APPLICATION OF HYPEREUTECTOID STEEL FOR MANUFACTURE OF HIGH STRENGTH STEEL WIRE

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ABSTRACT

In order to extend the application of hypereutectoid steel (C≧0.90 mass%) from a limited sphere such as needles, tools, etc. to high strength steel wire products such as tire cord, saw wire, spring wire, etc., the relationship between the microstructure and mechanical properties of hypereutectoid steel wire has been studied and then the optimum patenting conditions to obtain the microstructure which has excellent drawability and a high work hardening rate during drawing have been investigated. Based on the results of the above basic research, higher strength steel wires with small diameter have been manufactured on a production basis.

1) Provided that an appropriate cooling rate corresponding to the carbon content is secured, the precipitation of thick proeutectoid cementite can be prevented.
2) In the practical patenting temperature range, the cementite plate thickness as well as the pearlite lamellar spacing decreases as the carbon content increases.
3) The work hardening rate during drawing and the delamination resistance are enhanced through reducing the upper bainite in pearlite.
4) The maximum strength of 0.04 mm wire manufactured from 0.96%-0.2%Cr steel without delamination occurrence has reached to as high as 5.70 GPa.

INTRODUCTION

In response to the market trend toward thinner and lighter wire products such as tire cord, saw wire, spring wire, etc., there is an increasing demand for higher strength steel wires. Thus far, the highest strength steel wire has been manufactured from a eutectoid steel, that is, 0.82 mass% C plain carbon steel. However, in order to attain further strengthening in the future, a comprehensive study in both aspects of basic metallurgy and manufacturing technology is essential.

A description is given below about the metallurgical research results on a hypereutectoid steel (C≧0.90 mass%) and properties of higher strength steel wires made on a production basis based on the above results obtained.

BASIC CONCEPTS OF STRENGTHENING

Figure 1 represents the basic concepts of strengthening the steel wire. At present, a eutectoid steel (0.82 mass%C plain carbon steel) is employed as a raw material for steel wire having the highest strength (i.e., piano wire). As a means of increasing the strength of the steel wire, the following are available: 1) Increasing the strength of patented wire ($\Delta\sigma_1$). 2) Increasing the rate of work hardening during drawing ($\Delta\sigma_2$). 3) Increasing the total amount of reduction ($\Delta\sigma_3$). The strengthening can be achieved by raising the sum total ($\Delta\sigma=\Delta\sigma_1+\Delta\sigma_2+\Delta\sigma_3$).

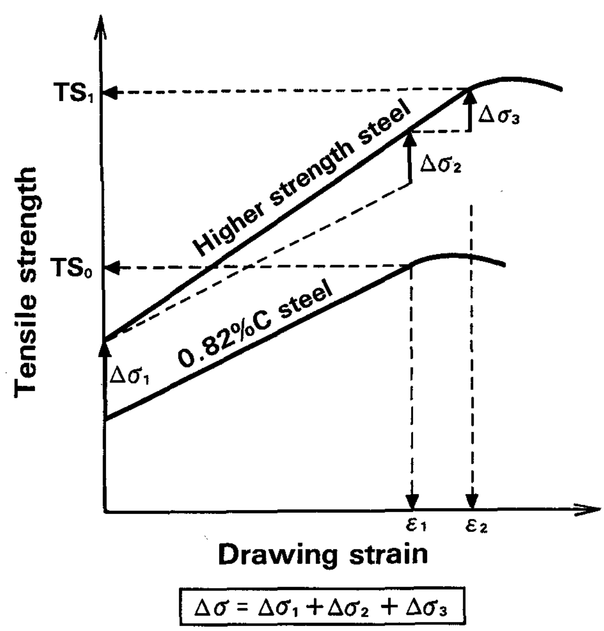

Figure 1. Strengthening of steel wire

Until now, the strengthening of steel wire has been examined in a direction which increases the strength of patented wire by adding alloying elements to the eutectoid steel. However, it should be noted here that the contribution of the work hardening during drawing toward the wire strength is by far greater than that of patented wire strength. Thus the authors, aiming at increasing the work hardening, have investigated the effect of the microstructure of patented wire on a work hardening behavior during drawing and on occurrence of delamination in the drawn-wire.

MATERIALS AND METHODS

Wire rod: Test steels were melted with a 100 kg vacuum induction furnace. Table 1 shows the chemical composition of the test steels. The ingots were forged into 122 mm square billets, and then they were rolled into wire rods of 5.5 mm in diameter through ordinary wire rod rolling.

