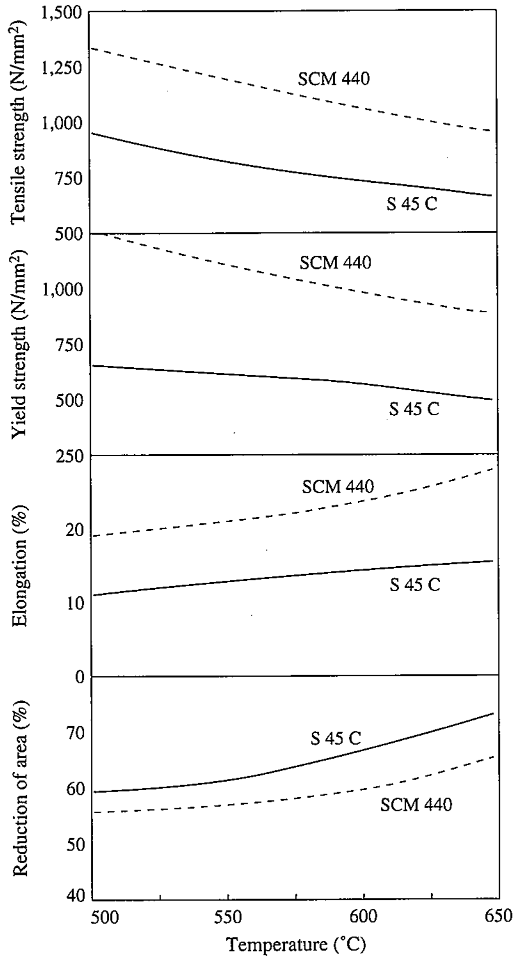


Fig. 8 Tempered performance curves

structure is formed as predominant microstructure in place of the conventional pearlite structure to prevent this problem, hypereutectoid steel wire to 3.25mm diameter can be drawn with a higher reduction without delamination. The main reason for this drawability improvement is that the upper bainite structure exhibits a low work hardening rate in the wire drawing process. Therefore, if a wire rod predominantly composed of the upper bainite structure showing good direct drawability (hereinafter referred to as bainite wire rod) is manufacturable at the wire rod mill, the user can expect to reduce the manufacturing cost by simplifying or eliminating intermediate heat treatment in the wire drawing process. Bainite wire rods were produced from a more common 0.8%C steel and investigated for its properties. The obtained results are reported in this chapter.

3.2 Manufacturing process of bainite wire rods

Test steels were melted in a 250-ton converter at the Kimitsu Works, continuously cast, billeted, and rolled into 5-mm diameter wire rods of SWRS 82A. The chemical compositions of the test steels are given in **Table 1**. Steel B was used to investigate upper bainite

Table 1 Chemical compositions (mass%) and cooling conditions of test steels

Steel	C	Si	Mn	Cooling condition
A	0.82	0.17	0.51	Molten salt immersion
B	0.83	0.21	0.48	Air cooling

