Direct Heat Treatment Technique for High-Strength, Large-Diameter PC Steel Bars with Pearlite Microstructure

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In PC steel bar production, Sumitomo Electric uses a direct heat treatment technique utilizing sensible heat from hot-rolled steel. To produce high-strength PC steel bars with pearlite microstructure, mist cooling is conducted using a mixture of water and air as a coolant after hot rolling.
This technique enables us to control the temperature where pearlite transformation starts and the resulting heat generation. This paper introduces the direct heat treatment technique that can provide higher tensile strength to large-diameter PC steel bars while being economical and environmentally friendly. It also outlines the mist cooling equipment and the properties of PC steel bars made by using this technique.

Keywords: direct heat treatment, hot rolling, mist cooling, pearlite transformation, high-strength PC steel bar

1. Introduction

Sumitomo Electric Industries, Ltd. operates hot rolling facilities consisting of a wire rod mill and bar rolling mill. The wire rod mill roughs steel billets and rolls them into 4 ~ 16 mm diameter steel wire rods, while the bar rolling mill rolls steel billets into 17 ~ 36 mm diameter steel bars.

The outstanding feature of these mills is that they employ a direct heat treatment technique that uses sensible heat of hot-rolled steel as a heating medium and boiling water or mist (mixture of air and water) as a coolant. This technique, developed originally by Sumitomo Electric, uses an environmentally friendly coolant to control the structural-phase transformation of steel, thereby enabling economical production of high-strength, high-toughness wire rods and steel bars.

Steel bars are usually heat-treated directly by one of the following methods: (1) air-cooling subsequent to hot rolling, to obtain a normalized steel microstructure, and (2) direct hardening of bar surface by water-cooling, with subsequent self-tempering of the surface to transform the microstructure into tempered martensite.

In contrast to these conventional methods, Sumitomo Electric uses a mixture of air and water (mist) as a coolant to control the pearlite transformation initiation temperature, and the heat generated by transformation to produce high-strength pearlite steel bars.

This paper describes the method for increasing the strength of steel bars, outlines the mist cooling system and details the properties of high-strength, large-diameter PC steel bars produced using our original technique.

2. Increasing the Strength of Pearlite Steel

2-1 Features of pearlite steel

Since PC steel bars are used under high tension in most applications, their delayed fracture resistance is a very important factor in increasing their strength. It is commonly recognized that pearlite structure is advantageous over tempered martensite structure in increasing the strength of steel bars. An example of the delayed fracture properties test results for pearlite steel wires and tempered martensite steel wires is shown in **Fig. 1**. A water solution of ammonium thiocyanate (concentration: 20%, temperature: 20°C) was used for this test. This figure shows that no test pearlite steel wire samples broke, even after 200 hours in the test stress range, confirming that pearlite steel wires are superior to tempered martensite steel wires in delayed fracture properties.

To realize higher-strength, large-diameter steel bars of pearlite structure using a conventional air-cooling system, the alloy elements content should be increased to improve hardenability, but this method lowers the economical competitiveness of the bars. A large scale air-cooling system is essential for evenly cooling the entirety of the steel bar length in an existing highly productive hot rolling process.

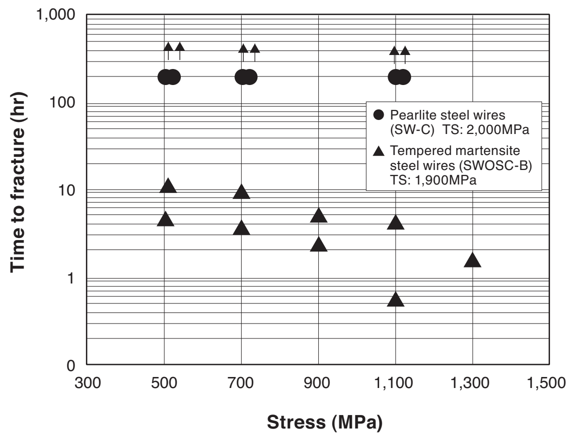

Fig. 1. Delayed Fracture Properties Comparison between Pearlite Steel and Tempered Martensite Steel

2-2 Increasing the strength

Sumitomo Electric produces high-strength, high-toughness steel bars by cutting hot-rolled steel bars into a predetermined length and cooling them at a controlled rate with mist spray (mixture of air and water).

It is widely known that pearlite steel strength increases as the transformation initiation temperature decreases and the heat generated by transformation decreases.

A cooling curve of a steel bar accompanied by pearlite transformation is schematically illustrated in **Fig. 2**. In this figure, the lowest temperature at the start of pearlite transformation is denoted by T1 and the highest temperature resulting from the heat generated by transformation is denoted by T2. This test was carried out to clarify the correlation between these transformation temperatures and strength.