Patenting and drawing: For a primary and secondary drawing, a bull-block was used and for a final drawing, a continuous drawing machine (600 m/min) was used. Both intermediate and final patenting are a lead patenting (LP).

TABLE 1

Chemical composition of steels

(mass%)

Steel	C	Si	Mn	P	S	Cr	Al
A	0.82	0.20	0.52	0.004	0.003	0.01	0.001
B	0.82	0.16	0.31	0.002	0.001	0.00	0.001
C	0.82	0.19	0.32	0.002	0.001	0.19	0.002
D	0.92	0.16	0.31	0.001	0.001	0.00	0.001
E	0.92	0.21	0.31	0.002	0.001	0.22	0.001
F	0.96	0.19	0.31	0.002	0.001	0.20	0.001
G	0.82	0.15	0.50	0.003	0.001	1.02	0.002
H	0.82	1.00	0.50	0.003	0.002	0.00	0.002
I	0.82	0.19	1.02	0.002	0.002	0.01	0.002

Microstructure: Polished and picral etched cross section of the specimens was examined with a scanning electron microscope (SEM). The lamellar spacing of pearlite was measured by an intercept method [1].

Delamination resistance: The delamination resistance of a wire after drawing was evaluated according to the shape of twist-torque diagram in a torsion test [2]. That is, the delamination resistance of the test piece is good if the twist-torque curve is smooth as illustrated in Figure 2-a. And, in cases where serration is observed as illustrated in Figure 2-b, it proves that delamination has occurred in the test piece.

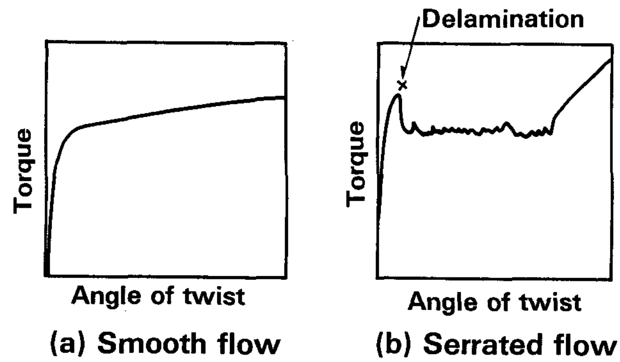

Figure 2. Torque-twist diagrams

RESULTS AND DISCUSSION

Microstructure Control

Effect of microstructure on strength of steel wire: Wires of 1.75 mm in diameter made from 0.96 mass%C-0.2 mass%Cr steel (Steel F) were lead patented at a temperature range of 400 to 650°C. Figure 3 shows the effect of transformation temperature on microstructure and mechanical properties of wires. The microstructure of patented wire is composed of a little coarser pearlite at 600°C and a fine pearlite at 575°C (nose temperature in

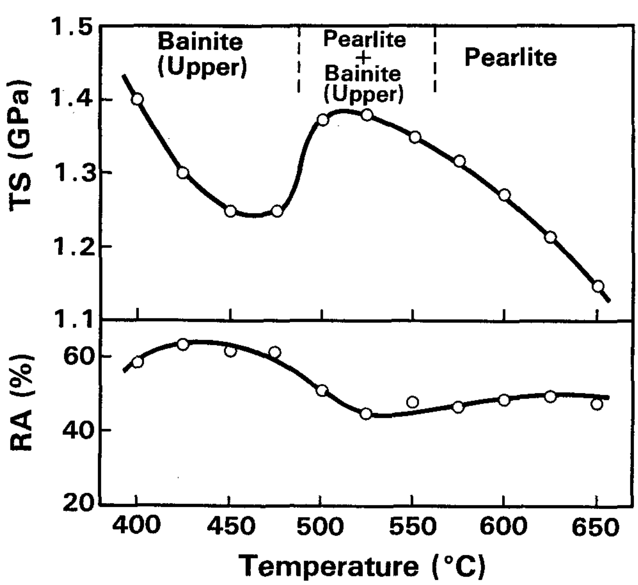

Figure 3. Effect of transformation temperature on microstructure and mechanical properties (Steel F, 0.96C-0.2Cr)

TTT diagram of Steel F). In any case, the upper bainite does not exist. Whereas at 550°C, since the upper bainite is formed at austenite grain boundaries, a mixed structure of extremely fine pearlite and coarse upper bainite is observed. Further at a lower temperature of 450°C, only the upper bainite is formed. As shown in Figure 3, the strength of upper bainite, transformed at 450°C is as low as about 10%, compared with that of fine pearlite transformed at 575°C. Nevertheless, the strength of the patented wire reaches a maximum in a mixed structure of pearlite + upper bainite. This is due to a low volume fraction of upper bainite, such that strengthening by pearlite lamellae refinement predominates.