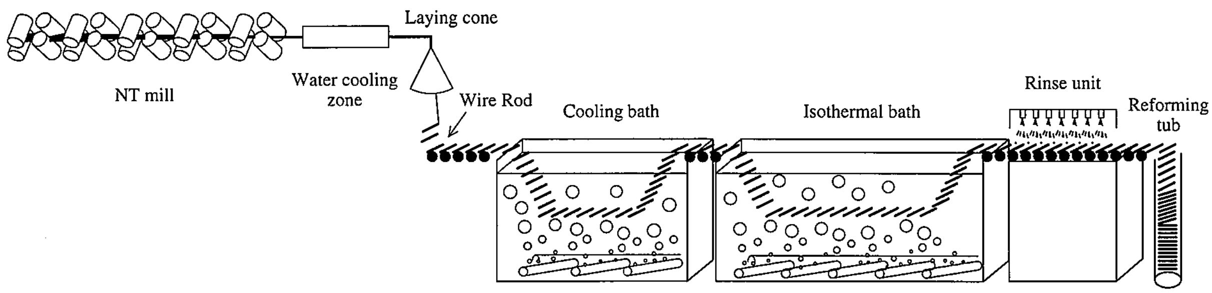


Fig. 9 Schematic of DLP equipment

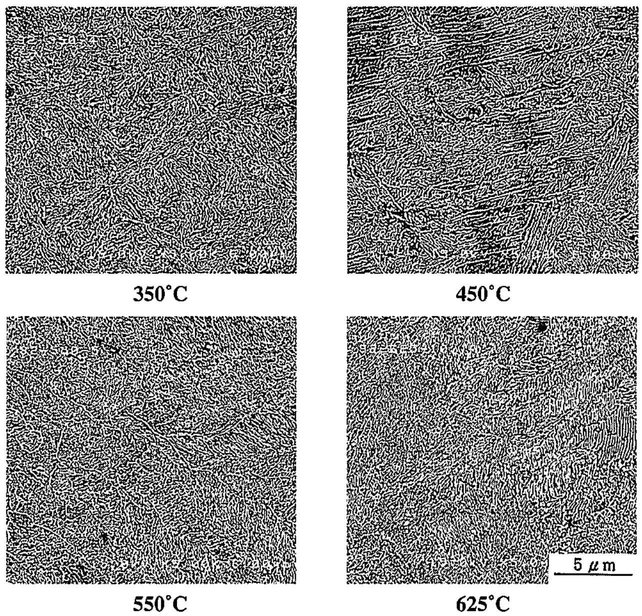


Photo 2 Typical isothermal transformation microstructures of steel A

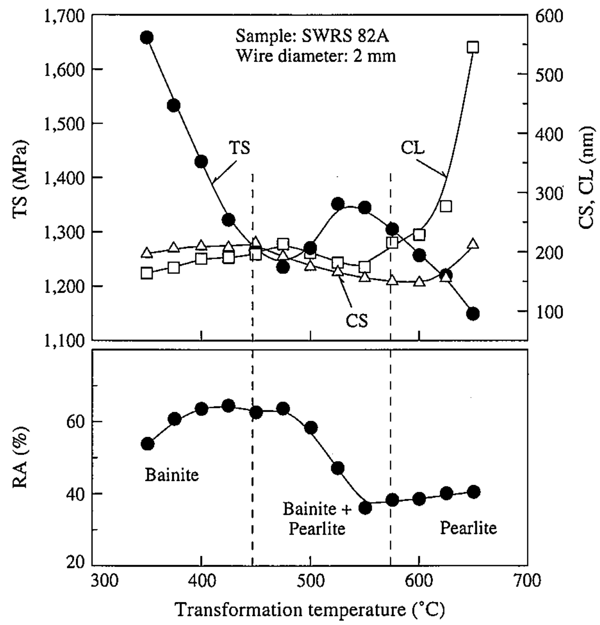


Fig. 10 Effect of isothermal transformation temperature on tensile strength (TS), reduction of area (RA), cementite length (CL) and cementite spacing (CS)

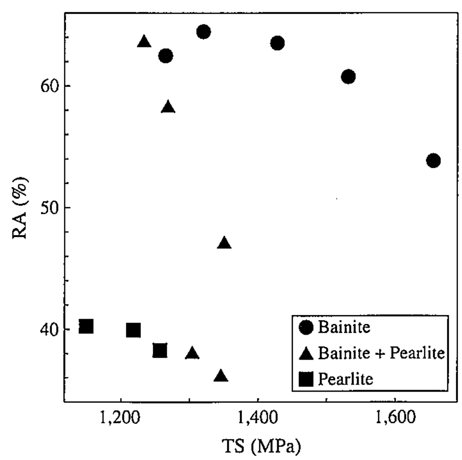


Fig. 11 Relationship between tensile strength (TS) and reduction of area (RA)

wire rods on the laboratory scale, while steel A was used to test for producing bainite wire rods at the wire rod mill[5,6]. Steel B was drawn to 2 mm on a single bull-block drawing machine in the laboratory and isothermally transformed by lead patenting in a temperature range of 350 to 650°C. Steel A was isothermally transformed directly in the bainite transformation temperature region after hot rolling, using the direct lead patenting (DLP) equipment[7] of the wire rod mill at the Kimitsu Works. The DLP equipment is schematically illustrated in **Fig. 9**.