Dependence of 32 mm diameter steel bar tensile strength on transformation temperature is shown in **Fig. 3**. This figure was obtained by varying air/water ratio and mist spray time. The chemical compositions of the test steel bar samples are shown in **Table 1**.

Figure 3 confirms that tensile strength increases as transformation initiation temperature (T1) and highest temperature (T2) decrease.

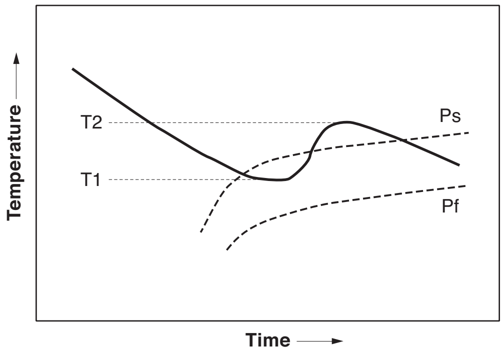

Fig. 2. Schematic Illustration of Cooling Curve

Table 1. Chemical Compositions of Test Steel Bar Samples (wt%)

C	Si	Mn	P	S	Cr
0.72	0.80	1.20	0.017	0.020	0.80

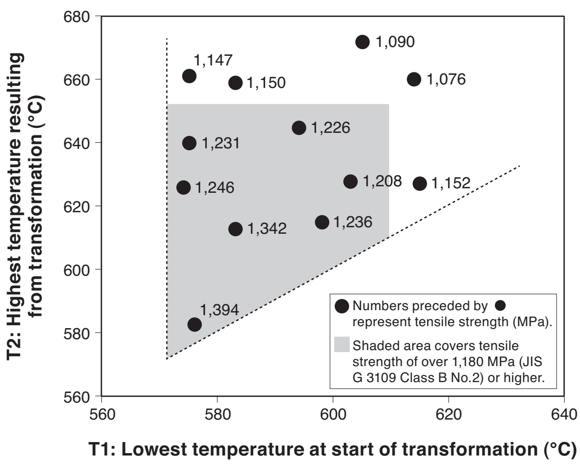

Fig. 3. Relation between Pearlite Transformation Temperature and Tensile Strength

3. Mist-Cooling System

We developed the mist-cooling system shown in **Fig. 4** to cool hot-rolled steel bars evenly in both circumferential and longitudinal directions, thereby achieving the desired cooling conditions. This system comprises a cooling bed that receives hot-rolled steel bars, cuts them to a predetermined length, then rotates and transports them in parallel with each other, in an oblique direction with respect to their longitudinal axis. Parallel mist spray nozzle lines cover the entire ceiling of the cooling bed to cool the steel bars evenly in both circumferential and longitudinal directions. Since this cooling system can independently control steel bar-cooling rates before the start of transformation and during transformation heat generation, the cooling capacity of the mist nozzles can be flexibly adjusted according to the required steel bar grade, diameter and strength etc. In this steel bar rolling mill, hot-rolled steel bars are cooled with mist until pearlite transformation starts; the mist is

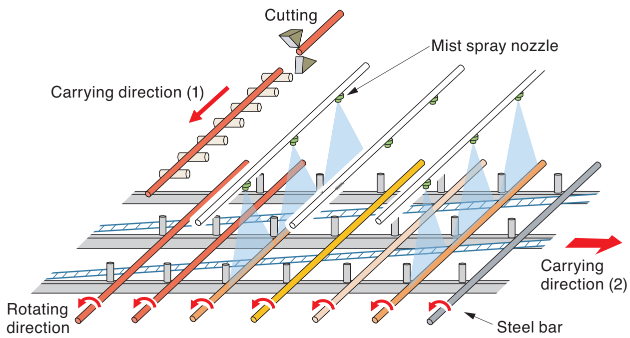

Fig. 4. Schematic Illustration of Steel Bar Mist-Cooling System

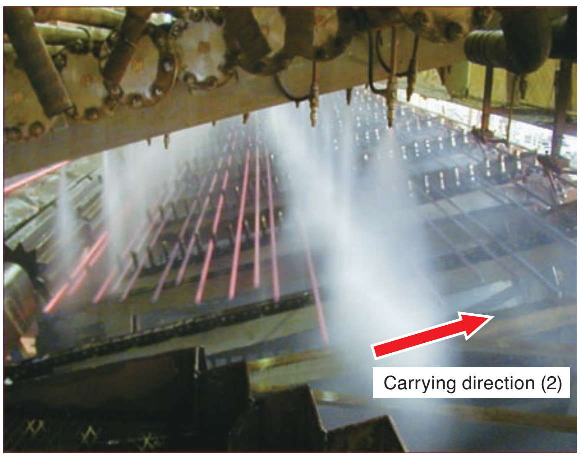

Photo 1. External Appearance of Steel Bar Mist-Cooling System in Operation

then stopped and cooling is conducted only by air until transformation heating restarts. The system restores mist-cooling after transformation heating restarts. External appearance of the cooling system in operation is shown in **Photo 1**.