The effect of transformation temperature on the work hardening behavior was investigated. Figure 4 shows the work hardening curves of typical microstructures, from which it is understood that the rate of work hardening of the upper bainite is lower than that of the fine pearlite. Also in Figure 5, the effect of the transformation temperature on the work hardening (ΔTS) is shown. In this case, since the drawing limit differs depending on the structure, an increase of tensile strength at 0.59 mm (88.5%, ε=2.17) was measured. Because the pearlite lamellar spacing decreases as the transformation temperature decreases, the work hardening

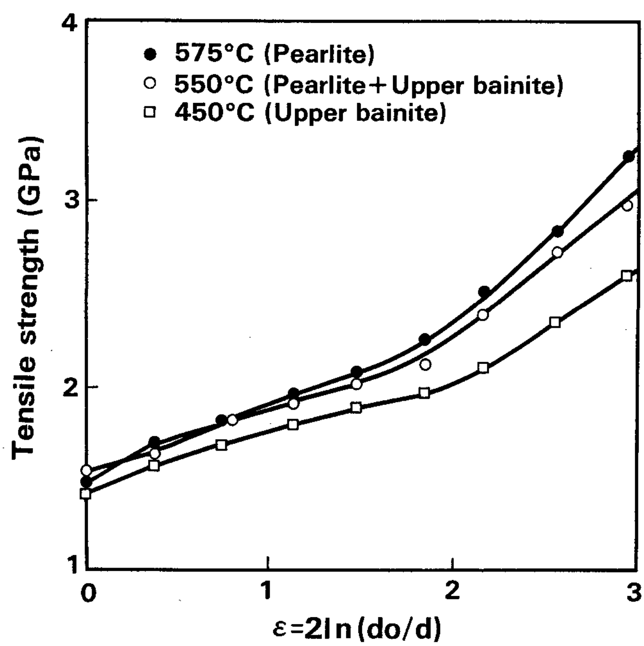

Figure 4. Effect of transformation temperature on work hardening behavior (Steel F, 0.96C-0.2Cr)

reaches a maximum at 575°C. However, at temperatures below 575°C, an upper bainite whose work hardening rate is lower than that of the pearlite is formed, resulting in the work hardening decreasing.

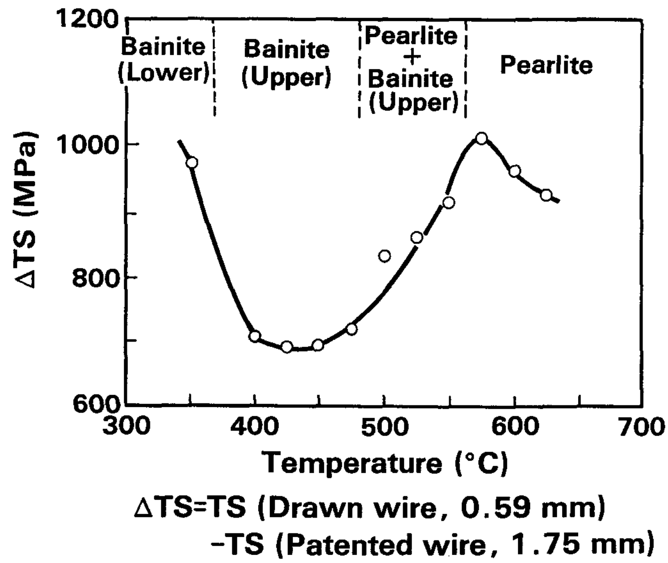

Figure 5. Effect of transformation temperature on work hardening (Steel F, 0.96C-0.2Cr, ε=2.17)

Effect of microstructure on delamination resistance of steel wire: A wire of 1.75 mm in diameter was drawn as thin as 0.30 mm after patenting at temperatures of 600°C, 575°C and 550°C. Table 2 shows the microstructure and mechanical properties of the wires. It indicates that though the strength of patented wire increases with a lowering of the lead bath temperature, the strength of filament wire is reversed to reach a maximum at 575°C.