3.3 Microstructure and mechanical properties of bainite rods

3.3.1 Effect of isothermal transformation temperature on microstructure and mechanical properties

Photo 2 shows typical isothermal transformation microstructures of steel A. As the isothermal transformation temperature rises from 350°C to 550°C, the predominant microstructure changes from lower bainite to upper bainite. At the isothermal transformation temperature of 625°C, the microstructure is entirely composed of pearlite. The tensile strength (TS), reduction of area (RA), cementite length (CL), and cementite spacing (CS) measured by image processor are shown in **Fig. 10**. The formation of bainite slightly increases the cementite spacing and substantially reduces the cementite length. The bainite structure formed in the vicinity of 450°C is as low as the pearlite structure formed at 600°C in strength and exhibits a higher reduction of area. The relationship between the tensile strength and the reduction of area is shown in **Fig. 11**. When compared at the same tensile strength, bainite indicates an extremely high reduction of area.

3.3.2 Reason for high reduction of area

The wire rods transformed at 450°C and at 625°C, that are same in tensile strength and very different in reduction of area, were observed as to microstructural changes before and after tensile test by FE-SEM. **Photo 3** shows the microstructures of the wire rods at the quarter-point position below the surface. When the microstructures after tension are compared, the bainite wire rod has the major-axis direction of cementite aligned in the tensile direction, but the pearlite steel rod does not exhibit such an orientation tendency.

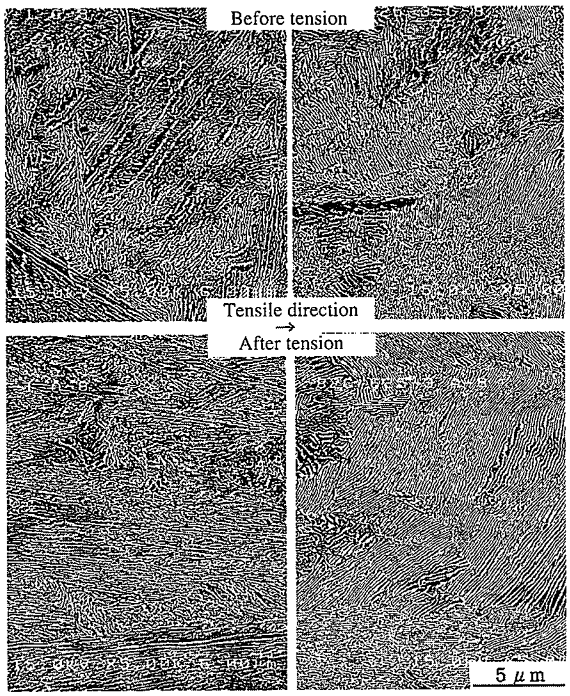
This orientation property of cementite is represented by the angle of inclination from the direction of the tensile axis in **Fig. 12**. The cementite in both pearlite structure and bainite structure exhibits no particular orientations before the tensile test. After the tensile test, the cementite only in the bainite structure is aligned in the direction parallel to the tensile axis in both the surface and quarter-point positions. This may be explained as follows. Since the bainite structure is shorter in cementite length and longer in cementite spacing, the ferrite matrix can relatively easily deform without being strongly constrained by the cementite, with the result that the deformation is likely to penetrate deep inside.