4. Properties of Pearlite Steel Bar

4-1 Example of production conditions

A steel billet with the chemical compositions shown in **Table 1** was hot-rolled to 32 mm diameter steel bars at a roll-finishing temperature of 925°C and cut into predetermined lengths.

The steel bars were then rotated at 8.2 rpm, mist-cooled on a cooling bed and transported in direction (2) at a speed of 0.86 m/min. The mist was a mixture of air fed at a rate of 90 Nm^3/min and water fed at a rate of 1.5 m^3/min. In the cooling process, the steel bars were mist-cooled for 96 seconds until the transformation began, air-cooled for 13 seconds, then mist-cooled again for 90 seconds.

The cooling curve in the above cooling process is shown in **Fig. 5**. A cooling curve for steel bars cooled only with air (at 15°C) is additionally shown for comparison. This figure shows that the lowest temperature (T1) at the start of mist-cooled steel bar transformation was 578°C, while the highest temperature (T2) resulting from the heat generated during transformation was 634°C. In contrast, T1 and T2 of the air-cooled steel bars were 606°C and 669°C, respectively. The heat transfer coefficient of mist cooling (approximately 180 $W/m^2 \cdot K$) is more than twice that of air cooling (70 $W/m^2 \cdot K$).

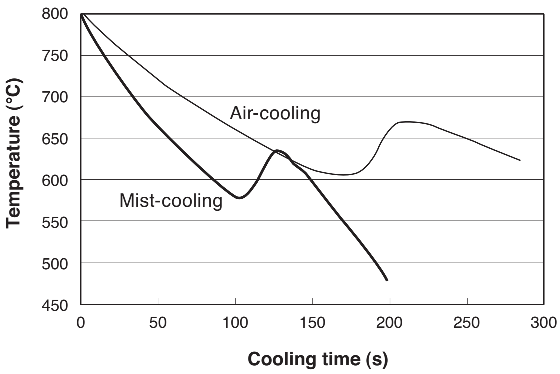

Fig. 5. Cooling Curve for Steel Bars

4-2 Microstructures

The microstructures of mist- and air-cooled steel bars are pictured in **Photo 2 and 3**. In particular, **Photo 2** shows the pearlite blocks structures obtained by electron backscatter diffraction (EBSD) analysis of the surface, intermediate (between surface and center) and center positions of both mist- and air-cooled steel bars, while **Photo 3** shows scanning electron microscopic (SEM) pictures of lamellar structures in the above three portions. These figures confirm that the microstructure in each position of steel bars produced at a lower transformation temperature is finer than that in air-cooled steel bars. When the intermediate position of mist-cooled steel bars is compared with that of air-cooled steel bars, the average pearlite block size decreased from 25 µm to 19 µm and the average lamella space decreased from 0.22 µm to 0.14 µm.