TABLE 2

Microstructure and mechanical properties of wires (Steel F)

Lead bath temp (°C)	Patented(1.75mm)			Drawn(0.30mm)				Work hardening (GPa)
	TS (GPa)	RA (%)	Structure※	TS (GPa)	RA (%)	Twists (100d)	Delamination	
600	1.45	36.3	P	3.76	38.4	23.9	Not occurred	2.31
575	1.50	31.6	P+B	3.91	38.6	25.4	Not occurred	2.41
550	1.52	32.2	P+B	3.83	38.6	17.5	Occurred	2.31

※) P:Pearlite, B:Upper bainite

It should be noted here that the delamination occurred in the wire where the upper bainite is formed. This, as stated above, would be caused by the heterogeneity of the microstructure of wire patented at 550°C. In other words, since the fine pearlite contains an upper bainite having a lower flow stress than that of the fine pearlite and a different work hardening behavior (deformation mode), strain is concentrated on the upper bainite in the drawing process. The result is that microcracks initiate in the upper bainite phase, which would develop to the delamination in a high-strength wire.

Optimum temperature for lead patenting: A summary of the results described above is shown in Figure 6, which indicates schematically an optimum temperature for lead patenting. It is important to select the optimum temperature from the viewpoints of the work hardening during drawing and delamination resistance rather than the strength of patented wire. The optimum temperature discussed here is a temperature at which the upper bainite is not produced, i.e., a temperature just above the nose in TTT diagram.

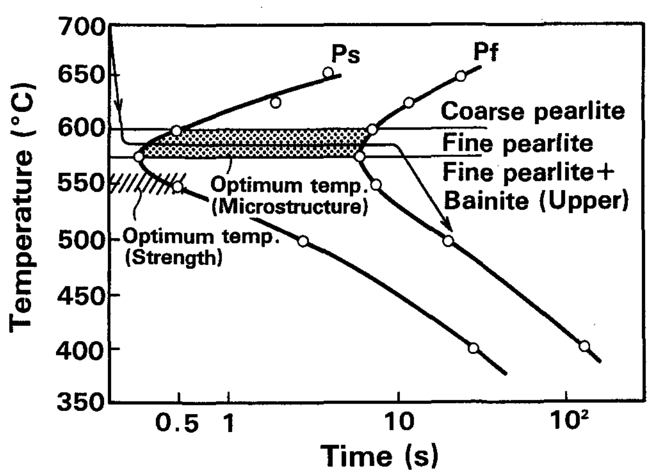

Figure 6. Schematic representation of optimum patenting temperature

Hypereutectoid Steel

Composition and transformation behavior: In this paper, steels with a C content of 0.90 mass% or more are defined to be a hypereutectoid steel and assumed to contain about 0.2 mass%Cr. A small amount of Cr is added for the purpose of improving the pearlite morphology and refining the lamellar spacing. However, adding Cr in excess of 0.25 mass% has a critical effect on the transformation behavior, thus it has been determined to add about 0.2 mass%Cr. Addition of Mn has been kept as low as about 0.3 mass% because it is prone to segregate and also delays the transformation of a segregated portion.

Figure 7 shows an example of a TTT diagram of hypereutectoid steel, from which it is found that the TTT diagram is almost similar to that of the plain carbon eutectoid steel. In view of the fact that the hypereutectoid steel can be patented in almost the same conditions as with the eutectoid steel, the industrial significance of the hypereutectoid steel is great.