3.3.3 Wire drawability of bainite wire rods

Table 2 compares the mechanical properties and microstructure of a 5-mm bainite wire rod and a 5-mm pearlite wire rod, both manufactured by using the DLP heat treatment equipment at the wire rod mill. The bainite structure fraction of the bainite rod is 85%. Despite its high strength, the bainite wire rod exhibits a high reduction of area as indicated by the laboratory test results. The wire drawing limit of the bainite rod was investigated by using the single bull-block drawing machine. The drawing limit is defined as the wire diameter of the die before the die where the wire is broken. The drawing limit of the bainite wire rod is shown as compared with that of the pearlite wire rod in **Fig. 13**. The bainite structure has the better drawing limit improved by 3 dies than that of the pearlite structure and allows wire to be directly drawn from 5 to 0.635 mm.

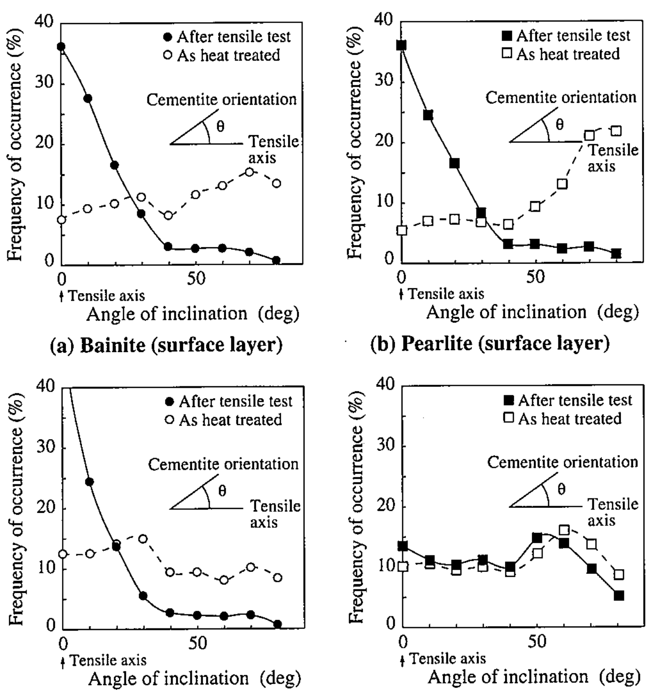
3.3.4 Reason for high direct drawability

Photo 4 shows the cementite and dislocations observed when thin-foil specimens of the pearlite structure (steel B) and the bainite structure (steel A) were tensioned in a high-voltage transmission electron microscope at the Kyushu University. The region where the dislocations of the pearlite structure can move is limited to the narrow ferrite area surrounded by the cementite. While the cementite in the bainite structure is fragmented short, so that the dislocations can move between the cementite fragments over long distances. These conditions are schematically illustrated in **Fig. 14**. Generally, the longer



Bainite (450°C) Pearlite (625°C)

Photo 3 Microstructural changes before and after tensile test (1/4 point)



(a) Bainite (surface layer) (b) Pearlite (surface layer)

(c) Bainite (1/4 point) (d) Pearlite (1/4 point)

Fig. 12 Changes in cementite orientation before and after tensile test

Table 2 Mechanical properties and microstructures of wire rods

Steel	TS (MPa)	RA (%)	Microstructure
A	1,183	60.8	Bainite (85%)
B	1,090	45.4	Pearlite