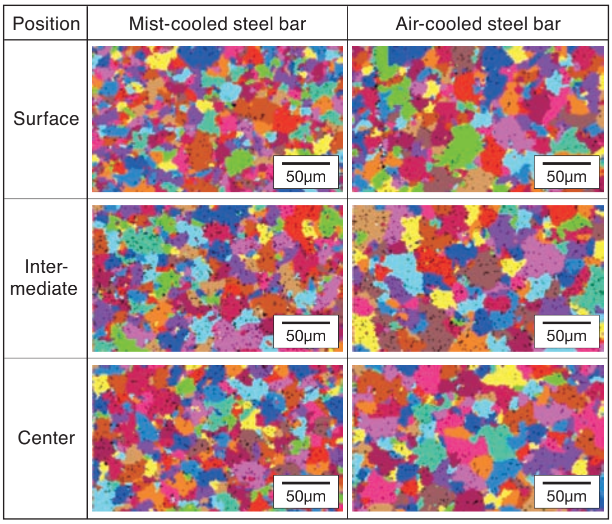

Photo 2. Pearlite Block Structures by EBSD

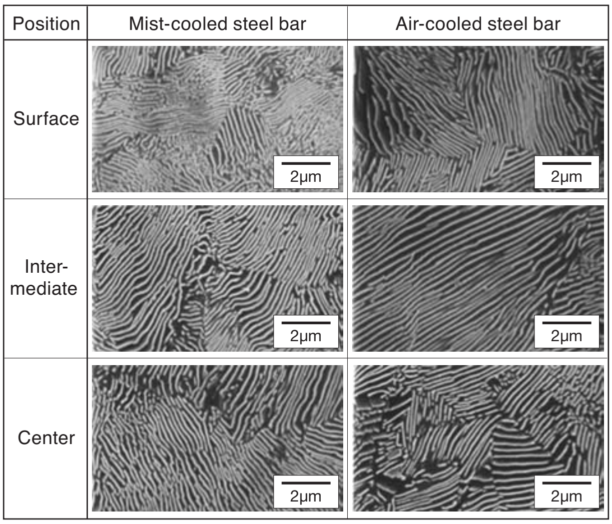

Photo 3. Pearlite Lamella Structures by SEM

4-3 Mechanical properties

Figure 6 compares the mechanical properties of mist-cooled and air-cooled steel bars. Each value was determined by averaging the measurement results for 15 test samples. Tensile strength and value of reduction in area of the mist-cooled steel bars were 1,244 MPa and 36.0%, respectively, while those of the air-cooled steel bars were 1,136 MPa and 34.7%, respectively.

This confirms that the mist-cooling system is effective in producing high-strength, high-toughness steel bars. This cooling system reduces pearlite transformation temperature, thereby reducing the pearlite block size and lamella space.

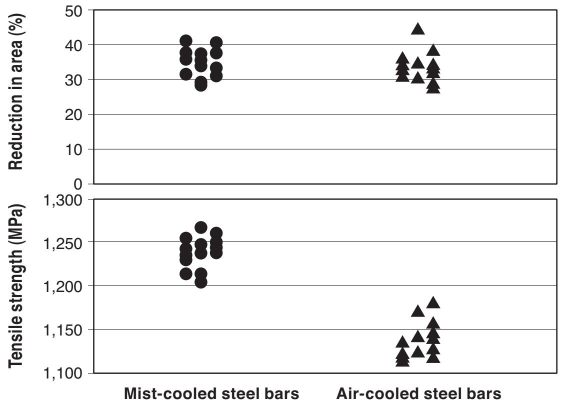

Fig. 6. Mechanical Properties of Steel Bars

4-4 Delayed fracture property

A delayed fracture test of mist-cooled steel bars was carried out. In this test, 12 test samples were pretreated with so-called stretching and bluing treatment, in which they were maintained at 375°C with a load of 80% of the tensile strength. Then they were immersed in a water solution of ammonium thiocyanate (concentration: 20%, temperature: 50°C) for more than 400 hours with stress of 944 MPa (80% of the strength specified in JIS G 3109 Class B, No.2). The test results, shown in **Fig. 7**, confirmed that all test samples exhibited excellent delayed fracture resistance without breaking, even after 420 hours.

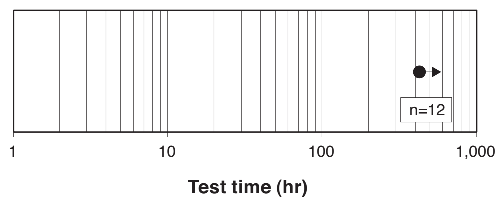

Fig. 7. Delayed Fracture Property

4-5 Relaxation property

A relaxation test of mist-cooled steel bars was carried out in compliance with JIS G 3109. Test samples were pretreated by the stretching and bluing treatment described in Section 4-4. **Figure 8** shows the relaxation curve obtained in the test. The relaxation value of the mist-cooled steel bars was 2.95% after 1,000 hours, verifying that they fully met the JIS requirement (4.0% or less).

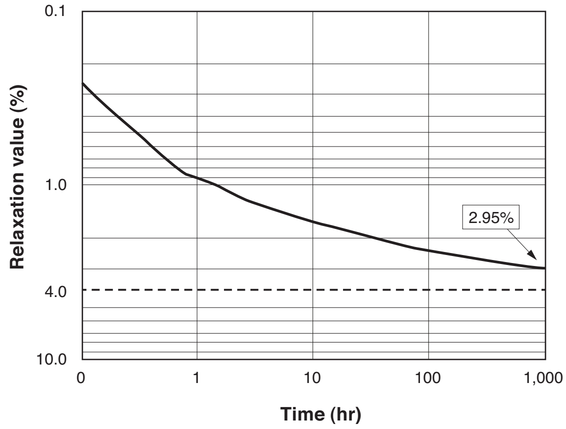

Fig. 8. Relaxation Property

5. Conclusion

In Sumitomo Electric, by utilizing direct heat treatment, based on a mist-cooling system directly connected to hot-rolling equipment, we developed a technique which controls the steel bar cooling pattern so as to reduce pearlite transformation temperature.

With this technique, Sumitomo Electric supplies high-strength, high-toughness, large-diameter steel bars having excellent delayed fatigue properties, and moreover, these steel bars are produced economically in an environmentally friendly rolling mill.

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