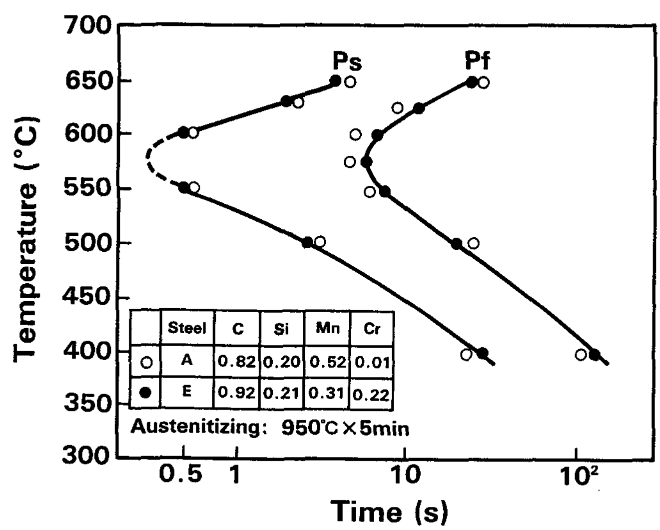

Figure 7. TTT diagram of hypereutectoid steel

<u>Proeutectoid cementite</u>: The precipitation of thick proeutectoid cementite onto the austenite grain boundaries deteriorates the drawability of wire rod (cuppy breakage). In order to extend the application of hypereutectoid steel from a limited sphere such as needles, tools, etc. to general wire products, it is indispensable to make the precipitation behavior of proeutectoid cementite clear and establish a precipitation prevention technique.

The authors, with the use of vacuum melted 0.2 mass%Si-0.5 mass%Mn steels having different C contents, investigated the effects of C content and cooling rate on the precipitation of proeutectoid cementite onto the austenite grain boundaries. An alkaline sodium picrate solution etching (JIS G0551) was employed for emergence of the proeutectoid cementite.

Figure 8 shows the experimental results. In general, the cooling rate of 5.5 mm wire rod in Stelmor-cooling is 10 to 15°C/s at the center of the wire rod. From Figure 8, it can be concluded that no proeutectoid cementite is precipitated in a Stelmor-cooled wire rod so long as the C content of steel is less than approximately 1.10 mass%. This means that even a wire rod produced from hypereutectoid steel is able to be drawn without lead patenting.

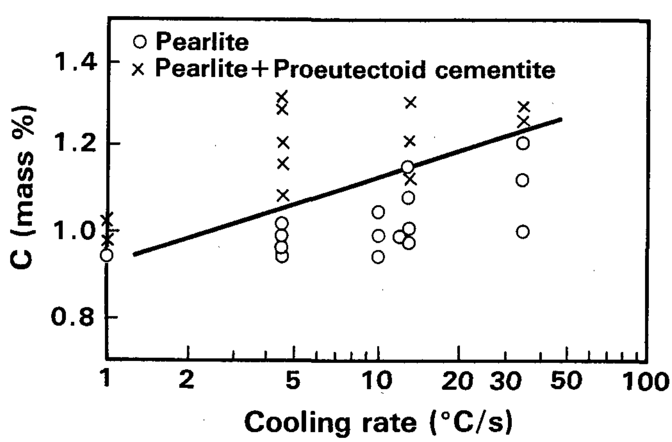

Figure 8. Effects of C content and cooling rate on proeutectoid cementite precipitation in 0.2Si-0.5Mn steel

A method has hitherto been proposed, which adds such element as Si [3] or Co [4] for suppressing the precipitation of proeutectoid cementite of hypereutectoid steel. But, as seen from this experimental result, the precipitation of proeutectoid cementite is able to be prevented if only the cooling rate corresponding to C content is secured.

Lamellar spacing of pearlite: Figure 9 shows the effects of C and Cr on a pearlite lamellar spacing at an isothermal transformation. At a temperature range of over 625°C, according to the Zener relation [5] ($1/\lambda \propto \Delta T$, λ: Lamellar spacing, ΔT: Supercooling), the lamellar spacing depends only on the supercooling and the effect of C content is scarcely recognized. However at a temperature below 600°C, which is a practical patenting temperature range, the diffusion rate of C decreases and therefore, the measured lamellar spacing deviates from the Zener relation [6]. In this temperature region the lamellar spacing is reduced by the increase of C content. Cr refines the lamellar spacing regardless of the transformation temperature because it decreases a cementite/ferrite interfacial energy.

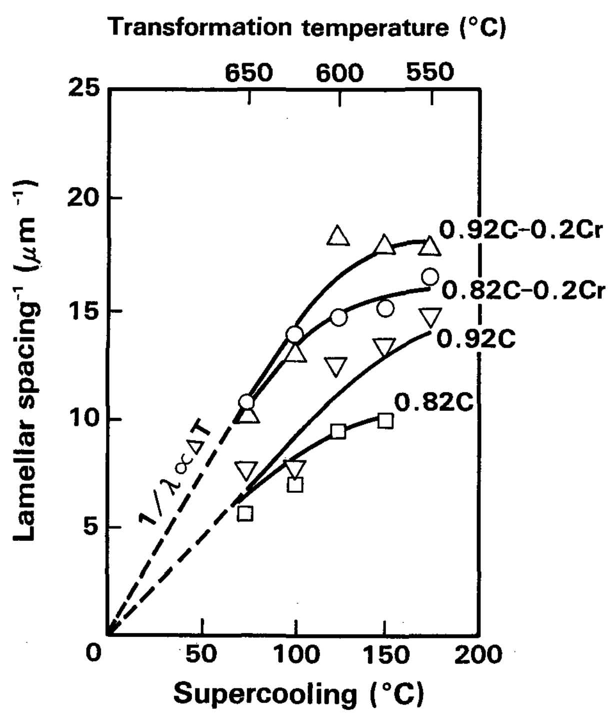

Figure 9. Relationship between pearlite lamellar spacing and transformation temperature