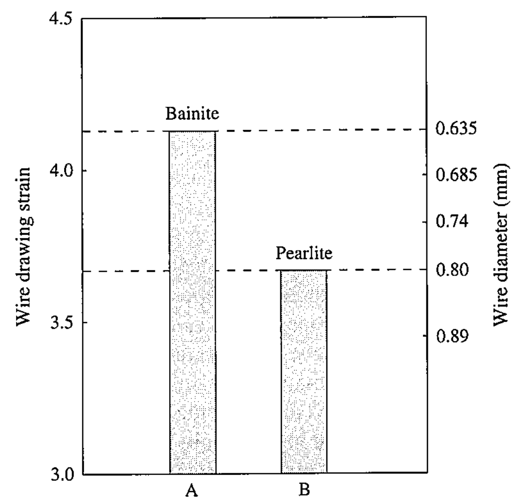


Fig. 13 Drawing limit of bainite rod

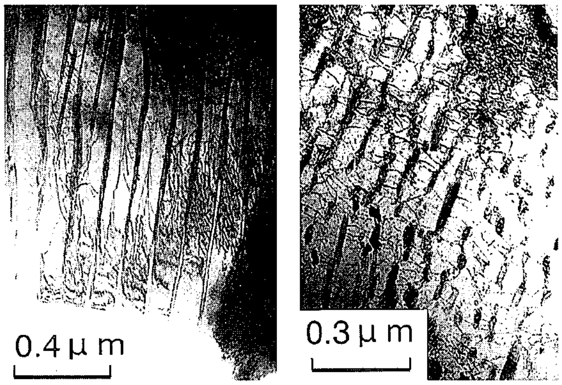


Photo 4 Interaction between cementite and dislocations (observed under high-voltage transmission electron microscope at Kyushu University)

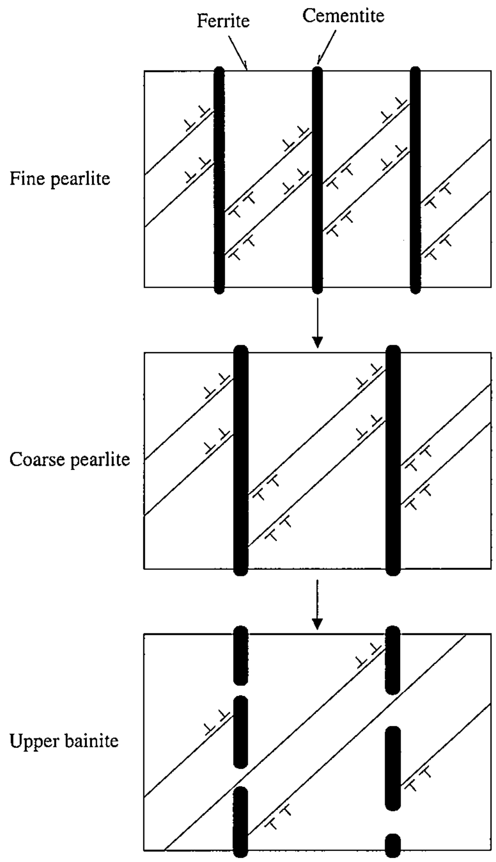


Fig. 14 Schematic of effect of cementite morphology on free spacing of dislocation

the distance the individual dislocations can move, the smaller the number of dislocations required to produce the same strain and the smaller the amount of dislocation strengthening[8]. That is, in the bainite structure, the dislocations are weakly restrained by the cementite and can move over long distances, so that the amount of work hardening is small when the wire is drawn to the same size. This is considered as the reason why the bainite wire rod exhibits high direct drawability.

3.4 Summary of bainite wire rods

The bainite structure of a 0.8%C steel exhibits a higher reduction of area and drawing limit as compared with the pearlite structure of the same steel. This is because the bainite structure is larger in cementite spacing and smaller in cementite length than that of the pearlite structure. That is, the deformation of the bainite wire rod is easy to penetrate throughout the entire cross section from the surface to the center. This makes localized reduction less likely to occur and increases the reduction of area. Because dislocations in the bainite wire rod can move between short cementite fragments and over longer distances without being pinned by cementite, the same amount of deformation can be accomplished at the smaller dislocation density. As a result, the work hardening rate is reduced, and good direct drawability is obtained.

4. Conclusions

The manufacturing processes and characteristics of in-line QT wire rods produced at the Muroran Works and bainite wire rods produced at the Kimitsu Works have been described as examples of in-line heat-treated wire rods developed by Nippon Steel. Each wire rod has the microstructure controlled and homogenized by optimizing the feature of in-line heat treatment and is provided with far better properties than those of rods manufactured by conventional off-line heat treatment.

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