Thickness of cementite plate: The thickness of cementite plate composing pearlite was calculated for the pearlite transformed at a temperature of 575°C. The results are shown in Table 3. It is clear that the lamellar spacing decreases on account of the increase of C content and also the addition of Cr, and accordingly the cementite plate thins. This raises the wire drawability as described later [7].

TABLE 3

Lamellar spacing of pearlite and thickness of cementite

	0.82%C		0.92%C	
	0 Cr	0.2%Cr	0 Cr	0.2%Cr
Lamellar spacing (nm)	100	67	76	57
Thickness of cementite(nm)	12.8	8.6	10.9	8.2

1) Transformation temperature: 575°C
2) Thickness of cementite: Calculated values

So far, it has been considered that even if C content is increased in excess of an eutectoid composition, 1) the lamellar spacing is not refined, 2) the cementite plate thickness, and 3) a mean ferrite path merely lessens. This is because the previous studies were conducted at a high temperature of over 600°C, where the diffusion rate of C is sufficiently high. Even in this experiment, when the pearlite was transformed at a high temperature of over 625°C, the lamellae refinement effect of C was not observed as in the previous studies (Figure 9).

Strength of patented wire: A hypereutectoid steel having different C content was lead patented at a temperature of 575°C (nose temperature). Figure 10 shows the effect of C content on the tensile strength of the patented wire. Even in the hypereutectoid steel, as in a hypoeutectoid steel, the strength of patented wire is enhanced almost in proportion to the increase in C content.

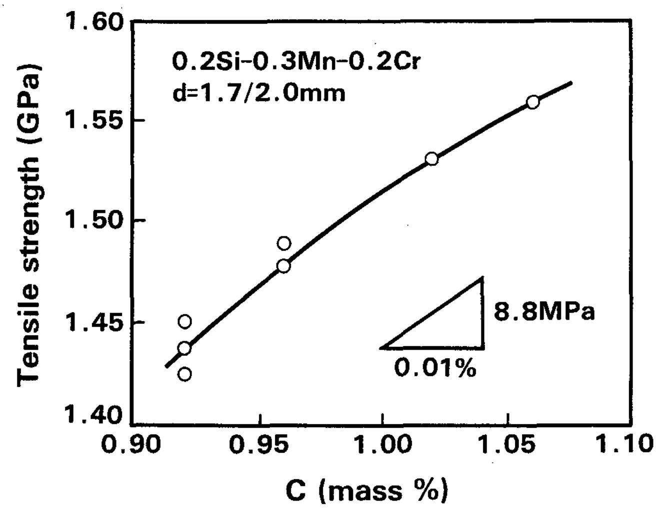

Figure 10. Effect of C content on tensile strength of lead patented wires (LP: 575°C × 12s)

Work hardening: 1.80 mm wires having different C content were lead patented at 575°C and drawn to 0.30 mm. Figure 11 shows the effect of C content on the work hardening. The work hardening increases sharply with the increase of C content. This is because the pearlite lamellar spacing decreases due to the increase of C content.

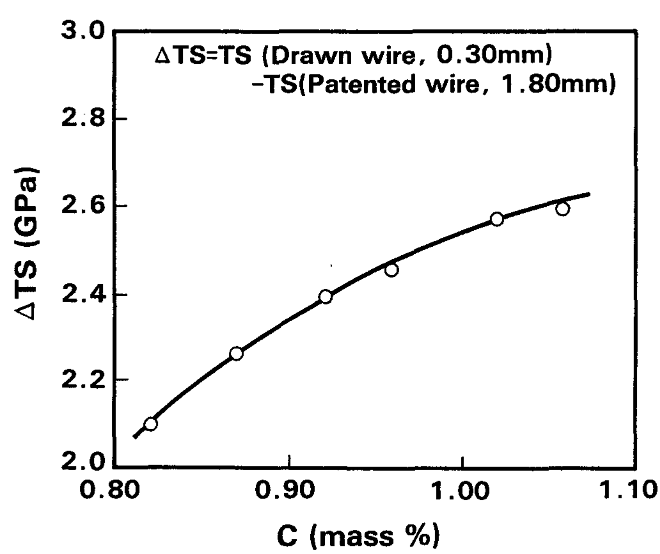

Figure 11. Effect of C content on work hardening of lead patented wires (LP: 575°C × 12s)

<u>Drawability of wire rod</u>: A Stelmor-cooled wire rod (5.5 mm) made from 0.96 mass%C-0.2 mass%Cr steel (Steel F) was drawn without lead patenting. As shown in Figure 12, the wire rod of 5.5 mm can be drawn as thin as 1.55 mm (ε=2.53) free of delamination. This is virtually the same as the drawability of 0.82 mass%C steel. The reason why the wire rod made from the hypereutectoid steel has a high drawability is that the precipitation of proeutectoid cementite has been prevented and the cementite plate has become thin, resulting in an improved ductility of pearlite.

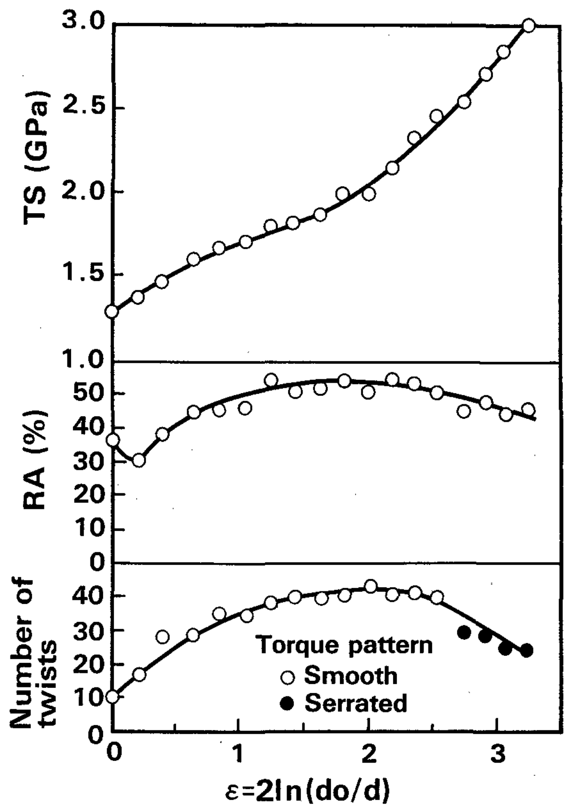

Figure 12. Drawability of Stelmor-cooled wire rod (Steel F, 0.96C-0.2Cr, do=5.5mm)

Drawability of finally patented wire: Wires with a varying C content from 0.82 to 0.92 mass% and diameter from 1.7 to 2.0 mm, were lead patented at 575°C and subsequently drawn to wires of 0.30 mm in diameter. Figure 13 shows the relation between C content and strength of 0.30 mm wire. It indicates that the maximum strength free of delamination increases in agreement with the increase in C content and also even if C content is increased, the drawability does not deteriorate.

Thus far, a view has prevailed that the hypereutectoid steel cannot be utilized for raising the wire strength by reason of its low ductility. This seems to be because the patenting conditions (austenitizing conditions and transformation temperature) were different from those in this experiment. In fact, it is possible to assure a sufficient drawability even for the hypereutectoid steel if only the optimum patenting conditions are selected.

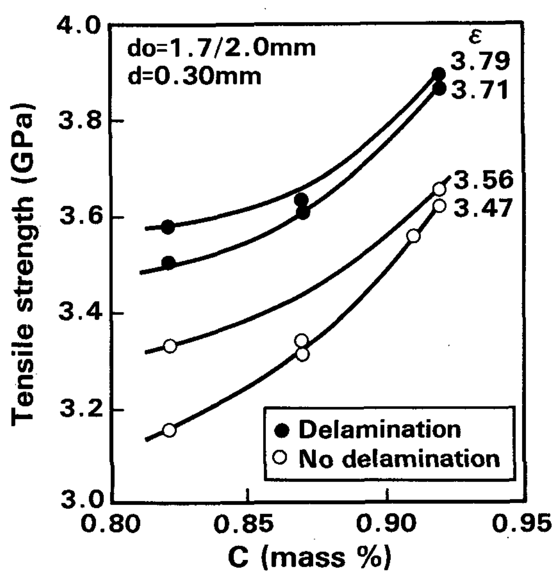

Figure 13. Effect of carbon content on threshold strength of delamination (0.2Si-0.3Mn-0.2Cr, LP: 575°C × 12s)

Manufacture of Higher Strength Wire

Steels having the composition shown in Table 4 were melted with 250 t BOF (basic oxygen furnace) at Kimitsu Works of Nippon Steel Corporation and then cast into a bloom of 300 mm × 500 mm through continuous casting after secondary refining. After the blooms were made into billets of 122 mm square by bloom and billet rolling, they were rolled into wire rods of 5.5 mm in diameter and subsequently Stelmor-cooled. For drawing, a continuous drawing machine was employed. Lead patenting was performed on all for patenting.

The tensile strength of wire is shown in Figure 14. It is possible to greatly raise the strength of existing highest strength wire of eutectoid steel wire (i.e., piano wire) with the hypereutectoid steel, and thus the maximum strength of 0.04 mm wire has reached to as high as 5.70 MPa.

TABLE 4

Chemical composition of steel (mass%)

C	Si	Mn	P	S	Cr	Al
0.96	0.21	0.30	0.005	0.003	0.21	0.001

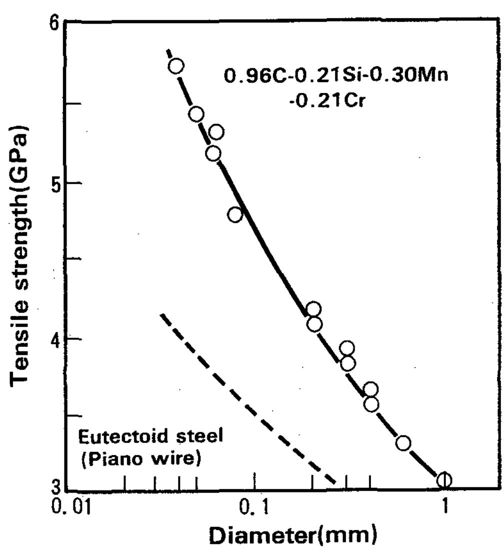

Figure 14. Tensile strength of hypereutectoid steel wire

CONCLUSIONS

In order to endow a high strength steel wire with even higher strength, research was conducted on strengthening by increasing the work hardening. After the investigation of a microstructure providing a high work hardening rate and a great delamination resistance, the effect of increasing carbon content was examined. The results obtained are as follows:

(1) Reducing a non-lamellar structure (upper bainite) out of pearlite makes it possible to increase the delamination resistance together with the work hardening rate during drawing.

(2) An optimum patenting temperature, from the viewpoint of microstructure, is a temperature just above the nose in TTT diagram regardless of the steel composition.

(3) By controlling the microstructure properly, it is possible to manufacture a steel wire having a far higher strength than that of the ordinary eutectoid steel wire, using a hypereutectoid steel as a raw material.

(4) The maximum strength of 0.04 mm wire manufactured from 0.96 mass%C-0.2 mass%Cr steel without delamination occurrence has reached to as high as 5.70 GPa.

REFERENCES

1. DeHoff, R.T. and Rhines, F.N., Quantitative Microscopy, McGraw-Hill, New York, 1968, pp.99-102.
2. Aihara, K., Sudo, C., Tsukamoto, T. and Nishimura, S., High-strength and high-fatigue limit zinc galvanized steel cord for ACSR. Wire J., 1983, 16, No. 4, 50-61.
3. Heckel, R.W. and Paxton, H.W., Rates of growth of cementite in hypereutectoid steels. Trans. Metall. Soc. AIME, 1960, 218, 799-806.
4. Kanetsuki, Y., Improvement of drawability of hypereutectoid steel wires by Co addition. Tetsu-to-Hagane (in Japanese), 1990, 76, 120-127.
5. Zener, C., Kinetics of the decomposition of austenite. Trans. Amer. Inst. Min. Metall. Engrs., 1946, 167, 550-595.
6. Bolling, G.F. and Richman, R.H., Forced velocity pearlite. Metall. Trans., 1970, 1, 2095-2104.
7. Langford, G., Formation of pearlite. Metall. Trans., 1977, 8A, 861-875.